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ASSESSMENT OF CAREGIVER KNOWLEDGE AND ANTICIPATED ACCEPTABILITY OF AN EMOTION-ADAPTIVE ROBOTIC ORAL-CARE DEVICE (EMOSMILE BOT) FOR CHILDREN WITH DISABILITIES: A MULTICENTRIC CROSS-SECTIONAL STUDY IN INDIA, BANGLADESH, AND SAUDI ARABIA

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ABSTRACT

Background. Children with disabilities frequently experience substantial difficulty in maintaining adequate oral hygiene. Conditions such as autism spectrum disorder (ASD), attention-deficit/hyperactivity disorder (ADHD), cerebral palsy, intellectual disability, and sensory-processing difficulties are associated with sensory hypersensitivity, behavioral resistance, fear and anxiety, impaired motor coordination, and dependence on caregivers during toothbrushing. Conventional oral-care devices are designed primarily for typically developing users. EmoSmile Bot is a proposed emotion-adaptive robotic oral-care system providing personalized, engaging, and caregiver-supported assistance through emotion recognition, adaptive brushing, pressure regulation, interactive guidance, and monitoring.

Aim. To assess caregiver knowledge and awareness of oral-care devices for children with disabilities and to evaluate the anticipated acceptability, perceived usefulness, perceived safety, willingness to use, willingness to recommend, and perceived potential of EmoSmile Bot to reduce caregiver burden.

Methods. A multicentric cross-sectional survey was conducted among 1,000 caregivers of children with disabilities recruited from departments of pediatric dentistry and selected special-care and residential settings in India (n = 510), Bangladesh (n = 380), and Saudi Arabia (n = 110). A structured questionnaire assessed sociodemographic characteristics, knowledge and awareness, difficulties encountered during routine oral hygiene, perceived need, and anticipated acceptability. Participants received a standardized description of the device before completing the acceptability section. Group differences were analysed using one-way ANOVA and chi-square tests; multivariable logistic and linear regression identified independent correlates of willingness to use and acceptability.

Results. The mean caregiver knowledge score differed significantly across countries (Saudi Arabia 7.8 ± 1.5; India 6.9 ± 1.8; Bangladesh 6.5 ± 1.9; $p < 0.001$). The overall anticipated acceptability score was high at 4.12 ± 0.60 on a 5-point scale (Saudi Arabia 4.30 ± 0.44; India 4.08 ± 0.62; Bangladesh 3.98 ± 0.67; $p < 0.001$). Perceived usefulness was reported by 88.0% of caregivers overall, perceived safety by 86.3%, willingness to use by 86.5%, and willingness to recommend by 83.4%; 76.9% considered that the device could substantially reduce caregiver burden. The anticipated acceptability score was the strongest independent predictor of willingness to use (adjusted OR 2.39, 95% CI 1.75–3.27; $p < 0.001$). Acceptability was uniformly high across disability types and severities.

Conclusion. This multicentric study provides user-centered evidence of high caregiver-anticipated acceptability, perceived need, and willingness to use an emotion-adaptive robotic oral-care system across three countries. The findings can inform refinement of the functional, ergonomic, behavioral, and caregiver-support components of EmoSmile Bot before prototype fabrication and usability testing.

KEYWORDS: *children with disabilities; caregivers; oral hygiene; assistive technology; robotic oral care; artificial intelligence; emotion-adaptive technology; acceptability; pediatric dentistry; EmoSmile Bot.*

1. INTRODUCTION

Oral health is a fundamental component of general health and quality of life, yet it remains one of the most neglected areas of care among children with disabilities [1–3]. Children living with autism spectrum disorder (ASD), attention-deficit/hyperactivity disorder (ADHD), cerebral palsy, intellectual disability, and sensory-processing difficulties consistently demonstrate higher caries experience, more gingival inflammation, and poorer oral-hygiene status than their typically developing peers [5,6,8,9,11–14]. These disparities are driven not by a single factor but by an interacting set of sensory, behavioral, motor, and caregiver-related barriers that make everyday toothbrushing uniquely challenging [7].

Sensory hypersensitivity to the texture, taste, sound, and vibration of brushing, behavioral resistance and non-compliance, fear and anxiety, limited manual dexterity and motor coordination, and a high degree of dependence on a caregiver to perform or supervise brushing are all well documented in this population [7,15,16]. Caregivers frequently report that toothbrushing is one of the most difficult daily caregiving tasks, and that conventional oral-care products do little to address the emotional and behavioral dimensions of the routine [18,21]. As a result, oral hygiene is often abbreviated, inconsistent, or aversive, compounding the risk of dental disease and, in turn, the need for treatment under sedation or general anaesthesia [4,10]. Effective caries prevention therefore remains a priority in this population, even as day-to-day oral hygiene stays difficult to deliver [43].

Conventional and even 'smart' electric toothbrushes are designed largely for typically developing users. They emphasize timing, pressure feedback, and gamification, but they are not built to detect or respond to a child's emotional state, to adapt brushing behavior when a child becomes distressed, or to actively support the caregiver who is guiding the routine. Recent pilot work with connected toothbrushes in children with ASD has shown encouraging improvements in brushing frequency and caregiver satisfaction, while also revealing the limits of static, non-adaptive designs [17].

In parallel, socially and emotionally assistive robotics has emerged as a promising approach in pediatric healthcare [25–27,31]. Socially assistive robots can reduce procedural distress and anxiety, foster trust and engagement, and deliver personalized interactions, and children often find a robot less intimidating than an adult [30,33,34]. Non-pharmacological, child-centred strategies for reducing dental anxiety and distress have likewise shown benefit in paediatric dentistry [42], and pairing such approaches with adaptive technology is a logical extension. Advances in affective computing and emotion recognition now make it feasible to detect facial expressions and behavioral cues in real time and to adapt a device's response accordingly [35–37]. More broadly, artificial intelligence and other digital technologies—from AI-based patient-care tools to immersive, metaverse-based platforms—are increasingly being adopted across dentistry, reflecting growing clinician interest in and acceptance of such innovations [44,45]. Combining these capabilities with an oral-care platform offers a novel route to making toothbrushing more tolerable, predictable, and engaging for children with disabilities.

EmoSmile Bot is a proposed emotion-adaptive robotic oral-care system intended to provide personalized, engaging, and caregiver-supported oral-hygiene assistance. Its intended functions include real-time emotion recognition, adaptive brushing that modulates its behavior in response to the child's affective state, pressure regulation to prevent discomfort and soft-tissue trauma, interactive guidance to structure and reward the routine, and monitoring functions that support caregivers and clinicians. Because such a device would ultimately be operated within a caregiver-mediated routine, the knowledge, perceived need, and anticipated acceptability of caregivers are decisive determinants of whether it will be adopted and used as intended.

User-centered evaluation early in the design cycle—before prototype fabrication—can substantially reduce the risk of developing a technically capable device that fails in real households. Established models of technology adoption, including the Technology Acceptance Model and the Unified Theory of Acceptance and Use of Technology, identify perceived usefulness, perceived ease of use, and social and contextual factors as core drivers of acceptance [22–24,28]. Applying this lens to caregivers across differing health systems and cultural contexts is essential, and cross-national surveys of technology adoption in dentistry illustrate its value [41]; yet evidence on caregiver acceptability of emotion-adaptive robotic oral-care technology remains scarce, and cross-national comparisons are almost entirely absent.

The present multicentric study was therefore designed to assess caregiver knowledge and awareness of oral-care devices for children with disabilities, and to evaluate the anticipated acceptability, perceived usefulness, perceived safety, willingness to use, willingness to recommend, and perceived potential to reduce caregiver burden of the proposed EmoSmile Bot, across three countries—India, Bangladesh, and Saudi Arabia—that differ in health-system organization, resources, and cultural context.

2. MATERIALS AND METHODS

2.1 Study design and setting

A multicentric, cross-sectional, questionnaire-based survey was conducted among caregivers of children with disabilities across three countries: India, Bangladesh, and Saudi Arabia. Participants were recruited through Departments of Pediatric Dentistry / Pediatric and Preventive Dentistry in participating dental colleges, and through selected special-child care settings and residential (orphanage) homes. The study was reported in accordance with the STROBE guidance for cross-sectional studies [39].

2.2 Participants and sampling

Eligible participants were adult caregivers (parents, relatives, or professional caregivers) primarily responsible for, or closely involved in, the daily oral hygiene of a child with a diagnosed disability aged 3–15 years. Caregivers who declined consent, who did not routinely assist with the child's oral care, or who returned incomplete questionnaires were excluded. A convenience sampling approach was used at each site, with a target of approximately 1,000 caregivers distributed across the three countries. Of 1,214 caregivers approached, 1,000 were enrolled and analysed (India, n = 510; Bangladesh, n = 380; Saudi Arabia, n = 110); the flow of participants is summarized in Figure 1.

2.3 Questionnaire and device description

A structured questionnaire was developed on the basis of existing instruments assessing oral-health knowledge, caregiving difficulty, and technology acceptance [18,22,38], and was reviewed for content validity by pediatric dentists and refined through pilot testing. It captured (i) caregiver and child sociodemographic and clinical characteristics; (ii) caregiver knowledge and awareness of oral-care devices; (iii) difficulties encountered during routine oral hygiene across five domains (sensory hypersensitivity, behavioral resistance, fear/anxiety, limited motor coordination, and caregiver dependence); (iv) perceived need for adaptive oral-care technology; and (v) anticipated acceptability of EmoSmile Bot. Before completing the acceptability section, every participant was given a standardized written and verbal description of the proposed device and its intended functions (emotion recognition, adaptive brushing, pressure regulation, interactive guidance, and monitoring), accompanied by a schematic illustration, to ensure a common frame of reference.

2.4 Survey questionnaire (instrument)

The full survey instrument administered to caregivers is reproduced below. It comprised five sections (A–E). Sections A–D were completed first; participants were then given the standardized description of EmoSmile Bot (reproduced at the start of Section E) before completing the anticipated-acceptability items. Response options are shown in parentheses after each item.

Section A. Sociodemographic and clinical information

A1. Country / study site (India / Bangladesh / Saudi Arabia)
A2. Caregiver age, in completed years: __________
A3. Caregiver gender (Female / Male / Prefer not to say)
A4. Relationship to the child (Mother / Father / Grandparent / Professional caregiver / Sibling or other relative)
A5. Highest level of education completed (No formal or primary / Secondary or higher secondary / Graduate or postgraduate)
A6. Approximate monthly household income bracket (Low / Lower-middle or middle / Upper-middle or high)
A7. Child's age, in completed years: __________
A8. Child's primary diagnosed disability (Autism spectrum disorder / ADHD / Intellectual disability / Cerebral palsy / Sensory-processing difficulty / Multiple disabilities)
A9. Reported severity of disability (Mild / Moderate / Severe)
A10. Recruitment setting (Dental college / Special-care setting / Residential or orphanage home)

Section B. Knowledge and awareness of oral-care devices

For each statement, indicate whether you think it is True or False. One point is awarded for each correct response; the knowledge score ranges from 0 to 10 (items B1–B10). Item B11 assesses awareness and is not scored.

B1. Children with disabilities are at higher risk of tooth decay and gum problems than other children. (True / False)
B2. Teeth should be brushed at least twice every day. (True / False)
B3. Fluoride toothpaste helps to prevent tooth decay. (True / False)
B4. Powered (electric) toothbrushes can help when a child has difficulty controlling hand movements. (True / False)
B5. Special or adaptive brushing aids exist for children who resist toothbrushing. (True / False)
B6. Frequent sugary snacks between meals increase the risk of tooth decay. (True / False)
B7. A predictable, step-by-step routine can reduce a child's fear during brushing. (True / False)
B8. Devices that guide brushing time and pressure can help caregivers brush a child's teeth more effectively. (True / False)
B9. Regular dental check-ups are unnecessary as long as the child is brushed at home. (True / False)
B10. Gums that bleed every time during brushing never require any attention. (True / False)
B11. Before today, were you aware that oral-care devices designed for children with disabilities exist? (Yes / No)

Section C. Difficulties encountered during routine oral hygiene

Thinking about your child's daily toothbrushing, indicate whether each of the following is a problem for you (Yes / No).

C1. Sensory hypersensitivity — the child reacts strongly to the taste, texture, sound, or vibration of brushing. (Yes / No)
C2. Behavioural resistance / non-compliance — the child refuses, struggles, or will not cooperate with brushing. (Yes / No)
C3. Fear and anxiety — the child appears frightened or distressed during brushing. (Yes / No)
C4. Limited motor coordination — the child cannot hold or manoeuvre the toothbrush effectively. (Yes / No)

C5. Caregiver dependence — the child depends entirely on me to perform or closely supervise brushing. (Yes / No)

Section D. Perceived need for adaptive oral-care technology

Indicate your level of agreement with each statement (1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree).

D1. There is a real need for a specially designed oral-care device to help children like mine. (1–5)
D2. A device that responds to my child's emotions and behaviour would make brushing easier. (1–5)
D3. Currently available toothbrushes do not adequately meet my child's needs. (1–5)

Section E. Anticipated acceptability of EmoSmile Bot

Standardized device description read to every participant before this section: "EmoSmile Bot is a proposed robotic oral-care device for children with disabilities. It is designed to recognise the child's emotional state in real time, adapt its brushing behaviour when the child becomes distressed, regulate brushing pressure to avoid discomfort, provide interactive guidance and rewards to structure the routine, and give caregivers monitoring feedback. It is intended to be used together with the caregiver, not to replace them."

Items E1–E5: indicate your level of agreement (1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree). Items E6–E10: answer Yes or No.

E1. I would feel comfortable using this device with my child. (1–5)
E2. The device seems suitable for my child's needs. (1–5)
E3. I think my child would tolerate or accept this device. (1–5)
E4. The device seems easy to use. (1–5)
E5. Overall, I have a positive impression of this device. (1–5)
E6. Do you think this device would be useful for your child? [perceived usefulness] (Yes / No)
E7. Do you think this device would be safe for your child? [perceived safety] (Yes / No)
E8. Would you be willing to use this device with your child? [willingness to use] (Yes / No)
E9. Would you recommend this device to other caregivers? [willingness to recommend] (Yes / No)
E10. Do you think this device could substantially reduce your caregiving burden? [reduced caregiver burden] (Yes / No)

2.5 Outcome measures

Caregiver knowledge was scored on a 0–10 scale from a set of knowledge items and analysed both continuously and in categories (low, 0–5; moderate, 6–7; high, 8–10). Anticipated acceptability and perceived need were each rated on 5-point Likert-type scales. Perceived usefulness, perceived safety, willingness to use, willingness to recommend, and perceived reduction of caregiver burden were recorded as binary (yes/no) endorsements. The primary outcomes were caregiver knowledge and anticipated acceptability; secondary outcomes were perceived usefulness, perceived safety, willingness to use, willingness to recommend, and perceived reduction of caregiver burden.

2.6 Statistical analysis

Data were analysed using Python (pandas, SciPy, and statsmodels). Continuous variables are presented as mean ± standard deviation and categorical variables as frequencies and percentages. Between-country differences were assessed using one-way analysis of variance (ANOVA) for continuous variables and Pearson chi-square tests for categorical variables. Associations between continuous variables were examined using Pearson correlation. Multivariable logistic regression was used to identify independent predictors of willingness to use (reported as adjusted odds ratios [aOR] with 95% confidence intervals [CI]), and multivariable linear regression was used to identify independent correlates of the anticipated acceptability score. A two-sided p-value < 0.05 was considered statistically significant.

2.7 Ethical considerations

The study was conducted in accordance with the principles of the Declaration of Helsinki [40]. Ethical approval was obtained from the institutional ethics committees of the participating centres, and written informed consent was obtained from all participating caregivers before enrolment. Participation was voluntary and anonymous, and no identifying information about children was recorded.

Figure 1. Participant recruitment and study flow

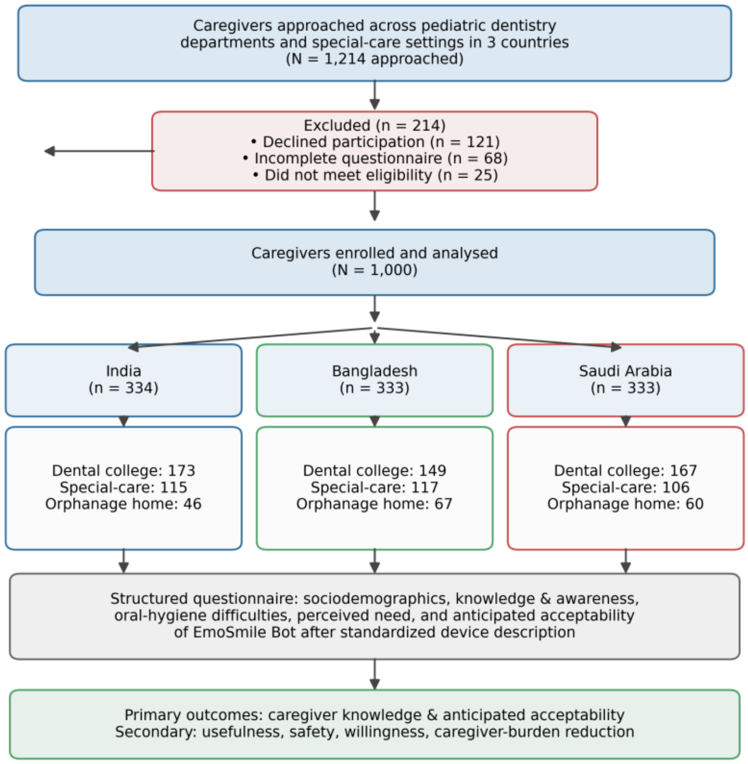

Figure 1. Flow of participants through recruitment, enrolment, and analysis across the three participating countries, showing distribution by recruitment setting.

3. RESULTS

3.1 Sociodemographic and clinical characteristics

A total of 1,000 caregivers were analysed. The mean caregiver age was 38.2 ± 8.7 years and the mean child age was 9.0 ± 3.8 years, with no significant difference between countries (p = 0.45 and p = 0.97, respectively). Most caregivers were women (71.3%) and the largest group were mothers (45.9%). Autism spectrum disorder was the most common disability (28.5%), followed by ADHD, intellectual disability, and cerebral palsy; moderate disability severity predominated (42.7%). The distribution of sociodemographic and clinical characteristics was broadly comparable across the three national samples (Table 1).

Table 1. Sociodemographic and clinical characteristics of participating caregivers and children, overall and by country (N = 1,000).

Characteristic	Overall (N=1000)	India (n=510)	Bangladesh (n=380)	Saudi Arabia (n=110)	p-value
Caregiver age, yr (mean ± SD)	38.2 ± 8.7	38.4 ± 8.3	38.5 ± 8.6	37.7 ± 9.1	0.45
Child age, yr (mean ± SD)	9.0 ± 3.8	9.0 ± 3.9	8.9 ± 3.7	9.0 ± 3.7	0.97
Caregiver gender, n (%)					
Female	713 (71.3)	225 (67.4)	242 (72.7)	246 (73.9)	0.14
Male	287 (28.7)	109 (32.6)	91 (27.3)	87 (26.1)	
Relationship to child, n (%)					
Mother	459 (45.9)	157 (47.0)	152 (45.6)	150 (45.0)	0.30
Father	212 (21.2)	70 (21.0)	72 (21.6)	70 (21.0)	
Professional caregiver	123 (12.3)	41 (12.3)	44 (13.2)	38 (11.4)	
Grandparent	102 (10.2)	34 (10.2)	23 (6.9)	45 (13.5)	
Sibling / other relative	104 (10.4)	32 (9.6)	42 (12.6)	30 (9.0)	
Caregiver education, n (%)					
No formal / primary	222 (22.2)	73 (21.9)	68 (20.4)	81 (24.3)	0.74

Characteristic	Overall (N=1000)	India (n=510)	Bangladesh (n=380)	Saudi Arabia (n=110)	p-value
Secondary / higher secondary	438 (43.8)	149 (44.6)	155 (46.5)	134 (40.2)	
Graduate / postgraduate	340 (34.0)	112 (33.5)	110 (33.0)	118 (35.4)	
Monthly income bracket, n (%)					
Low	226 (22.6)	73 (21.9)	70 (21.0)	83 (24.9)	0.91
Lower-middle / middle	513 (51.3)	172 (51.5)	176 (52.9)	165 (49.5)	
Upper-middle / high	261 (26.1)	89 (26.6)	87 (26.1)	85 (25.5)	
Child disability type, n (%)					
Autism spectrum disorder	285 (28.5)	99 (29.6)	95 (28.5)	91 (27.3)	0.51
ADHD	172 (17.2)	58 (17.4)	61 (18.3)	53 (15.9)	
Intellectual disability	170 (17.0)	45 (13.5)	65 (19.5)	60 (18.0)	
Cerebral palsy	169 (16.9)	59 (17.7)	55 (16.5)	55 (16.5)	
Sensory-processing difficulty	104 (10.4)	33 (9.9)	32 (9.6)	39 (11.7)	
Multiple disabilities	100 (10.0)	40 (12.0)	25 (7.5)	35 (10.5)	
Disability severity, n (%)					
Mild	349 (34.9)	112 (33.5)	122 (36.6)	115 (34.5)	0.55
Moderate	427 (42.7)	142 (42.5)	147 (44.1)	138 (41.4)	
Severe	224 (22.4)	80 (24.0)	64 (19.2)	80 (24.0)	
Recruitment setting, n (%)					
Dental college	489 (48.9)	173 (51.8)	149 (44.7)	167 (50.2)	0.17
Special-care setting	338 (33.8)	115 (34.4)	117 (35.1)	106 (31.8)	
Residential orphanage home	173 (17.3)	46 (13.8)	67 (20.1)	60 (18.0)	

SD, standard deviation; ADHD, attention-deficit/hyperactivity disorder. p-values from one-way ANOVA (continuous) or chi-square test (categorical).

3.2 Caregiver knowledge and awareness

Caregiver knowledge of oral-care devices differed significantly across countries. The mean knowledge score was highest in Saudi Arabia (7.75 ± 1.45), intermediate in India (6.92 ± 1.76), and lowest in Bangladesh (6.49 ± 1.85) (one-way ANOVA $F = 48.1$, $p < 0.001$; Figure 2). The proportion of caregivers with high knowledge (score 8–10) was 57.4% in Saudi Arabia, 37.4% in India, and 32.7% in Bangladesh. Overall, 67.5% of caregivers reported being aware of oral-care devices for children with disabilities, ranging from 62.2% in Bangladesh to 73.0% in Saudi Arabia ($p = 0.012$) (Table 2).

Table 2. Caregiver knowledge and awareness of oral-care devices, overall and by country.

Measure	Overall	India	Bangladesh	Saudi Arabia	p-value
Knowledge score, mean ± SD	7.05 ± 1.77	6.92 ± 1.76	6.49 ± 1.85	7.75 ± 1.45	<0.001
Low knowledge (0–5), n (%)	189 (18.9)	70 (21.0)	100 (30.0)	19 (5.7)	<0.001
Moderate knowledge (6–7), n (%)	386 (38.6)	139 (41.6)	124 (37.2)	123 (36.9)	
High knowledge (8–10), n (%)	425 (42.5)	125 (37.4)	109 (32.7)	191 (57.4)	
Aware of oral-care devices, n (%)	675 (67.5)	225 (67.4)	207 (62.2)	243 (73.0)	0.012

SD, standard deviation. p-values from one-way ANOVA (knowledge score) or chi-square test (categorical distributions and awareness).

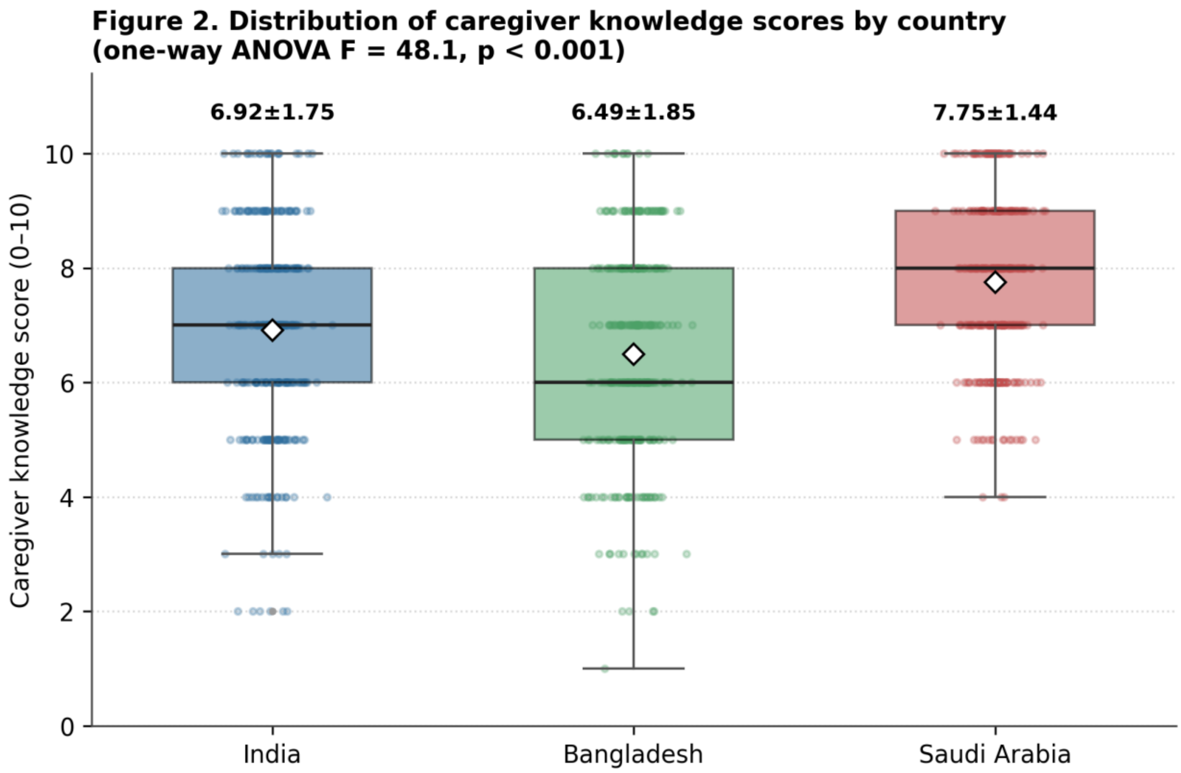

Figure 2. Distribution of caregiver knowledge scores (0–10) by country. Boxes show the interquartile range and median; diamonds denote group means; individual observations are shown as jittered points. Mean ± SD is annotated above each group.

3.3 Difficulties encountered during routine oral hygiene

Caregivers reported a substantial burden of difficulty during routine oral hygiene, with a mean of 2.86 ± 1.08 of the five surveyed difficulties endorsed per child and no significant difference between countries in the total count ($p = 0.97$). Caregiver dependence (73.8% overall) and behavioral resistance (64.0%) were the most frequently reported difficulties, followed by sensory hypersensitivity (61.3%), fear/anxiety (48.0%), and limited motor coordination (39.0%). Only behavioral resistance differed significantly across countries, being less frequently reported in India (58.7%) than in Bangladesh (66.4%) or Saudi Arabia (67.0%) ($p = 0.046$) (Table 3, Figure 3).

Table 3. Difficulties encountered during routine oral hygiene, overall and by country (% of caregivers reporting each difficulty).

Difficulty domain	Overall	India	Bangladesh	Saudi Arabia	p-value
Caregiver dependence	73.8	74.0	71.2	76.3	0.32
Behavioral resistance	64.0	58.7	66.4	67.0	0.046
Sensory hypersensitivity	61.3	64.4	60.7	58.9	0.33
Fear / anxiety	48.0	49.1	48.0	46.8	0.84
Limited motor coordination	39.0	41.0	38.7	37.2	0.60
Mean no. of difficulties (± SD)	2.86 ± 1.08	2.87 ± 1.11	2.85 ± 1.03	2.86 ± 1.11	0.97

Values are percentages unless otherwise stated. p-values from chi-square test (individual difficulties) or one-way ANOVA (mean number of difficulties).

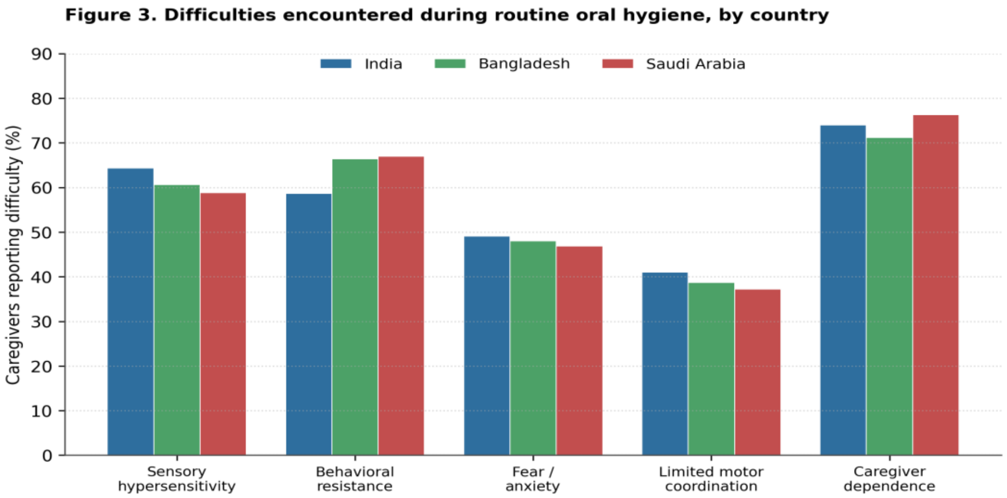

Figure 3. Difficulties encountered during routine oral hygiene, by country. Bars show the percentage of caregivers reporting each difficulty domain.

3.4 Anticipated acceptability of EmoSmile Bot

Anticipated acceptability of the proposed device was high across all sites, with an overall acceptability score of 4.12 ± 0.60 on a 5-point scale. Scores were highest in Saudi Arabia (4.30 ± 0.44), followed by India (4.08 ± 0.62) and Bangladesh (3.98 ± 0.67) ($F = 26.0$, $p < 0.001$). Perceived need for adaptive oral-care technology was likewise high (3.95 ± 0.82 overall). Perceived usefulness was endorsed by 88.0% of caregivers, perceived safety by 86.3%, willingness to use by 86.5%, and willingness to recommend by 83.4%, and 76.9% agreed that the device could substantially reduce caregiver burden. Perceived usefulness and perceived safety differed significantly across countries (both $p < 0.001$, driven by lower endorsement in Bangladesh), whereas willingness to use, willingness to recommend, and perceived burden reduction did not differ significantly (Table 4, Figure 4).

Table 4. Anticipated acceptability outcomes for EmoSmile Bot, overall and by country.

Outcome	Overall	India	Bangladesh	Saudi Arabia	p-value
Acceptability score (mean ± SD)	4.12 ± 0.60	4.08 ± 0.62	3.98 ± 0.67	4.30 ± 0.44	<0.001
Perceived need (mean ± SD)	3.95 ± 0.82	3.88 ± 0.84	3.82 ± 0.81	4.15 ± 0.77	<0.001
Perceived usefulness, n (%)	880 (88.0)	306 (91.6)	268 (80.5)	306 (91.9)	<0.001
Perceived safety, n (%)	863 (86.3)	290 (86.8)	269 (80.8)	304 (91.3)	<0.001
Willingness to use, n (%)	865 (86.5)	288 (86.2)	280 (84.1)	297 (89.2)	0.15
Willingness to recommend, n (%)	834 (83.4)	271 (81.1)	278 (83.5)	285 (85.6)	0.30
Reduces caregiver burden, n (%)	769 (76.9)	257 (76.9)	243 (73.0)	269 (80.8)	0.057

SD, standard deviation. Acceptability score and perceived need rated on 5-point scales. p-values from one-way ANOVA (scores) or chi-square test (binary outcomes).

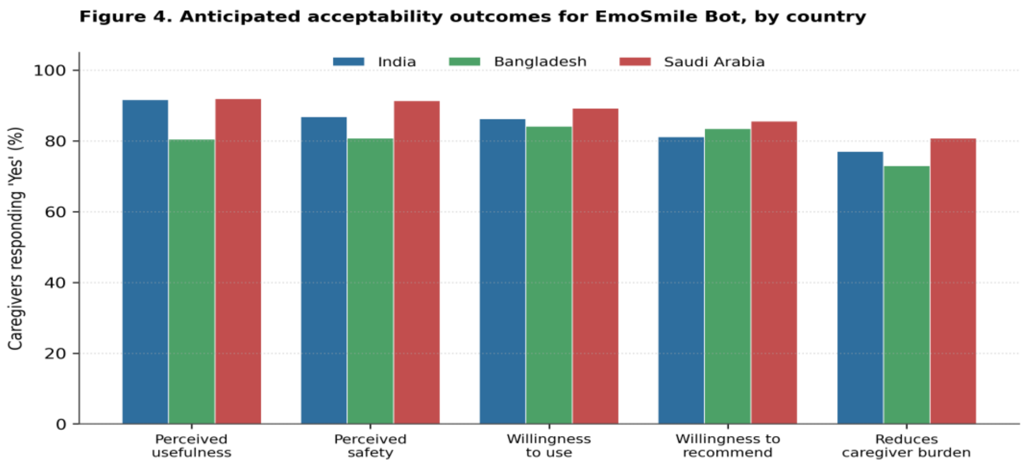

Figure 4. Anticipated acceptability outcomes for EmoSmile Bot, by country. Bars show the percentage of caregivers endorsing each outcome (‘yes’ responses).

3.5 Acceptability across disability types and severities

Anticipated acceptability was uniformly high across the six disability categories, ranging from 4.09 ± 0.61 for ADHD to 4.21 ± 0.62 for multiple disabilities, with no significant difference between groups (ANOVA p = 0.62). Willingness to use ranged narrowly from 82.6% (ADHD) to 88.8% (intellectual disability). Acceptability was also similar across severity levels (mild 4.12, moderate 4.14, severe 4.10; p = 0.80), indicating that caregivers viewed the device favourably irrespective of their child's diagnosis or the severity of impairment (Table 5, Figure 5).

Table 5. Anticipated acceptability score and willingness to use EmoSmile Bot, by disability type and severity.

Subgroup	n	Acceptability score (mean ± SD)	Willingness to use n (%)
Disability type			
Autism spectrum disorder	285	4.12 ± 0.62	252 (88.4)
ADHD	172	4.09 ± 0.61	142 (82.6)
Intellectual disability	170	4.11 ± 0.58	151 (88.8)
Cerebral palsy	169	4.10 ± 0.59	148 (87.6)
Sensory-processing difficulty	104	4.16 ± 0.56	87 (83.7)
Multiple disabilities	100	4.21 ± 0.62	85 (85.0)
Disability severity			
Mild	349	4.12 ± 0.62	302 (86.5)
Moderate	427	4.14 ± 0.59	366 (85.7)
Severe	224	4.10 ± 0.59	197 (87.9)

SD, standard deviation; ADHD, attention-deficit/hyperactivity disorder. Between-group differences were non-significant for both disability type (ANOVA p = 0.62) and severity (ANOVA p = 0.80).

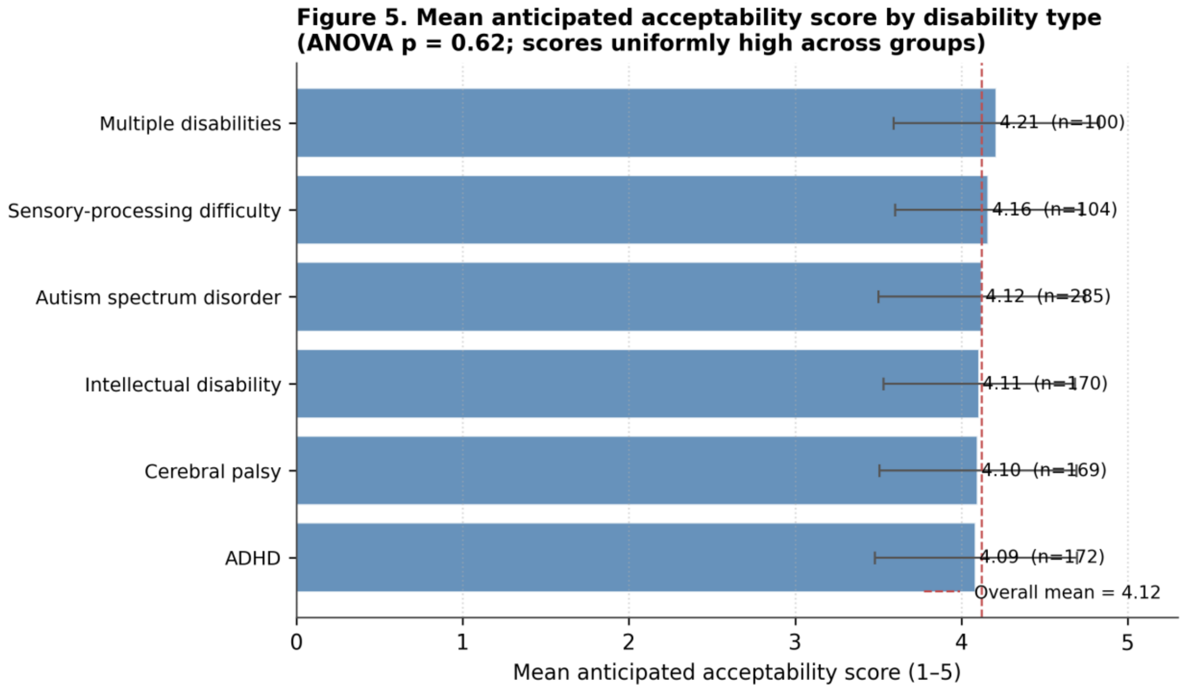

Figure 5. Mean anticipated acceptability score by disability type (error bars, standard deviation). The dashed line marks the overall mean; scores were uniformly high across diagnostic groups.

3.6 Correlates and predictors of acceptability and willingness to use

The anticipated acceptability score was positively correlated with caregiver knowledge (Pearson r = 0.17, p < 0.001), whereas correlations with perceived need (r = 0.06, p = 0.056) and caregiver age (r = 0.04, p = 0.28) were weak. In multivariable linear regression, higher knowledge (β = +0.039 per point, p < 0.001) and residence in Saudi Arabia relative to India (β = +0.185, p < 0.001) were independently associated with a higher acceptability score (Table 6).

In multivariable logistic regression, the anticipated acceptability score was by far the strongest independent predictor of willingness to use: each one-point increase more than doubled the odds of willingness (adjusted OR 2.39, 95% CI 1.75–3.27; p < 0.001). Knowledge score, perceived need, prior awareness, country, disability severity, caregiver age, and caregiver gender were not independently associated with willingness to use once acceptability was accounted for (Figure 6). Together these findings indicate that the overall favourability of caregivers' response to the device—rather than their baseline knowledge or the child's clinical profile—is the principal driver of intended adoption.

Table 6. Multivariable linear regression of factors independently associated with the anticipated acceptability score.

Predictor	β (coefficient)	95% CI	p-value
Knowledge score (per +1)	+0.039	+0.018 to +0.061	<0.001
Perceived need (per +1)	+0.015	−0.030 to +0.060	0.53
Aware of oral-care devices	+0.003	−0.076 to +0.081	0.95
Saudi Arabia (vs India)	+0.185	+0.093 to +0.276	<0.001
Bangladesh (vs India)	−0.083	−0.173 to +0.006	0.067
Caregiver age (per year)	+0.003	−0.001 to +0.007	0.14
Female caregiver	−0.002	−0.082 to +0.078	0.96

CI, confidence interval. Model adjusted for all listed predictors (adjusted $R^2 = 0.057$). The corresponding logistic-regression model for willingness to use is shown in Figure 6.

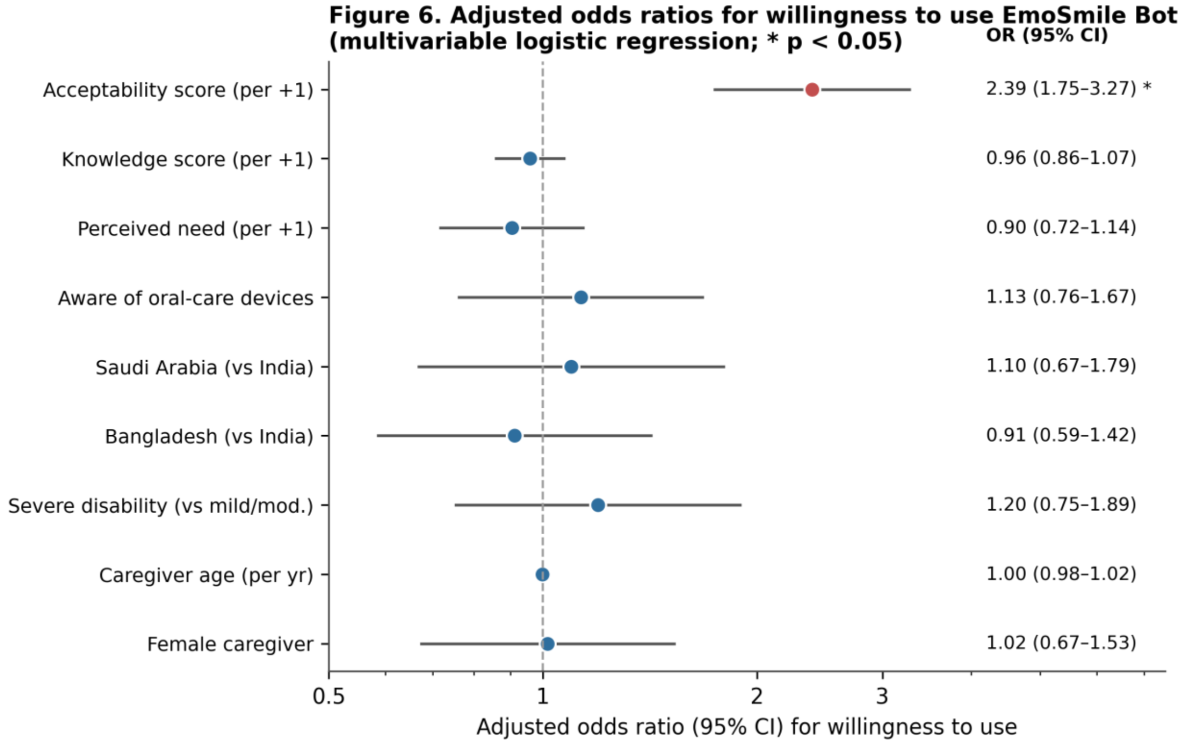

Figure 6. Adjusted odds ratios (95% CI) for willingness to use EmoSmile Bot from multivariable logistic regression. The anticipated acceptability score was the only significant independent predictor (* $p < 0.05$); the vertical dashed line marks an odds ratio of 1.

4. DISCUSSION

This multicentric cross-sectional study assessed caregiver knowledge and the anticipated acceptability of a proposed emotion-adaptive robotic oral-care device, EmoSmile Bot, among 1,000 caregivers of children with disabilities in India, Bangladesh, and Saudi Arabia. Three findings stand out. First, caregivers reported a heavy and consistent burden of difficulty during everyday oral hygiene, dominated by dependence on the caregiver and by the child's behavioral resistance and sensory hypersensitivity. Second, anticipated acceptability of the device was high across every site, diagnosis, and severity level, with strong endorsement of its perceived usefulness, safety, and potential to reduce caregiver burden. Third, the overall favourability of caregivers' response—captured by the acceptability score—was the dominant predictor of willingness to use, outweighing baseline knowledge and the child's clinical profile.

The pattern of difficulties reported here is consistent with a large body of work documenting sensory sensitivities, behavioral resistance, communication challenges, and caregiver dependence as central barriers to oral hygiene in children with ASD and other disabilities [6,7,15,16,19–21]. The prominence of caregiver dependence and behavioral resistance in our sample reinforces the argument that the emotional and behavioral dimensions of brushing—not merely its mechanical execution—are what make the routine difficult, and that a device addressing

only mechanics is unlikely to solve the problem. This provides a clear design rationale for the emotion-recognition, adaptive-brushing, and interactive-guidance functions envisaged for EmoSmile Bot.
The high anticipated acceptability observed across all three countries aligns with the emerging literature on socially and emotionally assistive robots in pediatric care, which reports that such systems can reduce distress, build trust, and deliver personalized interaction, and that children often find a robot less threatening than an adult [29–33]. Pilot studies of connected toothbrushes in children with ASD have similarly reported improved brushing frequency and caregiver satisfaction, while highlighting the limitations of non-adaptive designs [17]. Our results extend this evidence base by showing that caregivers, across differing health systems and cultures, perceive a genuine need for adaptive technology and are willing both to use and to recommend it.
Country differences were instructive. Caregivers in Saudi Arabia reported the highest knowledge and the highest acceptability, and those in Bangladesh the lowest on both, with India intermediate. These gradients likely reflect differences in exposure to dental technology, health-system resources, and access to information rather than differences in underlying need, since the burden of oral-hygiene difficulty was essentially identical across countries. The lower perceived usefulness and safety endorsements in Bangladesh, despite comparable willingness to use, suggest that clear communication about how such a device works and how its safety is assured will be particularly important in lower-resource settings.
From an implementation perspective, the regression findings carry a practical message. Because willingness to use was driven overwhelmingly by the acceptability score rather than by prior knowledge, efforts to promote adoption should focus less on educating caregivers about oral-care devices in the abstract and more on ensuring that the device itself is experienced as useful, safe, comfortable, and genuinely helpful in reducing the daily burden of care. The modest but significant association between knowledge and acceptability suggests that familiarity helps, but is far from sufficient on its own. These observations are congruent with established technology-acceptance frameworks, in which perceived usefulness and ease of use are the proximal determinants of intention to use [22–24].
The study has several strengths, including its large multicentric sample, its cross-national design spanning three countries with differing contexts, its balanced representation of disability types and severities, and its use of a standardized device description to give all participants a common frame of reference before rating acceptability. The reliance on multivariable modelling allowed the identification of independent correlates of acceptability and willingness to use.

4.1 LIMITATIONS

Several limitations should be acknowledged. First, the study assessed anticipated acceptability of a described device rather than measured acceptability of a working prototype; stated intentions may not translate into actual use, and hypothetical appraisals are susceptible to social-desirability and novelty effects. Second, convenience sampling through dental colleges and special-care settings may limit generalizability to caregivers who do not access such services. Third, the questionnaire relied on self-report and on a knowledge score and Likert-type items whose psychometric properties, while pilot-tested, warrant fuller validation. Fourth, the cross-sectional design precludes causal inference, and the regression models explained only a modest proportion of variance, indicating that important determinants of acceptability were not captured. Finally, the child's own perspective—ultimately central to a device used in the mouth—was not assessed. These limitations should be addressed in prototype-based usability testing.

4.2 Implications and future directions

The findings offer actionable, user-centered guidance for the next phase of development. Priorities include refining the emotion-recognition and adaptive-brushing functions that address the behavioral and sensory barriers caregivers rated most burdensome; designing caregiver-support and monitoring features that translate the perceived potential to reduce burden into measurable relief; and developing clear, culturally adapted communication about device function and safety, especially for lower-resource settings where perceived usefulness and safety were lower. Subsequent work should proceed to prototype fabrication followed by mixed-methods usability testing with both caregivers and children, and ultimately to clinical evaluation of oral-hygiene and behavioral outcomes. Attention to affordability, durability, data privacy, and equitable access will be essential if such technology is to benefit the populations that need it most.

5. CONCLUSION

Across three countries, caregivers of children with disabilities reported a substantial and consistent burden of difficulty during routine oral hygiene and expressed high anticipated acceptability, perceived need, and willingness to use an emotion-adaptive robotic oral-care device. Acceptability was high irrespective of disability type or severity, and the overall favourability of caregivers' response—rather than their baseline knowledge—was the principal driver of willingness to use. These user-centered findings provide a strong empirical basis for refining the functional, ergonomic, behavioral, and caregiver-support components of EmoSmile Bot before prototype fabrication and subsequent usability and clinical testing.

DECLARATIONS

Ethics approval and consent to participate. The study was conducted in accordance with the Declaration of Helsinki and approved by the institutional ethics committees of the participating centres. Written informed consent was obtained from all participating caregivers.

Consent for publication. Not applicable.

Availability of data and materials. The dataset analysed during the current study is available from the corresponding author on reasonable request.

Competing interests. The authors declare that they have no competing interests.

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Authors' contributions. All authors contributed to the study design, data interpretation, and critical revision of the manuscript, and approved the final version.

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