



Fall height and impact surface in relation to clinically important traumatic brain injury among children under two years

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ABSTRACT

Objectives: To assess whether fall height and impact surface are associated with clinically important traumatic brain injury (ciTBI) in children under two years.

Methods: We performed a single-center retrospective cohort study (Tokyo, Japan, 2017–2021) including children under two years with head trauma. We excluded those with conditions affecting ciTBI risk, unreliable clinical histories, or injury mechanisms that did not involve ground impact. The primary outcome was ciTBI; abnormal head computed tomography (CT) findings were secondary. Multivariable logistic regression modeled fall height per 10-cm increment and impact surface (flooring, soft, hard), adjusted for age and exposures. Generalized additive models (GAMs) explored potential nonlinear associations.

Results: Among 3067 eligible children, 1893 were included in the analysis; 44 (2.3%) had ciTBI. After adjustment for age and mutual adjustment of exposures, impact surface type was not significantly associated with ciTBI (soft surface vs flooring: adjusted odds ratio [aOR] 0.30, 95% CI 0.07–1.34; hard surface vs flooring: aOR 1.10, 95% CI 0.52–2.31). Fall height was significantly associated with ciTBI risk (aOR 1.31 per 10 cm increase, 95% CI 1.19–1.45). Similar associations were observed for abnormal head CT findings. GAMs demonstrated an approximately linear increase in risk with increasing fall height, without an inflection point.

Conclusions: In children under two years with head trauma, fall height was associated with ciTBI risk, whereas impact surface type was not. The association between fall height and ciTBI appeared approximately linear across the observed range, suggesting that fixed height thresholds may not fully reflect clinical risk.

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1. Introduction

Head trauma is one of the most common reasons for pediatric emergency department (ED) visits. In the United States, approximately 800,000 children present to EDs annually due to head injuries [1]. Although most pediatric head injuries are minor, a subset result in clinically important traumatic brain injury (ciTBI), which may require

invasive interventions such as endotracheal intubation or neurosurgical procedures [2]. In rare cases, these injuries can be fatal [3]. Therefore, identifying children at risk for ciTBI is essential to pediatric emergency care.

Primary brain injury following blunt trauma results from the immediate mechanical forces applied to the brain upon impact. Since higher energy transfer increases ciTBI risk, assessing the mechanism of injury is essential in risk estimation. Indeed, all established clinical decision rules for pediatric head trauma, such as the prediction rule developed by the Pediatric Emergency Care Applied Research Network (PECARN), the Canadian Assessment of Tomography for Childhood Head Injury (CATCH) rule, and Children's Head Injury Algorithm for the Prediction of Important Clinical Events (CHALICE), incorporate falls from heights exceeding defined thresholds as severe mechanisms of injury and include them as predictors of ciTBI [2,4,5].

Nevertheless, the relationship between specific injury mechanisms and the risk of ciTBI remains insufficiently characterized. Although established clinical decision rules define falls from ≥ 3 ft (91 cm) in children under 2 years of age as a severe mechanism, this cutoff is not

Abbreviations: CATCH, Canadian Assessment of Tomography for Childhood Head Injury; CHALICE, Children's Head Injury Algorithm for the Prediction of Important Clinical Events; CI, confidence interval; ciTBI, clinically important traumatic brain injury; CT, computed tomography; DAG, directed acyclic graph; ED, emergency department; EMR, electronic medical record; GAM, generalized additive model; IQR, interquartile range; MRI, magnetic resonance imaging; OR, odds ratio; PECARN, Pediatric Emergency Care Applied Research Network; STROBE, Strengthening the Reporting of Observational Studies in Epidemiology.

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derived from conclusive clinical evidence [2,4]. Similarly, regarding impact surfaces, a 3D simulation replicating infant biomechanics suggested that concrete surfaces may pose a higher risk of skull fracture than carpet, although clinical evidence supporting this remains limited [6]. Clarifying the associations between these mechanism-related factors and cTBI may improve risk stratification in young children with head trauma. In particular, because children under 2 years of age are often preverbal, symptom-based assessment is limited and objective mechanism-related information becomes especially important [7]. Accordingly, we limited the cohort to children under 2 years of age to reduce age-related heterogeneity and to focus on fall height and impact surface type.

This retrospective cohort study aimed to evaluate the association of fall height and impact surface with cTBI in pediatric patients under 2 years of age, and to determine whether fall height shows an inflection point for cTBI risk or whether the relationship is linear.

2. Materials and methods

2.1. Study design and setting

This retrospective cohort study was conducted at the National Center for Child Health and Development, a tertiary pediatric hospital in Tokyo, Japan. The hospital's ED serves both as a primary receiving facility for walk-in patients and emergency medical service transports, ranging from minor to critically ill cases, and as a tertiary referral center that accepts patients requiring intensive care or surgical intervention from other institutions. The study period (January 1, 2017, to December 31, 2021) was the most recent five-year period with complete electronic medical records available at the start of data collection in 2022.

Ethics approval for this study was obtained from the National Center for Child Health and Development ethics committee (2020–259). This manuscript was prepared following the Strengthening of Reporting of Observational Studies in Epidemiology (STROBE) guidelines [8].

2.2. Selection of participants

We included children younger than two years who presented to the ED with head trauma during the study period. Eligible cases were identified through the ED administrative database, which systematically records the presence and anatomical location of trauma. From trauma cases involving the head, face, neck, or entire body, those with confirmed head trauma were identified through EMR review by the first author.

Patients were excluded according to the following criteria. Initial exclusions were applied for conditions that could alter cTBI risk (history of neurosurgical intervention, genetic skeletal disorders associated with bone fragility, bleeding disorders, or current use of antithrombotic agents) or compromise data reliability (presentation more than 24 h after injury, or unknown mechanism of injury). Subsequently, patients were excluded if the injury mechanism did not involve ground impact, including falling down stairs or collisions with stationary or moving objects. Finally, cases referred to child protective services were excluded due to potentially unreliable clinical histories.

2.3. Measurements and definitions

Variables were collected from EMRs, including demographics (sex, age in months), injury characteristics (location of injury [indoors or outdoors], fall origin, fall height, impact surface), presentation findings (Glasgow Coma Scale score), neuroimaging (head computed tomography [CT] or magnetic resonance imaging [MRI] performed), imaging findings (skull fractures or intracranial abnormalities consistent with TBI, as defined in the Outcomes section), clinical interventions (intubation, neurosurgical procedures, intracranial pressure monitoring), and clinical course (hospitalization status and discharge disposition).

We documented two key fall-related variables: fall origin and fall height. The fall origin specified the object or position from which the child fell. Ground-level falls were defined as falls from sitting or standing positions where the child's head struck the ground directly, and these were uniformly assigned a fall height of 0 cm. For falls from elevated surfaces, we recorded the specific object involved, such as beds, chairs, sofas, or a caregiver's arms. Fall height was recorded as a continuous variable in centimeters, documented at ED presentation by triage nurses or attending physicians based on information obtained from caregivers.

Impact surface type was categorized into three groups: flooring (wood, laminate, vinyl), soft surfaces (carpet, cushion mat, tatami, futon, dirt ground), and hard surfaces (asphalt, concrete, tile, stone, brick, marble, gravel). The classification of some surfaces as soft or hard was informed by prior studies [6,9–12]. For surfaces not addressed in prior studies, categorization was based on whether the surface was judged to be softer or harder than flooring, as determined by consensus among the authors.

At our institution, the decision to obtain a head CT is generally guided by the PECARN decision rule [4]. However, the final decision is made by the treating clinician with caregiver agreement. Head MRI is performed only in admitted patients and is selectively obtained during hospitalization as follow-up imaging to minimize radiation exposure or to evaluate persistent altered mental status despite no clear abnormalities on CT. Board-certified pediatric radiologists routinely interpreted all head CT and MRI studies. For this study, the first author also reviewed all imaging reports and original scans to ensure consistent and accurate outcomes classification.

2.4. Outcomes

The primary outcome was cTBI, defined as TBI resulting in any of the following: death, neurosurgical intervention, intubation for more than 24 h due to TBI, or hospitalization for at least two nights due to TBI. The definition of TBI was determined in line with previous pediatric head injury research, including clinical decision rules developed by PECARN and CATCH, as well as the CHALICE algorithm [2,4,5]. Specifically, TBI was defined as intracranial hemorrhage or contusion, cerebral edema, traumatic infarction, sigmoid sinus thrombosis, midline shift of intracranial contents or signs of brain herniation, diastasis of the skull, pneumocephalus, or depressed skull fracture. The secondary outcome was defined as any abnormal findings on head CT, including TBI and/or skull fractures [13,14].

To mitigate potential outcome misclassification among children who did not undergo neuroimaging at the index ED visit, we performed a standardized, hospital-wide EMR review for all enrolled children for at least 12 months after the index visit. Because the EMR is shared across all departments within our institution, subsequent encounters, including those outside the ED, could be identified. In routine practice, our ED is available 24 h a day, 7 days a week, and caregivers receive standardized written return precautions at discharge, which may facilitate re-presentation if symptoms develop or evolve.

2.5. Statistical analysis

The primary analysis was performed using a multivariable logistic regression with cTBI as the outcome. Impact surface type and fall height were treated as the main exposures. Impact surface type was represented by two indicator variables for soft and hard surfaces, with flooring as the reference category. Fall height was modeled as a continuous predictor scaled per 10 cm increase. The selection of covariates was based on a directed acyclic graph (DAG) informed by prior research and clinical knowledge [11,12,15–17]. The DAG indicated that fall height and impact surface type could each confound the other's association with cTBI (Supplementary Fig. 1). Accordingly, in the final model, fall height and impact surface type were included simultaneously and

mutually adjusted for each other, with additional adjustment for age in months. Adjusted odds ratios (ORs) with 95% confidence intervals (CIs) were reported.

To explore potential nonlinear associations for fall height, we fitted a generalized additive model (GAM) with a thin-plate regression spline for fall height (basis dimension $k = 5$) and the same covariates as the primary model. The adjusted smooth term and its pointwise 95% CIs were used to graphically assess the relationship between fall height and the log-odds of ciTBI. A similar GAM was fitted for abnormal head CT findings to visualize its association with fall height.

Missing data were handled using multiple imputation by chained equations ($m = 20$; 50 iterations) implemented with the mice package in R [18]. The imputation model included all collected variables, including the main exposures (fall height and type of impact surface), the outcome, and other covariates used in the primary analysis. This comprehensive inclusion was based on the principle that imputation models should contain all variables used in the analysis model, and preferably additional ones, as supported by prior studies [19,20]. Each imputed dataset was analyzed separately, and the results were combined using Rubin's rules [21].

All statistical analyses were performed using R software (version 4.4.0; R Foundation for Statistical Computing, Vienna, Austria). Statistical significance was defined as a two-sided p -value < 0.05 .

2.6. Sensitivity analysis

We performed three sensitivity analyses to examine the robustness of the main findings: exclusion of ground-level falls, complete-case analysis, and dichotomization of impact surface type (soft vs. non-soft). The rationale and methods for each analysis are provided in the Supplementary Methods.

3. Results

3.1. Study population

During the study period, 3067 children under two years of age with head trauma presented to the ED (Fig. 1). Overall, 173 children were excluded based on initial medical and history-related criteria. Additional exclusions were made for injuries not involving ground impact, including falls down stairs or collisions with stationary or moving objects

($n = 993$), as well as for cases referred to child protective services ($n = 8$). Ultimately, 1893 children were included in the final analysis.

3.2. Patient characteristics

Table 1 summarizes the baseline characteristics of the study cohort. Fall height was missing in 253 of 1893 patients (13.4%), and the impact surface type was missing in 395 (20.9%). Age in months and outcomes had no missing values. Of the 1893 children included, 212 (11.2%) underwent head CT imaging. Among them, 85 (40.1%) had abnormal head CT findings, and 44 (20.8%) were diagnosed with ciTBI. Compared to those without ciTBI, patients with ciTBI were younger (median age 3.0 months [interquartile range (IQR), 1.0–4.2] vs. 10.0 months [IQR, 5.0–17.0]), less likely to have fallen onto soft surfaces (2/44 [4.5%] vs. 242/1849 [13.1%]), and experienced falls from greater heights (median 100 cm [IQR, 70–100] vs. 60 cm [IQR, 40–80]). Table 2 presents the distribution of radiological findings among the 85 patients with abnormal head CT findings. Among the 44 patients with ciTBI, 1 patient (2.3%) underwent neurosurgical intervention, 2 patients (4.5%) required endotracheal intubation for more than 24 h, and all patients were hospitalized for at least two nights. No deaths occurred during hospitalization. No case was reclassified as TBI based on MRI findings when CT findings did not meet the TBI definition.

3.3. Primary and sensitivity analyses

The results of multivariable logistic regression for ciTBI and abnormal head CT findings are presented in Table 3. After adjusting for age and fall height, impact surface type was not significantly associated with ciTBI. Compared to flooring, the adjusted OR was 0.30 (95% CI: 0.07–1.34) for soft surfaces and 1.10 (95% CI: 0.52–2.31) for hard surfaces. In contrast, fall height was significantly associated with the risk of ciTBI. For every 10 cm increase in fall height, the adjusted OR was 1.31 (95% CI: 1.19–1.45). Similar associations were observed for abnormal head CT findings, with fall height again showing a significant association (adjusted OR 1.34 [95% CI: 1.25–1.45] per 10 cm). Impact surface type was also not significantly associated with the outcome (soft: adjusted OR 0.46 [95% CI: 0.18–1.18]; hard: adjusted OR 1.22 [95% CI: 0.69–2.17], both vs flooring).

Fig. 2 illustrates the smoothed relationships between fall height and the log odds of each outcome, modeled using GAMs with the

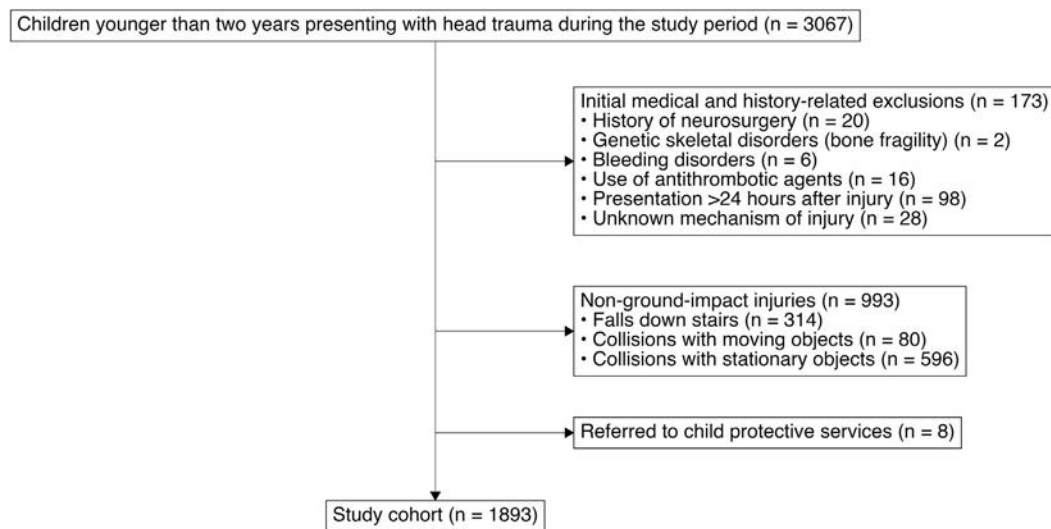


Fig. 1. Flow diagram of case selection for the study cohort.

Children younger than two years presenting with head trauma were screened, and cases were excluded for medical history-related factors, non-ground-impact mechanisms, or referral to child protective services.

Table 1
Characteristics of the study population.

Variables	Overall n = 1893	No ciTBI n = 1849	ciTBI n = 44
Sex (Female, n, %)	894 (47.2)	873 (47.2)	21 (47.7)
Age (months, median [IQR])	9.0 [5.0–17.0]	10.0 [5.0–17.0]	3.0 [1.0–4.2]
Location (n, %)			
Indoor	1344 (71.0)	1311 (70.9)	33 (75.0)
Outdoor	546 (28.8)	535 (28.9)	11 (25.0)
Unknown	3 (0.2)	3 (0.2)	0 (0.0)
Fall origin (n, %)			
Sitting	19 (1.0)	18 (1.0)	1 (2.3)
Standing	219 (11.6)	219 (11.8)	0 (0.0)
Sofa	205 (10.8)	204 (11.0)	1 (2.3)
Bed	419 (22.1)	411 (22.2)	8 (18.2)
Chair	233 (12.3)	230 (12.4)	3 (6.8)
Bouncer	23 (1.2)	23 (1.2)	0 (0.0)
Table	54 (2.9)	52 (2.8)	2 (4.5)
Changing table	17 (0.9)	17 (0.9)	0 (0.0)
Being held	258 (13.6)	238 (12.9)	20 (45.5)
Being carried on the back	6 (0.3)	6 (0.3)	0 (0.0)
Being carried on the shoulders	2 (0.1)	2 (0.1)	0 (0.0)
Stroller	10 (0.5)	109 (5.9)	1 (2.3)
Bicycle seat	88 (4.6)	88 (4.8)	0 (0.0)
Unclassifiable	240 (12.7)	232 (12.5)	8 (18.2)
Fall height (cm, median [IQR])	60 [40–80]	60 [40–80]	100 [70–100]
Impact surface type (n, %)			
Flooring	859 (45.4)	835 (45.2)	24 (54.5)
Soft	244 (12.9)	242 (13.1)	2 (4.5)
Hard	395 (20.9)	382 (20.7)	13 (29.5)
Unknown	395 (20.9)	390 (21.1)	5 (11.4)
GCS total (n, %)			
15	1851 (97.8)	1816 (98.2)	35 (79.5)
14	39 (2.1)	32 (1.7)	7 (15.9)
9–13	3 (0.2)	1 (0.1)	2 (4.5)
Head CT (n, %)	212 (11.2)	168 (9.1)	44 (100.0)
MRI (n, %)	48 (2.5)	8 (0.4)	40 (90.9)
Hospitalization status (n, %)			
Discharged from ED	1800 (95.1)	1800 (97.3)	0 (0.0)
Admitted for 1 night	9 (0.5)	9 (0.5)	0 (0.0)
Admitted for ≥2 nights	84 (4.4)	40 (2.2)	44 (100.0)
Hospital transfer (n, %)	2 (0.1)	0 (0.0)	2 (4.5)

ciTBI: clinically important traumatic brain injury; CT: computed tomography; ED: emergency department; GCS: Glasgow Coma Scale; IQR: interquartile range; MRI: magnetic resonance imaging.

same covariates as in the primary logistic regression. For both ciTBI (Fig. 2a) and abnormal head CT findings (Fig. 2b), the adjusted log odds increased approximately linearly with increasing fall height. No apparent non-linearity or inflection point was observed in either model, and the risk continued to rise steadily across the full range of fall heights.

Table 2
Types and frequencies of abnormal head CT findings.

CT findings, n (%)	n = 85
Isolated linear skull fracture	41 (48.2)
TBI with linear skull fracture	31 (36.5)
EDH	13 (15.3)
SAH	7 (8.2)
SDH	6 (7.1)
SAH + EDH	3 (3.5)
SAH + SDH	2 (2.4)
TBI without linear skull fracture	13 (15.5)
SAH	5 (5.9)
Depressed skull fracture	2 (2.4)
SDH	2 (2.4)
Depressed skull fracture + Cerebral contusion	1 (1.2)
Depressed skull fracture + EDH	1 (1.2)
IVH + Cerebral contusion	1 (1.2)
SAH + SDH	1 (1.2)

CT: computed tomography; EDH: Epidural hematoma; IVH: Intraventricular hemorrhage; SAH: Subarachnoid hemorrhage; SDH: Subdural hematoma; TBI: traumatic brain injury.

Table 3
Logistic regression analyses of risk factors for ciTBI and abnormal CT findings.

Outcome	Variables	OR (95% CI)	p-value
ciTBI	Impact surface type		
	Flooring	Reference	–
	Soft	0.30 (0.07–1.34)	0.12
	Hard	1.10 (0.52–2.31)	0.80
Abnormal head CT findings	Fall height, per 10 cm	1.31 (1.19–1.45)	<0.001
	Impact surface type		
	Flooring	Reference	–
	Soft	0.46 (0.18–1.18)	0.11
	Hard	1.22 (0.69–2.17)	0.50
	Fall height, per 10 cm	1.34 (1.25–1.45)	<0.001

CI: confidence interval; ciTBI: clinically important traumatic brain injury; CT: computed tomography; OR: odds ratio.

The results of all three sensitivity analyses were consistent with the primary analysis (Supplementary Results, Supplementary Table 1, and Supplementary Fig. 2).

4. Discussion

In this retrospective cohort study of nearly 1900 children younger than two years with head trauma, fall height was significantly associated with the risk of ciTBI and abnormal head CT findings, whereas impact surface type was not. The risk of ciTBI increased in an approximately linear fashion with fall height, without evidence of an inflection point. Impact surface was categorized into flooring, surfaces harder than flooring, and surfaces softer than flooring; none of these categories showed statistically significant associations with ciTBI or abnormal head CT findings. These findings were consistent across sensitivity analyses.

To our knowledge, no previous pediatric studies have evaluated fall height as a continuous variable in relation to ciTBI. Prior studies have instead relied on categorical cutoff values, such as 2 ft, 3 ft, or 100 cm, when examining associations with TBI or skull fractures [22–25]. Although these studies generally suggest that higher falls are associated with increased injury risk, the proposed cutoff values have varied substantially, and none have assessed fall height on a continuous scale. Consequently, the validity of specific thresholds remains uncertain, and whether dichotomizing fall height is appropriate warrants further consideration. In addition, many prior studies relied on univariate analyses or limited adjustment for confounders, further complicating interpretation [22,23,25].

We addressed these limitations in two ways. First, we analyzed fall height as a continuous variable. One reason prior studies may have relied on categorical classifications is that documenting fall height in centimeters can be difficult in clinical practice. Indeed, most prior studies reported fall height as a categorical variable, yet even in these simplified classifications, missing data rates were as high as 20–30% [24,26,27]. Although our investigation was conducted at a single institution, the systematic practice of documenting fall height both at triage and by the attending physician enabled a relatively low missing rate of 13.4%. Second, we employed a DAG to systematically identify and adjust for relevant confounders. This DAG-based approach facilitates theory-driven covariate selection and helps minimize both confounding bias and over-adjustment bias [28,29]. Using this approach, we observed an approximately linear association between fall height and ciTBI risk, suggesting that the clinical relevance of fixed cutoffs may warrant cautious interpretation.

Regarding impact surface, we found no statistically significant association between impact surface type and ciTBI. One possible explanation for this is limited statistical power. In particular, only two ciTBI events occurred among children who fell onto soft surfaces, and the resulting wide CIs indicate that the study might not have had sufficient power to detect a meaningful difference [30]. Prior experimental and finite element modelling studies in infants and young children have suggested

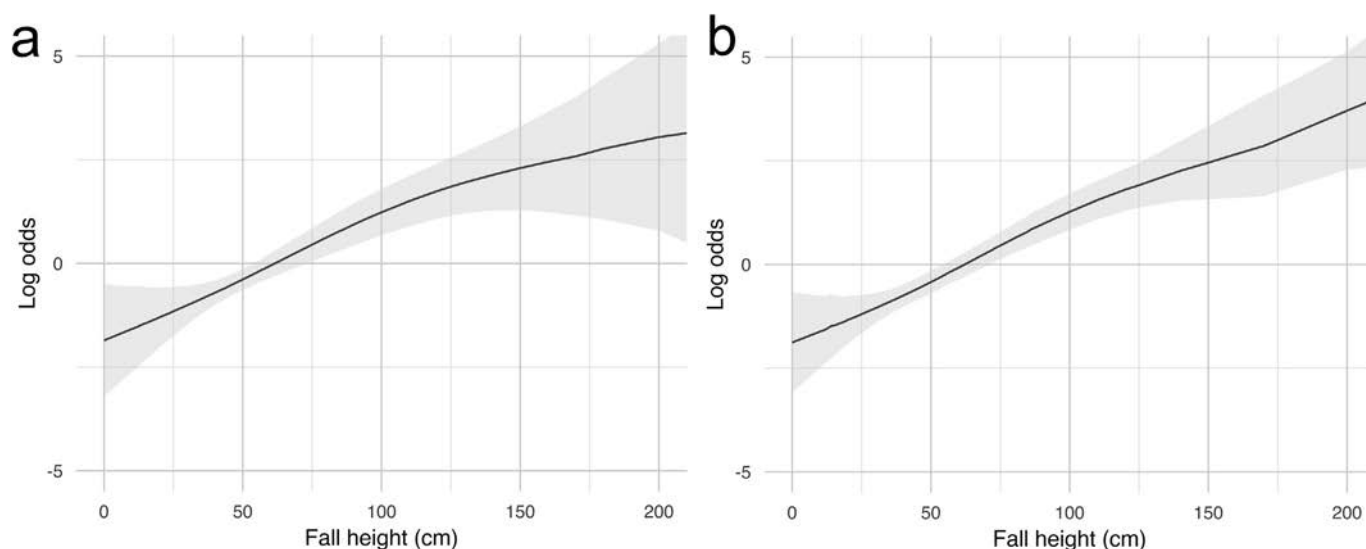


Fig. 2. Generalized additive models for the association between fall height and study outcomes in the primary analysis.

(a) Clinically important traumatic brain injury (ciTBI).

(b) Abnormal head computed tomography (CT) findings.

The solid lines represent the fitted log odds, and the shaded areas represent pointwise 95% confidence intervals.

that softer surfaces may mitigate head impact forces, thereby reducing the likelihood of skull fracture compared with harder surfaces [6,10]. Considering these prior findings, it is possible that softer surfaces reduce the risk of ciTBI or skull fracture. However, due to the small number of cases and the lack of statistical significance, our study cannot provide conclusive evidence for this hypothesis.

Our findings have several clinical and research implications. Clinically, the approximately linear relationship between fall height and ciTBI risk suggests that risk stratification based solely on fixed categorical thresholds may not fully capture the continuous nature of this association. Our results further suggest that clinicians may be able to achieve a more nuanced risk assessment by considering fall height as a continuous variable when estimating ciTBI risk. From a research perspective, although no significant association was observed between impact surface and ciTBI risk, this possibility cannot be excluded. Future studies should incorporate larger sample sizes, standardized surface classification, reduced missing data, improved generalizability (including evaluation in older age groups), and systematic follow-up of non-imaged patients. Multicenter prospective studies would be particularly valuable in addressing these limitations.

5. Limitations

This study has several limitations. First, as a single-center retrospective observational study, the generalizability of our findings is limited, and causal inferences cannot be made. Second, fall height was based on caregiver reports and impact surface classification involved subjective judgment, which may have introduced measurement error or misclassification. In addition, although multiple imputation was used to address missing data and yielded results consistent with complete-case analyses, residual bias cannot be entirely excluded. Third, the relatively small number of ciTBI cases may have limited statistical power, particularly for detecting associations with impact surface type. Finally, outcome misclassification is possible in patients who did not undergo head CT, which may have resulted in under-ascertainment of ciTBI. We performed a standardized EMR review for at least 12 months after the index visit; however, patients who did not seek further medical care or who presented to outside institutions could not be captured.

6. Conclusions

In this single-center retrospective study of children under two years of age with head trauma, fall height was significantly associated with the risk of ciTBI, with an approximately linear relationship, whereas impact surface type was not. These findings suggest that fixed fall-height cutoffs may not fully reflect clinical risk. Although no significant association was observed for impact surface type, this may be attributable to limited statistical power. Larger multicenter prospective studies with standardized assessments are needed to validate these findings.

Notation of prior abstract publication/presentation

None.

CRediT authorship contribution statement

Takatoshi Oishi: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Shunsuke Amagasa:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Satoko Uematsu:** Writing – review & editing, Supervision. **Takashi Moriya:** Writing – review & editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ajem.2026.03.002>.

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