CheerBrush: A Novel Interactive Augmented Reality Coaching System for Toothbrushing Skills in Children with Autism Spectrum Disorder

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Autism Spectrum Disorder (ASD) is a common neurodevelopmental disorder that impacts one in every 54 children in the United States. Some children with ASD have learning and fine motor skill challenges that contribute to difficulties completing daily living tasks such as toothbrushing. Lack of toothbrushing skills may cause increased need for dental care and negative social feedback from peers. Technology based intelligent support systems offer the advantages of being accessible, engaging, and cost-effective. In this work, we present a novel interactive augmented reality coaching system, CheerBrush, to improve the toothbrushing skills of children with ASD. CheerBrush allows children to manipulate virtual objects like a toothbrush and toothpaste with their actual hand motions to practice the steps of toothbrushing. The virtual tasks of CheerBrush demonstrate these steps using audio and visual cues, while also showing the brushing process through a virtual avatar. CheerBrush also assesses toothbrushing skills with a custom designed mechatronic toothbrush to evaluate the system's coaching effectiveness. A feasibility study with 12 children (six children with ASD and six typically developing children) was conducted to evaluate the acceptability and effectiveness of CheerBrush. The data showed improvements in the toothbrushing motions and reduced stress for the children in the post-test. CheerBrush detects real-time movement of children and interacts with them by augmented reality, feedback and multimodal hints. We believe that CheerBrush has the potential to provide a low-cost, engaging and, beneficial intelligent support system to improve the toothbrushing skills of children with ASD.

CCS Concepts: • **Human-centered computing** → **Interactive systems and tools**; • **Applied computing** → *Interactive learning environments*; • **Hardware** → Electromechanical systems;

Additional Key Words and Phrases: Augmented reality, virtual reality, virtual tasks, behavioral coaching, body gesture, human-computer interaction, autism spectrum disorder, support system, toothbrushing

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1 INTRODUCTION

Autism spectrum disorder (ASD) is a common neurodevelopmental disorder characterized by differences in communication and social interaction together with restricted, repetitive and stereotyped patterns of behavior [1, 2, 3]. One in 54 children is diagnosed with ASD in the US [4], with prevalence rates amongst school-aged children increasing from 1.16% to 2.00% between 2007 and 2012 [5]. Although ASD is a neurodevelopmental disability with life-long impact, intensive educational practices and behavioral supports can make a positive impact on the lives of children with ASD [6, 7]. However, conventional supports for ASD are costly and often inaccessible [8, 9] due to limited resources, with some treatments negatively impacted by low child engagement or motivation [10]. It is estimated that the average lifetime cost for ASD care is up to $3.2 million for each individual with ASD and their families [11]. Therefore, the development of novel ASD support paradigms that can provide low-cost and efficacious support options for a broader ASD population are important and in urgent need. In this work, to respect multiple stakeholder perspectives, we interchangeably use both identity-first ("autistic") and people-first language ("children with ASD") [12].

In recent years, computer assisted ASD supports have shown potential due to their low cost, their appeal to children with ASD, and their relatively broader accessibility [13, 14]. Many children with ASD exhibit an affinity for computer technologies that leads to a higher level of engagement and fewer interfering behaviors in computer-based interactions [15, 16, 17]. In particular, **virtual reality (VR)** technologies that allow users to actively participate in the interactive and immersive simulated situations have been used to provide an attractive, cost-effective, replicable, quantitatively measurable, and controlled teaching environment with real-time feedback [18, 19].

Several VR-based systems have been developed to investigate and teach important life skills to autistic children and results suggest that children were able to appropriately understand, use, and react to virtual environments [20, 21]. For instance, a novel VR-based driving stimulator was developed to teach driving skills to teenagers with ASD [22]. The participants drive a virtual vehicle in a virtual city to complete driving tasks such as passing traffic lights, pulling over, and entering the highway. The simulator detects participant errors and eye gaze and provides appropriate instructions. Another VR-based system, a virtual haptic training system, was designed to assess and improve fine motor skills of autistic children [23]. The system allows participants to grip and move virtual objects in games and thus provides opportunities for them to improve finger and hand motor control. Additionally, a VR-based social cognition training system was developed where participants can practice social tasks including social introductions, conversation initiation, meeting friends, and other social interaction scenarios [24]. These VR-based support systems have been shown to be acceptable, beneficial, as well as accessible to children with ASD to help with a variety of living skills.

The success of VR ushered in **augmented reality (AR)** into support systems for autistic children. AR is a computer-based technology that superimposes real-world actions and images on computer-generated displays of virtual characters, scenarios, and interactions, providing a composite view of the situation [25, 26]. In recent years, AR-based supports for children with

ASD have been reported in literature. A mirror-like AR system that allowed participants to see themselves and their constructed skeletons on the screen was developed to teach autistic children about their own body and allowed them to imitate body gestures [27]. In another study, a virtual agent was developed to let young adults practice job interviews [28]. The participant wears a Magic Leap AR goggle [29] so that they can see a virtual interviewer in the real world and interact with it. In [30], an AR smart glasses system was developed to coach social communication where gamified AR applications provided children with ASD coaching for emotion recognition, face directed gaze, and eye contact. The coaching was found to be well tolerated, engaging, and fun. Although an emerging field, existing research to date has shown the potential of AR-based support systems to help autistic children learn life skills by immersing them in real-life situations [31].

In this paper we present an AR-based coaching system called CheerBrush for helping children with ASD with their toothbrushing skills. Many children with ASD have challenges maintaining good oral health [32, 33]. Poor oral health and resulting breath odor can negatively affect individual self-esteem [34] and impede social interactions across the life-span [35]. Autistic children already experience challenges in understanding social situations and initiating social interactions [36] and poor oral health could exacerbate this situation. Increased plaque can also lead to more dental visits, which can traumatize some children and adults with ASD due to non-compliance, anxiety, and sensory sensitivity [37]. Children with ASD may have trouble learning how to brush their teeth and need assistance when brushing [38, 39]. This may be because of differences in motor dexterity, learning skills, and sensory sensitivity [40, 41]. Despite parents being an important part of teaching skills to children, parental interventions are not always possible for teaching children with ASD adequate toothbrushing skills [42]. Parental teaching attempts can gradually lose efficacy over times [43] and may be especially challenging if autistic children have limited motivation to attempt or complete a toothbrushing task [44, 45]. At the same time, technology-based systems have been shown to motivate children with ASD [13] and help them meet goals that would otherwise be difficult due to ASD symptoms [46]. Therefore, children with ASD could benefit both medically and socially from technology enhanced toothbrushing supports.

In recent years, there have been a few technology-based systems that aim to help children with ASD to improve their toothbrushing skills. In [47], a toothbrushing training program on tablets shows the steps of toothbrushing to autistic children, which resulted in some improvement. Another study used marker-based video triggering software to show children with ASD a clip of a peer brushing her teeth [48]. All participants learned how to brush their teeth and maintained the skill in their daily life nine weeks after the study. A **picture exchange communication system (PECS)** based toothbrushing program was used on gingival health in autistic children. The parents of 37 children rated the program as useful in improving gingival health for children with ASD [49]. A cartoon game called "Brush Up" was utilized on children with ASD and it resulted in significant reduction of visible plaque on post-support [50]. A pilot study with this app showed improvement on toothbrushing duration and distribution on 34 5—6 year-olds [51]. An interactive aid for teeth cleaning was developed utilizing an Arduino microcontroller and a custom designed software platform to reduce the burden of parental supervision and encourage children to brush their teeth [52]. There are also smartphone applications focused on motivating children to learn, perform and maintain optimal oral hygiene [53]. Although promising, most of the existing studies are limited to showing photos and video clips in an open-loop manner and did not teach toothbrushing skills in an interactive way to provide real-time feedback and instructions based on the performance of the children. We believe that a closed-loop system that can engage children through active participation and provide adaptive and individualized feedback in real-time will likely be more engaging and effective in imparting skill as is evidenced in other skill learning activities [23]. In addition, immersive learning experiences are more likely to help transfer skills into real-life situations [54]. In this work, we focus to help autistic children with their oral health through an immersive AR-based support system.

Thus, we present CheerBrush, a novel interactive AR coaching system for toothbrushing skills, to help autistic children learn toothbrushing skills. CheerBrush, which has both a coaching mode and an assessment mode, is an AR-based system that teaches children with ASD how to brush their teeth in a fun, playful way. In the coaching mode, CheerBrush combines a virtual realty task environment with an augmented reality motion tracking system to create an immersive practicing and learning experience for toothbrushing. The VR provides a toothbrush and toothpaste in the real-world surroundings with an avatar that guides children through the whole brushing process in a step-by-step manner with appropriate verbal and gestural help and feedback. The system provides several levels of practice opportunities based on task difficulty. The AR mechanism using the Microsoft Kinect V2 camera projects the body of the children on to the virtual environment and tracks and maps their actual brushing motion in real-time and overlays it on their face within the VR task environment. A supervisory controller monitors the whole process in a closed-loop manner and informs the avatar how to guide each participant. In the assessment mode, CheerBrush involves children brushing with an actual custom-designed mechatronic toothbrush equipped with sensors to measure their physical brushing motion and overlays the motion on to their face in the VR environment without any guidance from the avatar. In addition, in both coaching and assessment modes, CheerBrush measures stress responses of children through a wearable physiological sensor, E4. The idea is to observe whether children experience stress during brushing and whether stress level reduces with coaching using CheerBrush.

The primary contributions of this work are the design and development of a novel AR-based daily living activity coaching and assessment system for children with ASD that can provide autonomous coaching for toothbrushing in an individualized and adaptive manner based on quantitative measurement of the brushing process and can assess the impact of coaching. We also provide results from an initial feasibility study with autistic children as well as **typically developing (TD)** children to demonstrate the potential of CheerBrush. The rest of this paper is organized as follows: Section 2 describes the CheerBrush system design including the software development. Section 3 presents the feasibility study to validate the acceptability and potential of the system through human-participant experiments. It also presents the experimental results and data analysis. Finally, we present a summary of accomplishments and limitations of the current work, and future research directions in Section 4.

2 CHEERBRUSH SYSTEM DESIGN

CheerBrush shows the real-world surroundings, observes the toothbrushing movements of children, moves virtual objects based on real-time movements of children, and provides virtual reality-based coaching to the children. It also measures peripheral physiological response signals during coaching and movement data during the pre- and post-tests. There are several modules of CheerBrush: (1) an **augmented reality platform (ARP)** that projects the real-world surroundings around the children and demonstrates toothbrushing through the animation of virtual avatars as well as highlighting the target areas; (2) a Microsoft Kinect V2 sensor to capture the toothbrushing movements and facial expressions of the children in real-time; (3) a customized mechatronic toothbrush that can measure the toothbrushing motion and location of brushing on the face of children; (4) an E4 wearable sensor to capture physiological responses to infer stress experienced by the children during coaching; and (5) a supervisory controller to ensure communications among

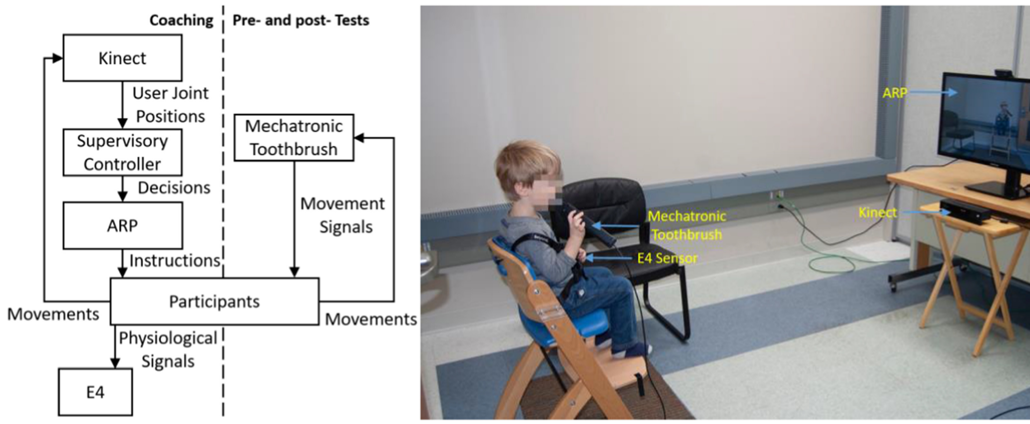

Fig. 1. System architecture and setup.

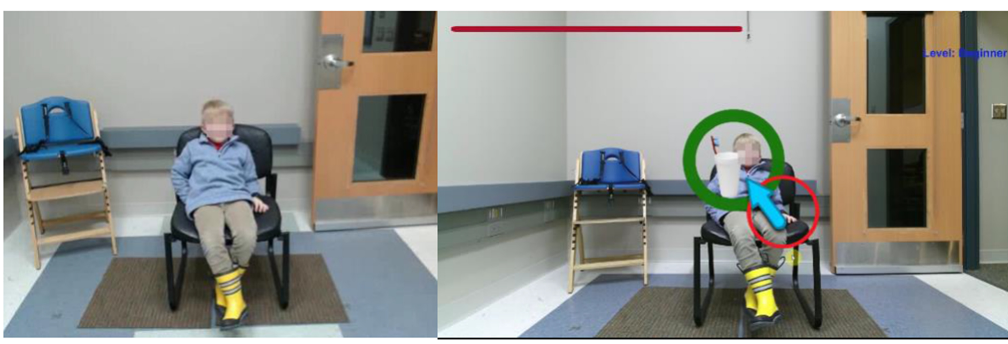

Fig. 2. Real-world picture of the child in the experiment room (left) and his projection on the ARP (right).

various system modules, to provide appropriate feedback to the children, and to collect data for analysis. The system architecture is shown in Figure 1.

2.1 ARP Development

The ARP was designed to display the combined real-world surroundings with the virtual environment and objects. The virtual environment is the real-world surrounding where the child is seated, and the relevant virtual objects include a virtual toothbrush, a glass cup, and toothpaste. Its **graphical user interface (GUI)** uses the video stream of the Kinect as the base display so that the GUI works as a mirror. Children can see themselves with their real-world surroundings and their body movement in real-time that are superimposed on to the virtual world. The children can manipulate the virtual objects on the ARP by grasping them. They move their arms, hands, and fingers in the air in front of them, which are then mapped on to the virtual space where the virtual objects lie. The GUI is presented on a 40-inch computer screen and children can observe themselves in the real-world surroundings. The ARP was designed and developed using the Unity 3D game engine [55], which is a developmental platform to help create VR and AR environments. The program can zoom in and out on the ARP by adjusting the Unity canvas scale so that children can manipulate virtual objects further away or focus more on the facial area. The ARP gives real-time instructions and feedback to the children. A screenshot of the ARP and the real-world that it represents at the same moment during the experiment are shown in Figure 2.

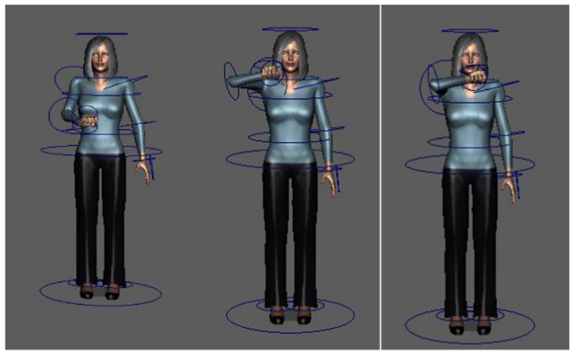

Fig. 3. The embedded avatar with animation capability in ARP.

As shown, children can see themselves in an augmented mirror projected in front of them, and they can interact with the virtual objects. We designed visual cues in the ARP to help children find the virtual objects and understand where and when to use them. For example, the red circle in Figure 2 indicates where the hand is, and the green circle highlights the brush to grab. These visual cues transfer to the correct positions and orientations corresponding to the gestures of children. Within the ARP, the visual cues take shape as blinking arrows, semi-transparent circles, and squares that highlight the areas of interest. The colors and the blink rate of these cues vary to keep the children engaged. There are also visual rewards to keep the children motivated and provide reinforcement for their behaviors. For instance, a virtual gold coin will flip and jingle when a child completes a subtask and his score will increase by 1 point, as displayed on the screen. The GUI was designed using feedback from behavioral therapists in the team and parents of children with ASD.

To demonstrate the appropriate toothbrushing movements, an avatar with several animations was created and embedded in the ARP as can be seen in Figure 3. Virtual avatars have been frequently used in VR systems for autistic children [56, 57] and they have been shown to effectively deliver audio and motion instructions [58]. Children appear to be better motivated by virtual avatars and learn more efficiently [59]. In order to clearly instruct and encourage the children, a few pre-recorded audio clips such as “Grab the brush”, “Go back and forth”, “Good job”, and “You are doing great” were delivered through the avatar at appropriate times using the supervisory controller.

2.2 Real-time Movement Detection

In order to create a real-time closed-loop coaching system, CheerBrush needs to recognize the children and their brushing motion along with the location of their brushing within the facial area so that it can provide real-time instructions and feedback as well as assess the effectiveness of brushing. We have integrated a Microsoft Kinect V2 and its SDK to accomplish these objectives. The Kinect uses a color camera and a depth sensor to provide video stream and compute human joint positions and facial expressions. In particular, the joint positions are used to capture the hand and head positions of the children. We also use Kinect data to determine whether the hands of children are open or closed (see Section 2.6). The facial expressions data are used to determine whether the eyes and mouths of children are open. The approximate eye gaze of the child is detected by the computer vision algorithm of the Kinect to infer whether children are looking at the screen or looking away. The video stream of Kinect is updated at about 30 frames per second, which is sufficient for smooth display. The joint positions of children are updated at about 10 Hz. We program the Kinect such that it tracks the first child that enters its field of view.

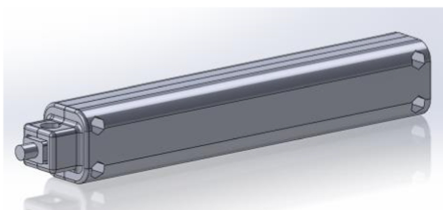

Fig. 4. The CAD design of the mechatronic toothbrush.

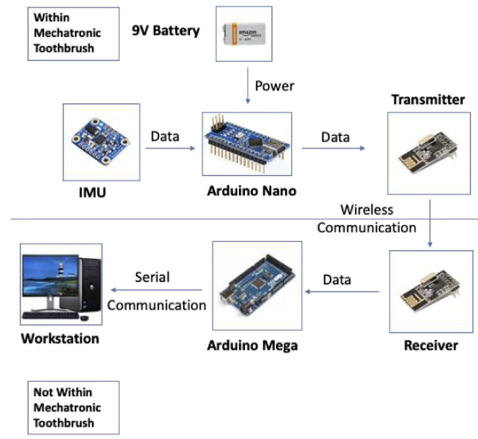

Fig. 5 Electronic components and communications within the mechatronic toothbrush.

In order to smoothly combine the physical movement of children with the motion of virtual objects, we needed to calibrate the ARP. For example, when the children grab a virtual toothbrush and bring it to their mouth, the motion of the virtual toothbrush must be consistent with the motion of their arm and mouth to make it appear that the toothbrush is moving as grabbed and touching their mouth. In order to perform this calibration to map the motion of children with different sizes, we introduced the following coordinate transformation between the real-world coordinates of the children detected by the Kinect and the ARP canvas coordinates as shown in Equations (1) and (2).

$$x_c = a_1 x_r + b_1 \tag{1}$$

$$y_c = a_2 y_r + b_2 \tag{2}$$

Here x_c and y_c are the canvas coordinates of children's joints on the ARP display and x_r and y_r are the real-world coordinates of children's joints detected by the Kinect. The coefficients a_i and b_i are related to the physical sizes of children. To conveniently and precisely acquire these coefficients to customize CheerBrush for children of different sizes, we conducted a human centered design approach where we invited five children of ages between 3 and 8 years. We measured their arm lengths, head circumferences, and heights since these were the key physical differences of the children that impacted the complementary motion of the virtual objects in our system. We then determined the coefficients in Equations (1) and (2) using regression analysis as functions of the above-mentioned key physical parameters through a task where the children were required to grab and move a virtual ball.

2.3 Mechatronic Toothbrush

We needed to measure and record how the children use a toothbrush in the real-world to both assess whether the coaching is effective and to provide feedback. In order to achieve these objectives, we designed a mechatronic toothbrush that approximately replicated the shape and dimensions of a commercial electronic toothbrush for kids [60], with an integrated motion measurement unit. The case of the brush as shown in Figure 4 was designed using the **computer aided design (CAD)** software SolidWorks [61] and 3D printed by a Stratasys 3D printer [62]. The mechatronic toothbrush was 22.86 centimeters long and weighed 94.4 grams. The electrical elements, which included an **inertial measurement unit (IMU)** [63], an Arduino Nano microcontroller [64], a wireless transmitter [65] and a 9V Lithium-ion rechargeable battery, were then integrated inside the 3D printed case. The electronics components and the communication scheme are shown in Figure 5. The IMU measures the inertial forces along the three orthogonal axes and then computes the roll, pitch, and yaw angles of the toothbrush. It also measures the absolute orientation and the angular velocity at 100 Hz and sends them to the Nano controller through I2C communication protocol. The Arduino Nano is a small microcontroller with general input and output ports that runs at 16 MHz. The wireless transmitter forwards the data from the microcontroller to the supervisory controller on a workstation. The wireless transmitter is a single chip radio transceiver with a 2.4 GHz radio band, a maximum baud rate of 2 Mbps, and a maximum transmission range of 100 meters. The total cost of the prototype is $71 excluding the computer.

We have developed software to gather and send the roll, pitch, and yaw angles from the IMU to the supervisory controller in the following manner. First, in the Arduino **integrated development environment (IDE),** we sent the data from the IMU to the radio transmitter. Then, another controller, an Arduino Mega [66], connected to the workstation, read from the radio and sent the data to the serial port of the workstation. Next, the supervisory controller read the data from the serial port and formatted the data with time stamps and recorded them for future analysis.

From these signals, the positions of the tip of the mechatronic toothbrush were computed by Equations (3)—(5).

$$x_e = x_h + 0.5L_{MT} \sin\theta \tag{3}$$

$$y_e = y_h + 0.5L_{MT} \sin\psi \cos\theta \tag{4}$$

$$z_e = z_h + 0.5L_{MT} \cos\psi \cos\theta \tag{5}$$

Here x_e, y_e and z_e are the 3D position coordinates of the end of the mechatronic toothbrush; x_h, y_h and z_h are the 3D position coordinates of the hand of children detected by Kinect; ψ and θ are the roll and pitch angles of the mechatronic toothbrush as detected by the integrated IMU in the mechatronic toothbrush; and L_{MT} is the length of the mechatronics toothbrush. From the motion of the tip position, we computed several metrics such as the frequency of a child's brushing movement, the variances of the brushing motion and the areas and angles the child had covered during brushing. We evaluated toothbrushing skill level by comparing these data to the data obtained from adults who were able to properly brush their teeth. Note that we used a virtual toothbrush during coaching for ease of coaching due to the controllability and flexibility of the virtual environment. We used a real brush during assessment to explore whether skill learned during virtual interaction could generalize in real world.

2.4 E4 Wristband

In order to track the physiological responses and estimate the stress of the children during the coaching sessions, we used an E4 sensor [67]. The E4 wristband is a medical grade wearable device that collects physiological signals of **blood volume pulse (BVP)** and **galvanic skin response (GSR**), from which **heart rate (HR)** and skin conductance can be computed. It has the shape of a smartwatch and the children can wear it on their wrist. It has been demonstrated in the literature that peripheral physiological response data can be used to infer human mental states [68, 69]. In this research, we used the physiological data of children to infer their stress levels. We logged these data for offline analysis to understand whether the children were stressed during the activities. Such information will potentially guide us to improve task design and interaction protocols in the future.

2.5 Task Design

In consultation with several ASD clinicians and parents of autistic children, we deconstructed the process of toothbrushing into smaller subtasks, which were then used to demonstrate the toothbrushing process and guide the children. These subtasks were: “grab the brush”, “put toothpaste on the toothbrush”, “open your mouth”, “put the toothbrush on your teeth”, and “move the brush back and forth on your teeth”. We designed and created four levels of toothbrushing tasks with varying difficulties: “beginner”, “simple”, “medium” and “hard”, so that the children could first become familiar with CheerBrush and gradually get coached towards the complete toothbrushing process. The levels differed in multiple areas such as how children must grab the toothbrush, the number of times children must move the toothbrush back and forth on their teeth, and the application of toothpaste on the brush. For example, in the beginner level, children were not required to grab the brush; instead, as soon as the level began, the brush was virtually attached to their hand. In the simple level, children must actually grab the brush, and in the medium level, children must move the brush back and forth on their teeth five times as opposed to the three times which were required in the beginner and simple levels. After the children mastered the toothbrushing tasks in the beginner, simple, and medium levels, we introduced the toothpaste in the hard level. In the former levels, the toothpaste was already on the brush so it was not necessary for the children to grab the toothpaste and put it on the brush. In the hard level, however, the children must apply the toothpaste and move the brush back and forth on their teeth ten times to successfully complete the level.

2.6 Supervisory Controller

The primary purpose of the supervisory controller is to coordinate the step-by-step demonstration of toothbrushing in the ARP. In addition, the supervisory controller needs to ensure communication between the Kinect and the ARP, capture toothbrushing data from the mechatronic brush, and provide real-time feedback. The steps of toothbrushing and transitions among them were formalized through a **finite state machine (FSM).** We implemented the FSM using C# programming language in the integrated IDE of Microsoft Visual Studio. An FSM is a mathematical model of computation based on the ideas of a system changing state due to inputs supplied to it with conditions that govern state to state transitions with some states being the final states [70]. It is easy to use, provides powerful algorithms for synthesis and verification, and has been successfully used in game design. An FSM is defined by the quintuple $(Q, \Sigma, \delta, Q_0, F)$, where Q is the set of finite number of states, Σ is a non-empty set of symbols of input to the states, δ is the state transition function, Q_0 is the initial state, and F is the set of final states.

For our FSM:

$$Q_0 - Q_4 = \{Start, GrabBrush, BrushOnTeeth, Brushing, LevelFinish\}$$
$$\sum_i = \{x_h, y_h, z_h, s_h, \ldots, s_m, t\}$$
$$Q_0 = \{Start\}$$
$$\delta_1 : Q_0 \times \sum (User\text{Recognized}) \rightarrow Q_1$$
$$\ldots$$
$$\delta_5 : Q_3 \times \sum (EnoughTimes) \rightarrow Q_4$$
$$F = \{LevelFinish\}$$

The $Q_0 - Q_4$ are the states of the FSM. The Σ_i are the inputs of the FSM. The inputs are: positions of hand x_h, y_h and z_h; whether the hand and mouth are open or not denoted by s_h and s_m, respectively; positions of the mouth x_m, y_m and z_m; and the time spent in a certain level, t. δ_i are the state transition functions expressing the input needed for a certain state to move on to the next corresponding state. The Q_0 and F stand for the start and finish states, respectively. The

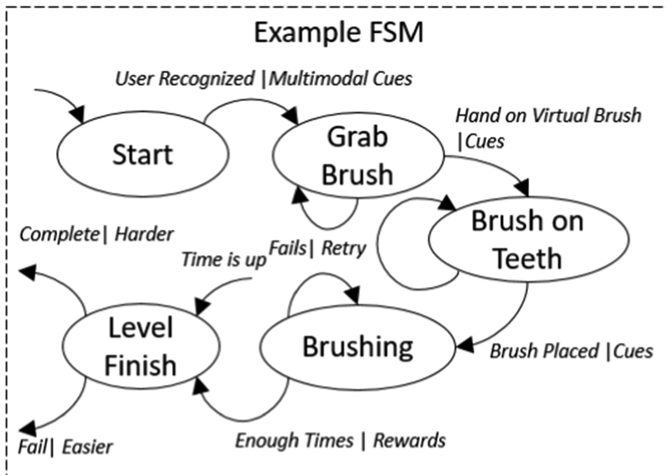

Fig. 6. An example FSM showing different states of the medium difficulty level.

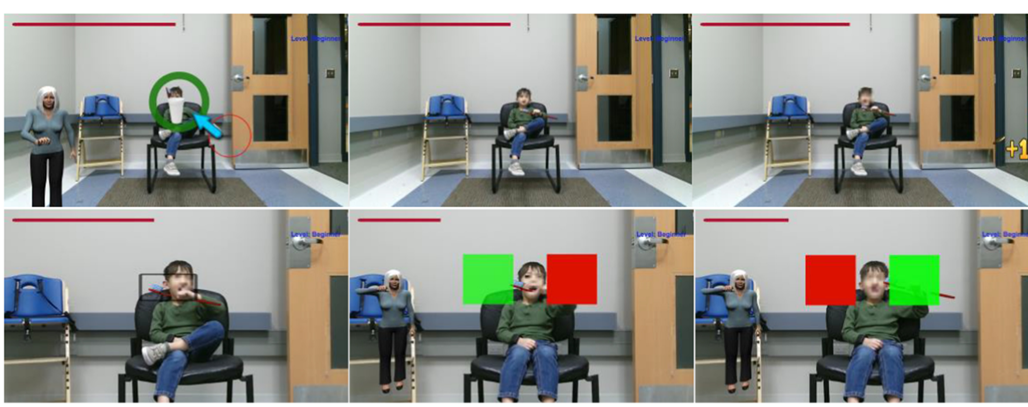

Fig. 7. ARP during different states.

start state and the finish state are shown as "Start" and "Level Finish" in Figure 6, respectively. There are five state-transitions functions to cover the virtual tasks that help FSM proceed from the current state to the following state based on inputs. The supervisory controller runs the FSM for the whole coaching procedure, communicates among different system components, and makes the right moves for different situations. An example FSM for the medium difficulty level is shown in Figure 6. Each difficulty level has a different number of state transition functions.

In Figure 6, the FSM starts with the "Start" state when the Kinect will be actively looking for the children. If it recognizes one, it will stop looking and take that child as the participant and move to the next state "Grab Brush". In the "Grab Brush" state, the virtual brush will show up on the ARP and the child is supposed to open her dominant hand, move it to the right position on the ARP, and close the hand to grab the virtual brush as shown in Figure 7. During the same time, multimodal cues will be delivered to the child, which are: a blinking arrow that continuously points from the hand of the child to the brush to indicate where to move to grab the brush, the avatar moving her arm and closing her hand to show how to grab the brush, and an audio cue saying, "Grab the brush". If successfully grabbed, the virtual brush will move with the hand of the child.

We noted in our pilot work that sometimes the image on the screen would flicker because of Kinect recognition errors of hand open and close state. We addressed this by designing a software fix that enabled the system to drop the virtual objects if and only if the hand close state was absent for a continuous three seconds of time interval during grabbing and moving. Rewards are given in the form of a falling gold coin with sound effects. A numerical score is added and shown with the audio cues offering encouragement such as “Good job,” or “Way to go”. The score is shown in the upper right corner of the ARP. Then the FSM moves on to the state “Put Brush on Teeth” where the cues for opening the mouth and putting the brush are provided. A blinking black box around the mouth will show up for the child. After successfully putting the brush on her teeth, the ARP automatically zooms in on the face of the children so that they can better observe the virtual cues around the face, as shown in Figure 7. Subsequently, the FSM will move on to the state “Brushing” and two blinking boxes will show up on the left and right side of the mouth to provide guidance with regard to the brushing motion. The child is supposed to move the brush from the current red box to the target green box. Once the target box is hit, it will become red and the other box (i.e., the former current box) will become green so that the child can move the brush back and forth. During the same time, the supervisory controller computes the speed of the back-and-forth motion. Appropriate audio cues “brush faster” or “brush slower” are provided to keep the brushing speed within an appropriate range. When either the task is completed or the time spent during a certain level reaches the limit, the state will directly move on to “Level Finish”. The FSM of different levels are similarly designed.

When the FSM of a single difficulty level reaches the final state, “Level Finish”, it moves on to a harder or an easier difficulty level based on whether the child completed the level. The difficulty levels, beginner, simple, medium, and hard, differ on various parameters including the time to brush back and forth, objects to manipulate such as the toothpaste, and degree of difficulty to grab the brush. The FSM runs with an average updating frequency of 48 Hz, which is fast enough to provide a smooth real-time interaction. We carefully debugged the system and since the system has only a small number of states, we applied an extensive brute-force test to explore every possible scenario to ensure that the FSM ran robustly. We did not observe any system glitches during experiments.

3 FEASIBILITY STUDY AND DATA ANALYSIS

3.1 Experiments

We conducted a feasibility study with children who did not know how to brush their teeth to explore the acceptability and usefulness of CheerBrush. We recruited 12 children (6 ASD and 6TD children; age range: 3—6 years) as participants. The inclusion criteria were: (1) height of at least 3 feet for successful Kinect recognition; (2) age 3—6 years; and, for children with ASD, (3) a documented diagnosis of ASD by a licensed clinical provider. Participants with ASD were recruited from a clinical registry which includes individuals with a medical diagnosis of ASD from a licensed clinical psychologist who scored at or above clinical cutoffs for risk on a research reliable administration of the Autism Diagnostic Observation Schedule, Second Edition [71], or based upon DSM-5 criteria. Participants showing typical development were recruited by word-of-mouth or study flyers shared on social media. The experimental protocol is shown in Figure 8. It is to be noted that the purpose of this current experiment was to assess whether CheerBrush was acceptable to the target population, whether they were interested in interacting with the game, and whether there was any potential for skill learning, which are necessary prerequisites for a future randomized clinical trial.

We first put the E4 sensor on the wrist of the non-dominant arm of the children. Then we let the children play with the toys scattered around the experiment area in the presence of their parents.

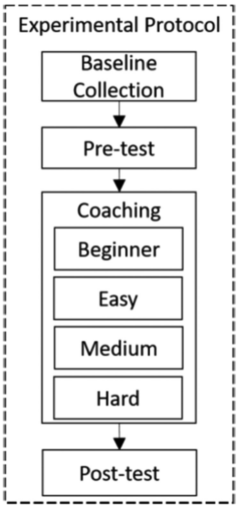

Fig. 8. Experimental protocol.

Fig. 9. Experimental space.

When the parent informed us that the children seemed comfortable in the new environment, we started recording their baseline physiological data. After five minutes of play, we asked the children to go into the experimental space and we put them in a Rifton chair (a supported chair with straps, appropriate for a variety of ages and developmental levels) facing the screen and the Kinect. In the current set-up, for best detection accuracy by the Kinect, the children needed to be at least 1.0 meter in height and sitting 1.5 meters away from the Kinect. The experimental space is shown in Figure 9. We played an age-appropriate cartoon on the monitor to attract the attention of children and measured their arm lengths, head circumferences and heights while they watched the video. With these measurements, the ARP calibration was completed.

Children first underwent a pre-test where they were asked to use the mechatronic brush to brush their teeth. All the data were recorded for analysis. Then the children went through the CheerBrush coaching, and finally they were asked to brush again using the mechatronic brush as a post-test to assess any improvement. The whole session lasted no more than 30 minutes. We obtained approval for this study from the **Institutional Review Board (IRB)** of Vanderbilt University. There were no known risks to children or parents regarding participation in the study and all procedures were in compliance with IRB approved procedures.

3.2 Data Analysis and Results

All children managed to finish the experimental sessions. To quantitatively evaluate the interaction with the CheerBrush, we conducted the following data analysis.

Engagement Analysis: During the game, we used a Kinect SDK extension [72] to measure whether the children were looking towards the computer screen. For the purpose of validating functionality of the pilot system, we utilized visual attention to the system as a proxy for engagement. The SDK, using computer vision, assessed whether both eyes of the users were open and they were looking toward or away from the computer screen at 1 Hz. From this data, we computed the percentage of time that they were engaged.

As seen in Figure 10, autistic children looked at the relevant **regions of interest (ROIs)** such as the face, brush, and the avatar about 66% of the CheerBrush coaching time. Their TD counterparts

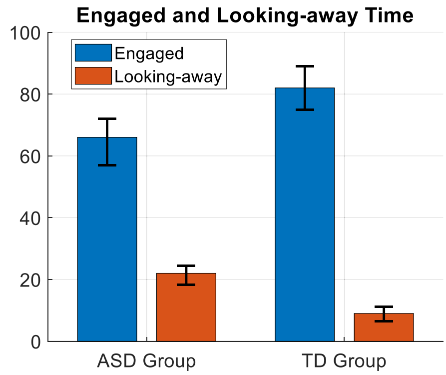

Fig. 10. Engagement time.

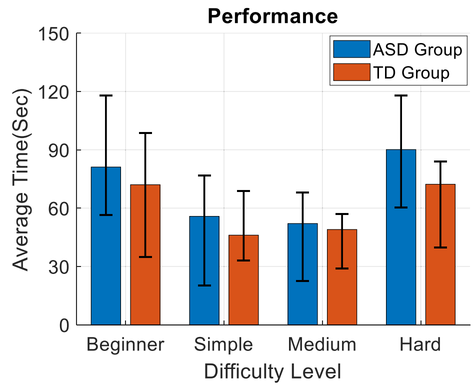

Fig. 11. Coaching performance.

paid attention to those ROIs about 82% of the time. The children with ASD looked away from the screen about 22% of the coaching time versus about 9% for the TD children. The remainder of the session, children with ASD looked at the screen but not at the relevant ROIs. We performed a two-sample t-test on engagement time percentage between the ASD and TD groups. We found that TD participants were statistically significantly more visually engaged with the system ROIs than participants with ASD (p-value = 0.00041) [73]. Although there were differences in engagement between groups, for the purpose of system validation and acceptability, we note that both groups were engaged for the majority of the interaction. From these results it can be inferred that the AR-based toothbrushing game was attractive and had the ability to engage children.

Performance Analysis: The performance of the children during different difficulty levels was also recorded as shown in Figure 11. On average, the ASD group and the TD group completed 3.00 and 3.67 levels of the game, respectively. The times spent on different levels show that the ASD group required more time at each level although the difference was most pronounced at the most difficult (Hard) level. On the Beginner, Simple, Medium and Hard levels they spent 12.63%, 21.01%, 6.27% and 24.69% longer, respectively. The ranges of time spent are shown by the error bars. We also performed two sample t-tests on the time spent by the ASD and TD groups and the resulted p-values were 0.4989 (Beginner), 0.4024 (Easy), 0.6408 (Medium) and 0.0049 (Hard). We found a statistically significant difference on the time spent on the Hard level between the two groups. We expected that the autistic children would spend significantly more time on the Hard level since the Hard level combines more aspects of tooth -brushing with which autistic children are known to struggle.

During the pre- and post-tests, we measured the speed and amplitude of brushing and compared them to the same features from adult participants who knew how to properly brush their teeth. Two typically developed healthy adult participants were asked to use the mechatronic toothbrush to brush their teeth so that we could obtain adult performance on brushing speed and amplitude. This comparison can quantitatively explore the potential toothbrushing skills' improvement in the children. The brushing speed and the distance covered by the brush on teeth are the two features that indicate the pattern of brushing [74]. Both brushing speed and distance were measured with respect to the yaw angle of the mechatronic brush and collected from its embedded IMU. Since we are trying to coach the basic toothbrushing skills, advanced toothbrushing skills such as covering occlusal and lingual surfaces are beyond the scope of this study [75]. It can be seen from Figures 12 and 13 that both sets of children, ASD and TD, improved both their brushing speeds and distances between the pre-test and post-test, indicating the impact of our system's coaching. Detailed results are shown in Table 2.

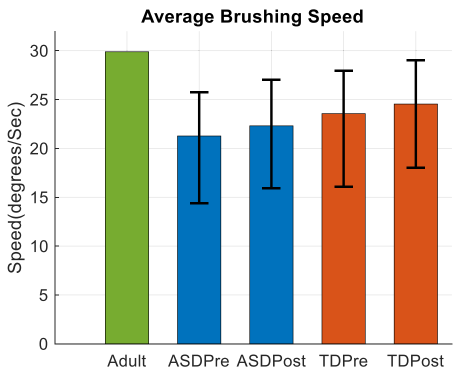

Fig. 12. Brushing speeds of children.

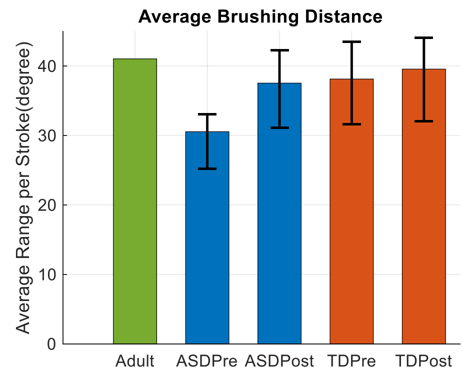

Fig. 13. Brushing distances of children.

Table 1. Participant Information

	ASD Group	TD Group
Age Mean	4.92	5.09
Age Std	0.91	0.95
Gender	5 Male, 1 Female	4 Male, 2 Female

Table 2. Brushing Speed and Distance

	Pre-assessment	Post-assessment	p-values
ASD Average Speed	21.27(4.59)	22.31(4.36)	0.7454
TD Average Speed	23.56(4.61)	24.54(4.26)	0.3140
ASD Average Distance	30.53(3.16)	37.52(4.43)	0.0300
TD Average Distance	38.11(4.67)	39.54(4.84)	0.6850

Though the TD children also improved, their changes were smaller than the autistic children. We conducted two-sample t-tests between pre- and post-assessments, for brushing speed and distance. We observed that although both average speed and average distance improved for both ASD and TD participants, only the brushing distance of autistic children reached statistical significance between pre- and post-tests (p-value of 0.03). These results, although based on a small sample size, indicate the potential of CheerBrush in improving the toothbrushing skills of the children.

Physiological Response Analysis: We also measured the physiological responses of the children as they went through the coaching using the E4 sensor. **Heart rate (HR)** and **skin conductance level (SCL)** were extracted from the BVP and GSR data obtained from the E4 sensor. These features are strong indicators of stress [76]. We compared the data collected during the coaching sessions to the baseline data. The physiological features are shown in Table 3. In Figure 14, the HR levels during the baseline and coaching sessions are shown. The HR levels decreased by 11.15% for the participants with ASD and it decreased by 5.21% for the TD children showing that the children were less distressed while playing with the system than they were when playing with the toys before the experiment began. Figure 15 shows the SCL at the baseline and during coaching sessions. For autistic children, the SCL decreased by 26.76% and for the TD children, the SCL stayed approximately the same from the baseline period to the coaching session. The physiological data during coaching sessions were similar to the patterns of calmness observed in [77]. We have also

Table 3. Physiological Feature

	Baseline	Training Sessions	p-values
ASD Average HR	98.89(5.24)	88.97(5.98)	0.0206
TD Average HR	102.90(5.92)	97.81(6.02)	0.2269
ASD Average SCL	0.71(0.23)	0.52(0.24)	0.0870
TD Average SCL	0.83(0.21)	0.81(0.22)	0.8332

Table 4. Questionnaire Results

	Question	Avg	Std	p-value
1	Did you like the game?	4.42	0.52	<0.0001
2	Were the instructions helpful?	4.25	0.45	<0.0001
3	Do you think this game will teach you (for the kids) how to brush?	4.17	0.72	0.00015
4	Do you think this game will teach your kids how to brush?	3.92	0.79	0.0046
5	Did you think this game made your kids more interested in toothbrushing?	4.67	0.49	<0.0001

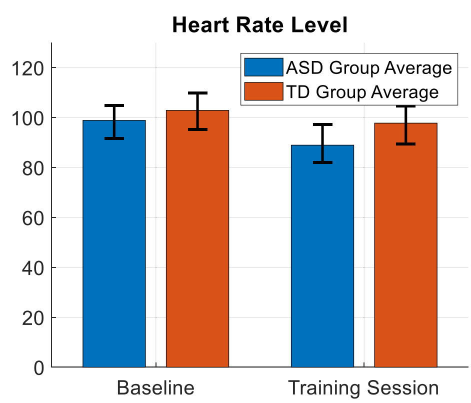

Fig. 14. Heart rate comparison.

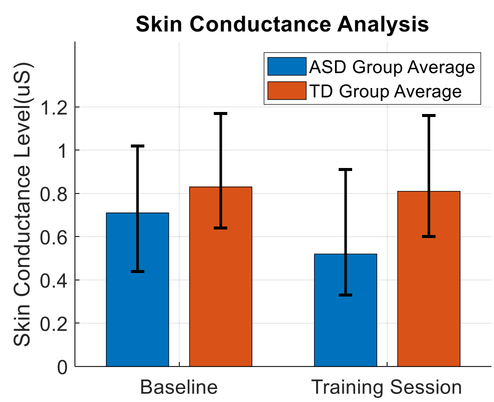

Fig. 15. Skin conductance level comparison.

conducted two-sample t-tests on the physiological features between baseline and training sessions, for both ASD and TD group. The HR and SCL differences of ASD group reached and was near statistically significant, respectively.

Qualitative Response Analysis: Finally, after the experiments, participants and their parents answered questions to evaluate the system feasibility on a 1—5 Likert scale, where 1 represents strong disagreement and 5 represents strong agreement. The questionnaire is shown in Table 4 and the results are shown in Figure 16. The blue and orange dots stand for results of ASD and TD groups, respectively. Questions 1—3 were asked of children by their parents. Questions 4—5 were answered by the parents themselves. We created the questionnaire with similar questions from the standardized and popular application usability validation [78].

As seen from the responses, most children had enjoyed interacting with CheerBrush. The parents enjoyed CheerBrush and found the instructions beneficial for their children. They also

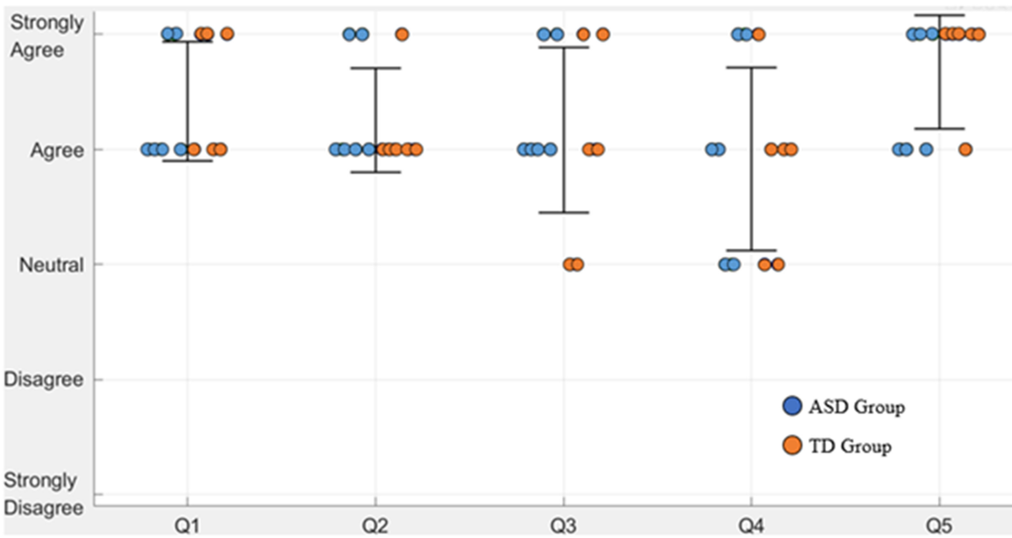

Fig. 16. Questionnaire Jitter Plot.

believed that the system would properly coach their children how to brush their teeth, and that it would make them more engaged in the interaction. We gathered several valuable suggestions from the parents for future improvement, such as use of more cartoon avatars, adjustable instructions, and better gamification. Additionally, the children themselves reported that the game would be helpful for them to learn toothbrushing. Overall, the responses from the parents and children were positive in all aspects of the questionnaire, indicating that CheerBrush has the potential to impact toothbrushing skills in all children including children with ASD.

4 CONCLUSIONS

We have created CheerBrush, a novel coaching and assessment system with interactive AR, for teaching toothbrushing skills to autistic children. CheerBrush projects the real-world surroundings and children on to a virtual environment and allows for manipulation of virtual objects with real hand and arm motion. The virtual toothbrushing task is broken into smaller subtasks, which are then demonstrated to the children via an avatar's animation and multimodal feedback. A mechatronic toothbrush is designed to measure brushing motion during pre- and post-tests to assess the impact of coaching.

In this work, we presented the system design, development, and integration of different modules and conducted a feasibility study of CheerBrush with 12 children. The system functioned as designed and the children with ASD as well as the TD children enjoyed interacting with CheerBrush. Both groups spent the majority of the session time paying visual attention to the system, although the TD group paid significantly more time than the ASD group. The physiological data pattern suggests that the coaching sessions of CheerBrush did not stress the children. A low-stress fun environment for coaching is important so that the coaching can be more effective and beneficial. Their brushing skills as measured between pre and post-test show some improvement, and the brushing movement patterns of the children became closer to the movement patterns of healthy adults.

Toothbrushing is a complex task. Relative to existing literature, CheerBrush offers an ineractive and immersive technology-based experience to teach toothbrushing skills. The toothbrushing training program by Cazaux et al. utilized a tablet application to show toothbrushing steps and reached statistically significant improvement in brushing on different teeth surfaces over an eight month longitudinal study [47]. However, this app had open loop teaching and did not provide close-loop feedback and immersive environment. In [46], the authors measured toothbrushing performance by the completion of task steps shown by their peers on video clips, which was improved when the system was introduced. This work required human effort for monitoring and scoring toothbrushing performance rather than embedding an automated intelligent system, and the small sample size precluded statistical analysis. Al-Batayneh et al utilized a picture exchange system, a well-established intervention [79] tool for children with ASD, and found based on questionnaire results that parent-reported brushing skills and dental details reached statistical significance after six months of usage of the system [49]. Again, this required human effort for administration and monitoring, with results based on parent perception rather than objective, system-based metrics of performance. Different teaching systems will likely have differential impact on children's performance based upon their preferences, and a variety of teaching approaches is important to ensure maximum reach. However, we note that although the results presented for CheerBrush are preliminary and exploratory, Cheerbrush achieved statistically significant improvement in quantitative brushing motion in only one visit, indicating the potential of effectiveness over long term use. In addition, we have presented engagement, stress, and user likability data that are encouraging.

Although CheerBrush showed promise regarding user engagement and coaching success, the current system and the presented study have several limitations. First, the current system only coaches brushing on mesial and facial surfaces and lacks complexity to include distal and lingual surfaces for complete, healthy toothbrushing. The current prototype system, which is designed for concept demonstration, is not portable and waterproof for bathroom use. The experimental setup requires that children sit 1.5 meters away from the Kinect to obtain the best detection accuracy, which is also a limitation. The feasibility study involved only a small number of participants for one session and consequently the results are not sufficiently generalizable. A longitudinal study with more participants and trials, as well as a control group of children not knowing how to brush their teeth, should be conducted to establish long-term gain and transfer of skills into the real world, which is our future goal. In the future, the physiological data of children could be analyzed in real-time and guide the virtual coach to dynamically adapt feedback to the stress level of the child. It may also be helpful to incorporate parents' likeness and feedback in the system to determine whether digital presentation of a familiar caregiver changes user attention or performance. Despite these limitations, CheerBrush is promising and demonstrates using quantitative and qualitative data the potential of an AR system in improving daily living activity habits of autistic children. In the process, we have made contributions in both the intelligent system design and in the field of potential ASD support. We believe the proposed system can effectively teach autistic children toothbrushing skills to not only improve the quality of life of the children, but also for their families and caregivers. Although the current work aims to engage children with ASD, this system is not limited to children with ASD alone. Developing systems and technologies that allow individuals to practice brushing their teeth, while tracking performance and engagement, has the potential to benefit groups with and without developmental disabilities.

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