OPEN

PRS GLOBAL OPEN

ORIGINAL ARTICLE

Hand/Peripheral Nerve

Derivation and Internal Validation of a Prediction Model for Pediatric Hand Fracture Triage

Rebecca L. Hartley, MSc, MD*
Frankie O.G. Fraulin, MD, FRCSC*†
A. Robertson Harrop, MSc, MD, FRCSC*†
Peter Faris, PhD‡
James Wick, MSc§
Paul E. Ronksley, MSc, PhD¶

Background: Pediatric hand fractures are common, and most can be managed by a period of immobilization. However, it remains challenging to identify those more complex fractures requiring the expertise of a hand surgeon to ensure a good outcome. The purpose of this study was to develop a prediction model for identification of complex pediatric hand fractures requiring care by a hand surgeon.

Methods: A 2-year retrospective cohort study of consecutively referred pediatric (<18 years) hand fracture patients was used to derive and internally validate a prediction model for identification of complex fractures requiring the expertise of a hand surgeon. These complex fractures were defined as those that required surgery, closed reduction, or four or more appointments with a hand surgeon. The model, derived by multivariable logistic regression analysis, was internally validated using bootstrapping and then translated into a risk index.

Results: Of 1170 fractures, 416 (35.6%) met criteria for a complex fracture. Multivariable regression analysis identified six significant predictors of complex fracture: open fracture, rotational deformity, angulation, condylar involvement, dislocation or subluxation, and displacement. Internal validation demonstrated good performance of the model (C-statistic = 0.88, calibration curve $p = 0.935$). A threshold of ≥1 point (ie, any one of the predictors) resulted in a simple, easy-to-use tool with 96.4% sensitivity and 45.5% specificity.

Conclusions: A high-performing and clinically useful decision support tool was developed for emergency and urgent care physicians providing initial assessment for children with hand fractures. This tool will provide the basis for development of a clinical care pathway for pediatric hand fractures. *(Plast Reconstr Surg Glob Open 2021;9:e3543; doi: 10.1097/GOX.0000000000003543; Published online 20 April 2021.)*

*From the *Section of Plastic Surgery, Department of Surgery, University of Calgary, Calgary, Alberta, Canada; †Section of Pediatric Surgery, Department of Surgery, Alberta Children's Hospital, Calgary, Alberta, Canada; ‡Alberta Health Services; §Department of Medicine, University of Calgary, Calgary, Alberta, Canada; ¶Department of Community Health Sciences, University of Calgary, Calgary, Alberta, Canada.*

Received for publication December 22, 2020; accepted February 14, 2021.

Presented in part at the Canadian Association for Health Services and Policy Research Conference in May 2019, Halifax, Nova Scotia, and the Canadian Society of Plastic Surgery Annual Meeting in June 2019, St. Johns, Newfoundland, Canada.

This study complied with the reporting standards outlined in the Transparent Reporting of a multivariable prediction model for Individual Prognosis or Diagnosis statement.[24] *This study was approved by the University of Calgary Conjoint Health Research Ethics Boards (REB14-1846).*

DOI: 10.1097/GOX.0000000000003543

INTRODUCTION

Hand fractures in children are common, and account for one-fifth of all pediatric fractures.[1–5] Rates of pediatric hand fractures referred to hand surgeons vary, with rates reported in the literature ranging from 6.5% to 100%.[6] Most pediatric hand fractures have good clinical outcomes,[1,7–10] as children have the capacity for quicker healing, better remodeling, and reduced rates of non-union compared with their adult counterparts.[11] The majority can be managed by immobilization alone.[3,7,8,10,12,13] There are, however, a subset of fractures (up to 14%)[7,8,10,12–15] that do not heal well or go on to malunion without surgical intervention. It is important to identify this subset of more complex fractures to ensure timely referral to, and management by, a hand surgeon to optimize clinical outcomes.

Rates of referral are likely influenced by a range of factors, including primary care provider discomfort, provider risk aversion, and parental pressures. However, given that

Disclosure: *All the authors have no financial interest in relation to the content of this article.*

Related Digital Media are available in the full-text version of the article on www.PRSGlobalOpen.com.

few pediatric fractures require surgery, a reliable method for discriminating between simple fractures with predictably good clinical outcomes and complex fractures requiring the expertise of a hand surgeon might help facilitate expedient and cost-effective care of these patients. This in turn might reduce burden on health care systems by reducing strain on waitlists and reducing cost of care while also decreasing inconvenience to these children and their parents.[16,17] Such a prediction tool could potentially be incorporated into a clinical care pathway for triaging and managing pediatric hand fractures. This pathway would optimize health care resources by aligning patients with the appropriate level of care at the right place and time. A key pre-requisite to such a pathway would be the ability of a referring physician to accurately discriminate between fractures that require specialized care by a hand surgeon (high-risk or "complex" fractures) and those that do not (low-risk or "simple" fractures). With this in mind, the objective of this study was to derive and internally validate a prognostic prediction model for complex pediatric hand fractures that require referral to a hand surgeon.

MATERIALS AND METHODS

A clinical registry was used to identify consecutively referred children (<18 years) to a single-center, tertiary hospital's pediatric hand surgery clinic with a diagnosis of hand fracture between January 1, 2013 and December 31, 2014. Consistent with other Canadian centers, all hand surgeons at this institution are plastic surgeons and are referred to as hand surgeons hereafter. A hand fracture was defined as a radiographically confirmed fracture distal to the carpus. Patients were excluded if they had a wrist fracture without an accompanying hand fracture, a soft tissue injury without an accompanying hand fracture, a complete amputation or incomplete chart information. If a patient had multiple fractures from a single injury, each fracture was counted as an independent entry.

A list of 20 candidate predictor variables was identified a priori from the pediatric hand fracture literature within 3 broad categories: demographic, physical exam, and radiologic variables. (**See Supplemental Digital Content 1,** (A) Candidate predictor variables. **http://links.lww.com/PRSGO/B632**.) Demographic and physical exam variables were collected from electronic and paper medical charts. Radiographic variables were assessed by the study team on AGFA Impax 6 (AGFA HealthCare NV, 2009, Belgium), and the hospital's picture archiving and communicating system.

The outcome of interest was "complex fracture requiring specialized care by a hand surgeon" (hereafter referred to as complex fracture). Complex fracture was a composite outcome defined as (1) fractures that required surgery (defined as any procedure under general anesthesia or any internal fixation), (2) fractures that required closed reduction (by any provider, not limited to a hand surgeon, before or after referral) or (3) fractures that required four or more appointments with a hand surgeon. Four or more appointments were chosen as a surrogate threshold indicator of fracture complexity. A proportion of high-risk fractures heal without surgery or closed reduction, but these fractures need to be closely followed by a hand surgeon in the interim and it was hypothesized that 4 or more appointments would capture this subset of fractures. A simple fracture was defined as any fracture that did not meet the criteria for complex fracture. All patients were followed from referral to June 1, 2017 to determine if the fracture was defined as complex or simple.

Initially, the proportion of complex fractures for each of the candidate variables was examined. Statistically significant differences were identified by the Mann-Whitney U test for non-parametric variables and chi-squared test for categorical variables. Next, collinearity was assessed using a correlation matrix ($|r| > 0.8$[18]) and then univariate analyses for each independent candidate variable was performed using logistic regression, where a Wald test P value of <0.1 was considered significant. A subset of candidate variables was then selected (angulation, condylar involvement, dislocation or subluxation, displacement, intra-articular, open, and rotation—ie, abnormal cascade of the digits), guided by the significant predictors from the univariate analyses as well as expert consultation, for multivariable logistic regression using complete-case analysis. Variables were removed one-at-a-time using stepwise backwards elimination of the candidate predictor variable with the highest Wald test P value. Each time a variable was removed, the model's Akaike information criterion and Bayesian information criterion were assessed. Variable elimination stopped when either (1) Akaike information criterion and Bayesian information criterion values both increased compared with the previous model or (2) all variables had a Wald test P value of <0.05. The model was internally validated using bootstrapping, with 1000 repetitions for each step of the model-building procedure. Once variable elimination had been completed, estimated regression coefficients and odds ratios (OR) with 95% confidence intervals (CI's) for each included variable were reported.

Model performance was evaluated using concordance statistic (C-statistic) for discrimination and a Cox calibration curve for calibration. Bootstrap-adjusted regression coefficient estimates, adjusted 95% CI's, and adjusted C-statistic as well as a shrinkage factor were reported.[19]

Following the framework that Sullivan et al outlined for the Framingham Study in 2006,[20] the multivariable regression model was then converted into an integer points score. The predictor variable with the lowest regression coefficient estimate acted as the baseline reference and was assigned a value of 1 point. All other points were assigned relative to this baseline reference depending on the magnitude of difference of each regression coefficient estimate. Next, the points score was used to develop a risk index for prediction of complex fracture. A threshold with a sensitivity above 95% was chosen because it has been argued that few physicians would tolerate missing more than 5% of outcomes.[21,22] Creating a risk index introduced a measure of error as relatively exact regression coefficient estimates from the model were translated into integer point values for the risk index. Thus, following the development of the risk index, model performance was re-evaluated.

Sensitivity analyses were performed. The first sensitivity analysis investigated varying thresholds for number of hand surgeon appointments. The second sensitivity analysis investigated the individual components within the composite outcomes of complex fracture (surgery, closed reduction, and four or more appointments with a hand surgeon) by creating three additional models, one for each surgery, closed reduction, and four or more appointments with a hand surgeon.

RESULTS

There were 1045 patients, who had 1172 fractures, included in this study. Of the 1172 hand fractures, 417 (35.6%) met the criteria for a complex fracture requiring specialized care. Surgery was the final management in 115 fractures (9.8%), and most surgeries were performed under a general anesthetic (88.7% of surgical fractures). One quarter of all hand fractures required a closed reduction (25.1%). One hundred and two fractures required 4 or more appointments with a hand surgeon (8.7%). The median number of appointments for all fractures was 2 (Inter-quartile range: 1–3).

The median patient age was 13 years (interquartile range: 10–14). There was no significant difference between those hand fractures that met the criteria for complex fracture and those that did not meet the criteria (ie, simple fractures) with regard to patient demographics (age, level of education, and gender). There were several significant differences observed with respect to fracture type and radiographic findings between complex fractures and simple fractures, such as bony location ($P < 0.001$), displacement ($P < 0.001$), and rotation ($P < 0.001$) (Table 1).

Main Results

Of the 1172 fractures, 1170 fractures were available for complete-cases analysis for univariate and multivariable logistic regression analysis (**See Supplemental Digital Content 1,** (B) Estimated univariate odds ratios and 90% confidence intervals and estimated unadjusted multivariable prediction model odds ratios and 95% confidence intervals for complex fracture. **http://links.lww.com/PRSGO/B632**.). A multivariable logistic regression model using bootstrapping identified 6 significant predictors of complex fracture, 2 from physical exam: open fracture ("open") and rotational deformity ("rotation), and 4 from radiograph: angulation of fracture fragments on any x-ray view ("angulation"), condylar involvement, dislocation or subluxation, and displacement (Fig. 1, Table 2).

Model discrimination was strong (C-statistic = 0.88) and well calibrated with a Pearson χ^2 P value of 0.935 (Fig. 2). The shrinkage factor was 0.96, and the bootstrap-adjusted C-statistic was 0.87.

To convert the prediction model into a points system, mild displacement, with an estimated regression coefficient of 0.51, acted as the reference variable. Integer points were then assigned to the remaining predictor variables based on the magnitude of their regression coefficients (Table 2). Individual fractures thus could receive a score (sum of scores for each predictor) from 0 to 19 points. Finally, the points system was translated into a risk index for predicting complex fractures. A graph of the number of fractures and the probability of a complex fracture requiring specialist care based on points score was reported (Fig. 3). The majority of fractures had a low point score, and few fractures had a point score over 12.

Different risk index points thresholds were trialed and ultimately, a threshold of ≥1 point was selected to yield a sensitivity > 95%.[21,22] With a threshold of ≥1 point, the risk index had a sensitivity of 96.4%, a specificity of 45.5%, a positive likelihood ratio of 1.77, and a negative likelihood ratio of 0.079. (**See Supplemental Digital Content 1,** (C) Risk indices' performance at different points thresholds for complex fracture. **http://links.lww.com/PRSGO/B632**.) Using this threshold, 63.6% of the fractures were correctly classified: 401 of the 416 (96.4%) complex fractures were identified as such, and 343 of the 754 (45.5%) simple fractures were identified as such. Conversely, 15 complex fractures (3.6%) were misclassified as simple (ie, false negatives, Table 3) and 411 simple fractures (54.5%) were misclassified as complex (ie, false positives).

Notably, a threshold of ≥1 point effectively rendered the ordinal categorization within predictor variables irrelevant. The degree of angulation and the amount of displacement became superfluous information. That is, if a fracture had any one predictor present, it was predicted "high risk" of being a complex fracture. This allowed for the creation of a simple risk index tool whereby physicians could check off any positive predictor (Fig. 4). The presence of any single predictor thus reaches a threshold of ≥1 point identifying the fracture as a complex fracture requiring specialist care. The discrimination of this risk index was also strong (C-statistic = 0.87) and was not statistically different than the prediction model based on regression coefficients ($P = 0.475$).

Finally, sensitivity analyses for varying numbers of hand surgeon appointments as well as each individual component of the composite outcome (surgery, 4 or more appointments with a hand surgeon, and closed reduction) all showed similar model performance. (**See Supplemental Digital Content 1**, (D) Estimated regression coefficients, odds ratios, and 95% confidence intervals for varying number of hand surgeon appointments; (E), varying Number of Hand Surgeon Appointments; (F), estimated regression coefficients, odds ratios, and 95% confidence intervals for individual component outcomes; (G) Individual component outcomes prediction models' performances. **http://links.lww.com/ PRSGO/B632**.).

DISCUSSION

A clinically useful prediction model to identify complex pediatric hand fractures requiring specialist care was derived and internally validated. The final model contained 6 predictors of complex fracture with strong discrimination and calibration. To facilitate clinical use, a scoring system was created in which each of the 6 predictors was assigned a point value proportional to its level of

Table 1. Baseline Characteristics for Each Pediatric Hand Fracture

Variable		Overall No. (%) (n = 1172)	Type of Fracture No. (%) Complex (n = 416)	Type of Fracture No. (%) Simple (n = 755)	*P*
Age (y)		Median 13 (IQR 10, 14)	13 (10, 15)	13 (10, 14)	0.180
Level of education	Preschool (0–5 y)	88 (7.51)	50 (9.11)	38 (6.62)	0.092
	Primary (6–11 y)	350 (29.86)	111 (26.62)	239 (31.66)	
	Secondary (12–17 y)	734 (62.63)	267 (64.27)	467 (61.72)	
Gender	Men	821 (70.05)	302 (72.66)	519 (68.61)	0.147
Mechanism of injury	Ball games	406 (34.56)	127 (30.46)	279 (36.82)	0.022
	Fall	201 (17.24)	68 (16.55)	133 (17.62)	
	Punch	132 (11.26)	60 (14.39)	72 (9.54)	
	Winter sport	107 (9.13)	31 (7.43)	76 (10.07)	
	Crush	105 (8.96)	41 (9.83)	64 (8.48)	
	Other	203 (17.32)	81 (19.42)	122 (16.16)	
	Missing	18 (1.54)	8 (1.92)	10 (1.32)	
Season	Spring†	276 (23.57)	105 (25.18)	171 (22.68)	0.427
	Summer‡	275 (23.57)	94 (22.78)	181 (24.01)	
	Fall§	363 (30.91)	119 (28.53)	244 (32.22)	
	Winter¶	257 (21.95)	98 (23.50)	159 (21.09)	
Side	Left	535 (45.64)	192 (46.04)	343 (45.42)	0.837
Soft tissue injury	None	853 (72.78)	308 (74.04)	545 (72.19)	<0.001
	Ligament or volar plate	107 (9.13)	18 (4.32)	89 (11.78)	
	Tendon or mallet	58 (4.95)	16 (3.84)	42 (5.56)	
	Dislocation/subluxation	33 (2.82)	27 (6.47)	6 (0.79)	
	Nail bed	19 (1.62)	9 (2.16)	10 (1.32)	
	Laceration	17 (1.45)	7 (1.98)	10 (1.39)	
	Missing	85 (7.25)	31 (7.45)	53 (7.02)	
Bony location	Thumb metacarpal	81 (6.91)	27 (6.47)	54 (7.15)	<0.001
	Finger metacarpals	297 (25.43)	93 (22.54)	204 (27.02)	
	Thumb proximal phalanx	126 (10.75)	33 (7.91)	93 (12.32)	
	Finger proximal phalanges	341 (29.10)	170 (40.77)	171 (22.65)	
	Finger middle phalanges	169 (14.42)	36 (8.63)	133 (17.63)	
	Thumb distal phalanx	0 (0)	0 (0)	0 (0)	
	Finger distal phalanges	158 (13.40)	57 (13.67)	101 (13.25)	
Multiple fractures	Present	168 (14.16)	54 (12.95)	114 (14.83)	0.376
Epiphyseal fracture pattern	Absent	659 (56.31)	257 (61.87)	402 (53.25)	0.004
	Salter-Harris I	24 (2.05)	3 (0.72)	21 (2.78)	
	Salter-Harris II	346 (30.20)	125 (30.70)	221 (29.93)	
	Salter-Harris III	117 (9.22)	24 (5.04)	93 (11.52)	
	Salter-Harris IV	21 (1.79)	4 (0.96)	17 (2.25)	
	Salter-Harris V	5 (0.43)	3 (0.72)	2 (0.26)	
Non-epiphyseal fracture pattern	Absent	513 (43.77)	160 (38.36)	353 (46.75)	0.234
	Transverse	243 (20.73)	118 (28.37)	125 (16.56)	
	Oblique/spiral	228 (19.54)	76 (18.27)	152 (20.13)	
	Avulsion	107 (9.13)	29 (6.97)	78 (10.33)	
	Tuft	45 (3.84)	14 (3.36)	31 (4.11)	
	Comminuted	35 (2.99)	19 (4.57)	16 (2.12)	
Intra-articular fracture	Present	273 (23.21)	105 (25.24)	168 (22.25)	0.240
Condylar fracture	Present	71 (6.06)	48 (11.54)	23 (3.05)	<0.001
Thirds	Proximal	698 (59.56)	216 (51.92)	482 (63.84)	<0.001
	Middle	132 (11.26)	54 (12.98)	78 (10.33)	
	Distal	339 (28.92)	146 (35.10)	193 (25.56)	
	All	3 (0.26)	0 (0)	3 (0.40)	
Displacement	None	497 (42.41)	78 (18.75)	419 (55.50)	<0.001
	Mild‖ (<2 mm)	404 (34.47)	145 (34.86)	259 (34.30)	
	Moderate (2–3.99 mm)	235 (20.05)	157 (37.74)	78 (10.33)	
	Severe (≥4 mm)	36 (3.07)	36 (8.65)	0 (0)	
Angulation on anterior-posterior x-ray	None	846 (72.18)	203 (48.80)	643(85.17)	<0.001
	Mild (<5 degrees)	49 (4.18)	23 (5.53)	26 (3.44)	
	Moderate (5–14.99 degrees)	136 (11.60)	87 (20.91)	49 (6.49)	
	Severe (≥15 degrees)	141 (12.03)	103 (24.76)	38 (5.03)	
Angulation on lateral x-ray	None	827 (70.56)	189 (45.43)	638 (84.50)	<0.001
	Mild (<5 degrees)	42 (3.58)	17 (4.09)	25 (3.31)	
	Moderate (5–14.99 degrees)	110 (9.39)	72 (17.31)	38 (5.03)	
	Severe (≥15 degrees)	193 (16.47)	138 (33.17	55 (7.28)	
Shortening	Present	227 (19.37)	151 (36.30)	76 (10.07)	<0.001
Rotation (abnormal cascade of digits)	Present	102 (8.70)	93 (22.306	9 (1.19)	<0.001
Open fracture	Present	52 (4.44)	37 (8.89)	15 (1.99)	<0.001

*Mann-Whitney or chi-squared test.
†Spring included months March, April, and May.
‡Summer included months June, July, and August.
§Fall included months September, October, and November.
¶Winter included months December, January, and February.
‖Millimeters.

$$\log(\textit{odds of complex fracture}) = -2.62 + (0.78 * \textit{mild angulation}) + (1.93 * \textit{moderate angulation}) + (2.37 * \textit{severe angulation}) + (1.42 * \textit{condylar involvement}) + (2.30 * \textit{dislocation or subluxation}) + (0.51 * \textit{mild displacement}) + (1.73 * \textit{moderate or severe displacement}) + (1.92 * \textit{open}) + (2.19 * \textit{rotation})$$

Fig. 1. Prediction model with regression coefficients and model intercept for complex fracture.

Table 2. Bootstrap-adjusted Multivariable Logistic Regression Model for Complex Fracture and Conversion into a Points System (n = 1170)

Variable	Bootstrap-adjusted OR* [95%CI]†	Bootstrap-adjusted β‡ [95%CI]	Calculation	Points
Angulation				
Absent	Reference	Reference		0
Mild (<5 degrees)	2.18 [1.08–4.40]	0.78 [0.076–1.48]	0.78/0.51 = 1.96	2
Moderate (5–14.99 degrees)	6.90 [4.49– 0.61]	1.93 [1.50–2.36]	1.93/0.51 = 3.78	4
Severe (≥15 degrees)	10.73 [7.21–15.97]	2.37 [1.98–2.77]	2.37/0.51 = 4.65	5
Condylar				
Absent	Reference	Reference		0
Uni- or bi-condylar	4.14 [2.13–8.05]	1.42 [0.76–2.09]	1.42/0.51 = 2.78	3
Dislocation or subluxation				
Absent	Reference	Reference		0
Present	9.93 [3.40–28.99]	2.30 [1.23–3.37]	2.30/0.51 = 4.51	5
Displacement				
Absent	Reference	Reference		0
Mild§ (<2 mm)	1.66 [1.14–2.42]	0.51 [0.13–0.88]	0.51/0.51 = 1	1
Moderate to severe (≥2 mm)	5.64 [3.69–8.62]	1.73 [1.31–2.15]	1.73/0.51 = 3.39	3
Open				
Absent	Reference	Reference		0
Present	6.80 [3.15–14.66]	1.92 [1.15–2.69]	1.92/0.51 = 3.76	4
Rotation (abnormal cascade of digits)				
Absent	Reference	Reference		0
Present	8.92 [3.98–19.99]	2.19 [1.38–3.00]	2.19/0.51 = 4.29	4
Constant	0.073 [0.053–0.10]	−2.62 [−2.94 to −2.29]		
Shrinkage factor	0.96			

*Estimated odds ratio.
†95% confidence interval.
‡Estimated regression coefficients.
§Millimeters.

risk. Selecting a threshold of ≥1 point resulted in a risk index with 96.4% sensitivity.

We hope to incorporate this prediction model into a clinical care pathway whereby emergency and urgent care physicians can apply the risk index tool during their initial assessment of a hand fracture, noting the presence or absence of each predictor. If any one of the 6 predictors are present, the fracture would be predicted as "complex," for which referral to a hand surgeon would be recommended. Otherwise, the fracture would be predicted as "simple," for which referral to a hand surgeon would not be required. The latter simple fractures would, according to the clinical care pathway, be managed by a non-specialist, likely region-specific, such as a family doctor or allied health care provider, with access to a hand surgeon for advice as required. Although this risk index tool still requires further external validation and impact analysis, we view it as a first step toward developing an efficient, patient-centered care pathway for pediatric hand fractures that would improve patient flow, optimize patient satisfaction, maintain or improve patient outcomes, and reduce burden on health care resources. This pathway would include standard 3-view hand radiographs and physical examination for assessment, as well as step-by-step instructions and guidelines for re-evaluation at different time points (ie, ongoing pain, failure to achieve full range of motion) for patients and families with simple hand fractures.

The 6 predictors included in the prediction model are commonly cited characteristics of fracture severity and, in the absence of surgery or other specific nonoperative management, increase the risk of complication or a less than optimal outcome. Fracture angulation, displacement, and malalignment may lead to malunion, altered range of motion, and reduced hand function through altered tendon excursion, changes in loading force, and shortened long axes. Condylar involvement has potential impact on joint function; anatomic alignment at the condyles is important for recovery of a patient's range of motion and minimizing the risk of arthritic changes.[1,23] Similarly, fractures with dislocations or subluxations can affect joint function due to joint malalignment or loss of ligamentous stability. Open fractures have an increased potential for infection and may be associated with more severe mechanisms of action such as crush injuries. Rotational deformities are not corrected by fracture remodeling and therefore may result in hand dysfunction. As such, each predictor was both statistically significant and clinically logical for inclusion in the model.

Two variables that were not found to be significant in the prediction model but receive attention in the literature are growth plate fracture patterns and concomitant soft-tissue injuries (eg, tendon or ligament injuries). Although half of the fractures in this study involved the growth plate, the majority of these epiphyseal fractures

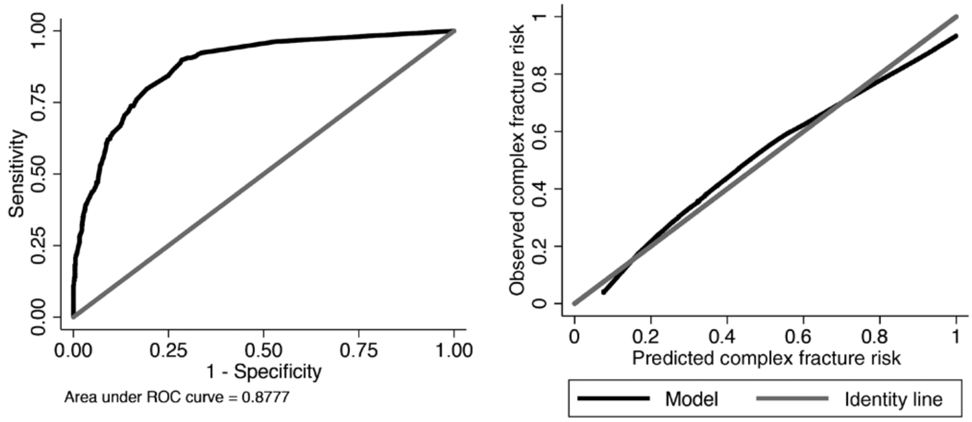

Fig. 2. Performance of the prediction model for complex fracture: A, Area under the receiver operating curve for the prediction model. B, Calibration curve for the prediction model.

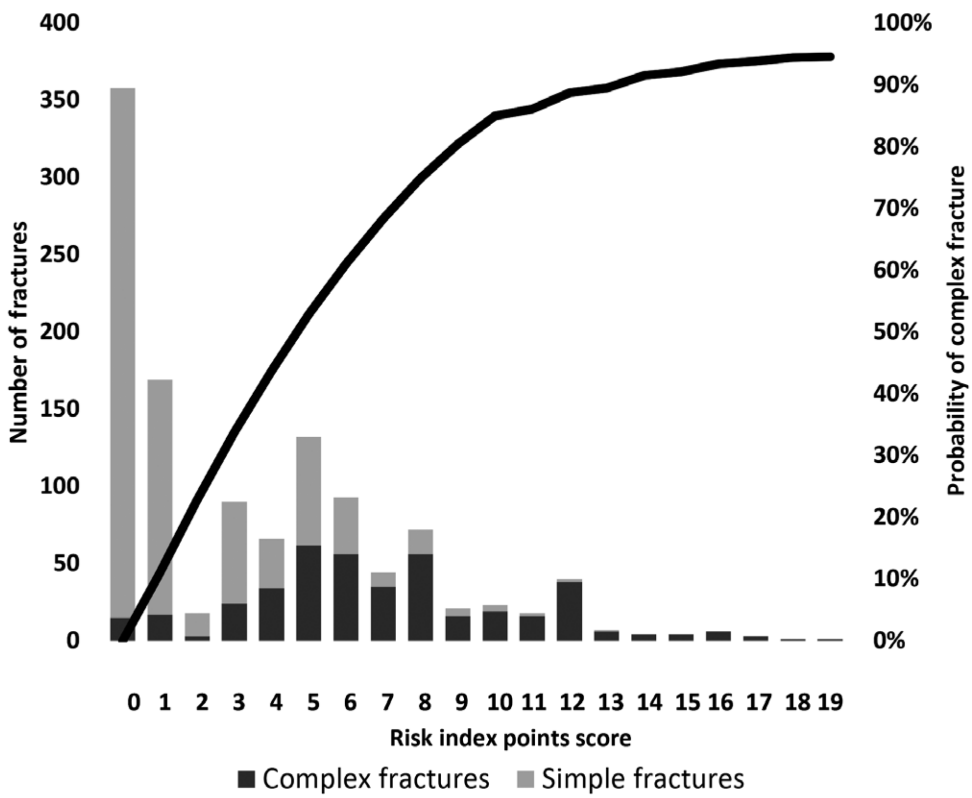

Fig. 3. Risk index figure depicting total number of pediatric hand fractures by points score and the number of complex and simple fractures within each point score category.

were Salter-Harris (SH) type II fractures, and thus this study may have been underpowered to detect an association between the other specific SH fracture types and complex fracture (SH type I n = 3, SH type II n = 346, SH type III n = 24, SH type IV n = 4, SH type V n = 3). Regarding the variable concomitant soft-tissue injury, those soft-tissue injuries that are less worrisome, such as a small volar plate avulsion, rarely have any of the six predictors present, whereas those soft-tissue injuries that are more worrisome, such as a large bony mallet or other large avulsion fractures, virtually always have at least one of the 6 predictors present. Thus, clinically important fractures with concomitant soft-tissue injuries are likely captured by the prediction model without requiring the variable soft-tissue injury to be explicitly included in the model.

Strengths of this study include its methodologic rigor, with TRIPOD guidelines for development of prediction models followed to ensure accuracy, consistency, and transparency in reporting results.[24] Of the 6 predictors included in the prediction model, many estimated regression coefficients had large effect sizes (eg, rotation OR 8.17 [95% CI 3.52–22.59]) and ordinal predictors displayed a

Table 3. Description of All 15 False Negative Fractures (Fractures That Did Not Have Any of the 6 Predictors Present but Required at Least One of Closed Reduction, Surgery, or Four or More Appointments with a Hand Surgeon)

Gender	Age (y)	Fracture Description	Closed Reduction	Surgery	4 or More Appointments
Woman	1	Crush injury with tuft fracture	—	—	YES
Man	13	Thumb ulnar collateral ligament fracture	YES	—	—
Woman	14	Finger volar plate avulsion fracture	—	—	YES
Woman	9	Crush injury to thumb proximal phalanx	YES	—	—
Man	6	Salter-Harris II fracture of distal phalanx	—	—	YES
Man	11	Salter-Harris II of finger proximal phalanx	YES	—	—
Woman	13	Finger volar plate avulsion fracture	YES	—	—
Man	13	Oblique fracture of finger distal phalanx	YES	—	—
Man	12	Salter-Harris II of finger proximal phalanx	YES	—	—
Man	11	Salter-Harris II of finger proximal phalanx	YES	—	—
Man	15	Finger volar plate avulsion fracture	YES	—	—
Woman	15	Crush injury with tuft fracture	—	YES	—
Woman	12	Salter-Harris III of thumb proximal phalanx	YES	—	YES
Man	12	Salter-Harris II of finger proximal phalanx	YES*	—	—
Man	10	Crush injury with tuft fracture and nail bed injury	—	YES	YES

*All closed reductions performed by Emergency Department physicians except for false negative patient 14, whose closed reduction was performed by the hand surgeon.

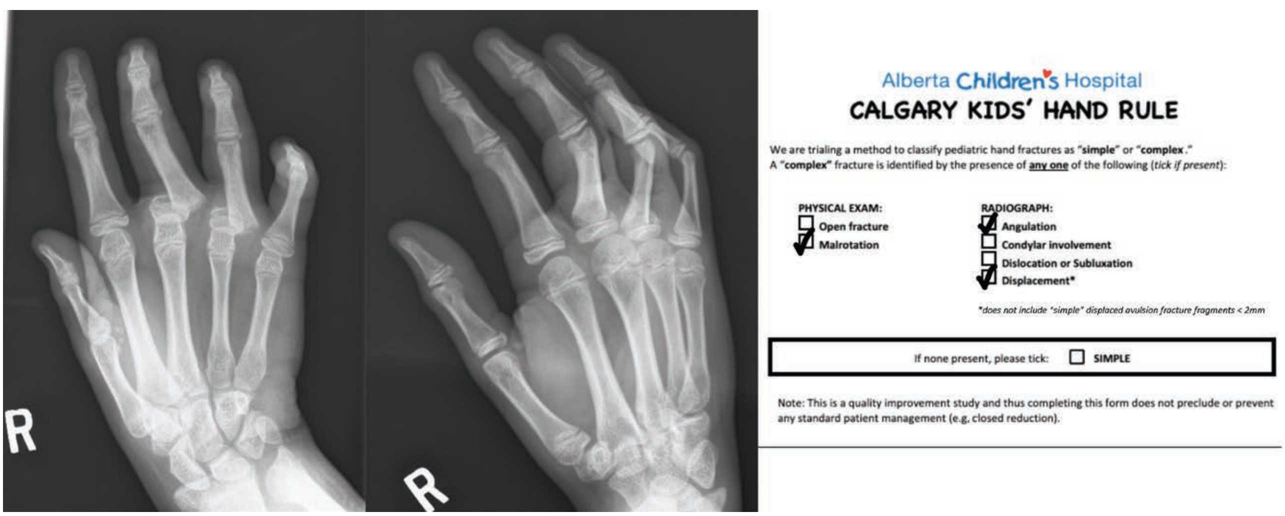

Fig. 4. Example of a clinical tool adapted from the prediction model for complex fractures with a threshold of ≥1 point and how to apply this clinical tool using a sample radiograph.

logical, clinically appropriate gradient. The risk index version of the prediction model with only 6 predictors and a threshold of ≥1 point (thus the presence of any one of the predictors predicts a fracture as complex) makes for a very simple, easy-to-use rule. The 2 physical examination and 4 radiographic predictors are readily identifiable during a standard assessment of a suspected hand fracture, which includes history, physical examination, and a radiograph. Unlike many prediction models, no additional, expensive, or time-consuming tests are required.

Of the 1170 fractures, there were 15 false negatives observed and 411 false positives (that is, 411 simple fractures that would have been predicted to require the special expertise of a hand surgeon unnecessarily). The high number of false positives is a reflection of the risk index tool's high sensitivity; to minimize false negatives, the tool must be overly inclusive in its prediction of "complex" fractures. Although the tool produced 411 false positives, it correctly identified 343 simple fractures. All prediction models represent a balance between sensitivity and specificity. As this tool is to be used for screening or triage, maximizing sensitivity will decrease the risk of false negatives while accepting the corollary of increased false positives.

Closer inspection of the false negatives (Table 3) shows that of the fractures that required closed reduction, some of these fractures did not have pre-reduction radiographs available, and thus, these fractures' predictors were collected from the post-reduction radiograph. This would have resulted in a potential false absence of predictors, especially predictors that would be ameliorated by a successful closed reduction, such as angulation and displacement. Prospective use of the prediction model would resolve this issue. Of the fractures that required surgery, both were tuft fractures and were operated on for the soft tissue component of the injury (ie, to repair the nailbed). These fractures were incorrectly recorded as closed fractures and should have been identified as "open." Of the 5 fractures that required 4 or more appointments with the hand surgeon, 2 were tuft fractures (requiring postoperative dressings and follow-up secondary to nailbed repair), 1 was a proximal phalanx fracture that also required a closed reduction, and one was a SH II distal phalanx fracture.

Limitations of the study include its retrospective nature, in which the outcome measure, complex fracture, was determined using the proxy measures: required surgery, closed reduction, or 4 or more appointments with a hand surgeon. Also, because of the study's retrospective nature, there was no ability to look at clinical outcomes, such as range of motion, presence or absence of pain or patient satisfaction. Because 4 of the predictors are radiographic findings, there is a risk of inter-rater variability, particularly with angulation and displacement measurements.[25,26] On the other hand, the risk index version of the prediction model which has a threshold of ≥1 point, renders the predictors as binary (present or absent), which would be expected to reduce inter-rater reliability for the measurement of angulation and displacement. Finally, this study was conducted within a referred patient population, possibly reducing its generalizability to other clinical settings. However, the baseline characteristics of the study sample and the proportion of surgeries in this study (9.81%) were similar to those of the previous studies that looked at both referred and community patient populations.[7,8,10,12–15]

In summary, a simple, yet high-performing and clinically useful decision support tool was developed for use by emergency and urgent care physicians providing initial assessment and care for children with acute hand fractures. This tool uses the presence or absence of any one of the 6 clinical or radiologic predictors to classify fractures as simple or complex; a point threshold of ≥1 identifies complex fractures for which the expertise of a hand surgeon is indicated. Although this tool still requires external validation, it is hoped that it will ultimately be incorporated into a clinical care pathway, which in turn will guide appropriate referral and treatment of these patients.

Paul E. Ronksley, MSc, PhD
Teaching Research and Wellness Building – Room 3E18B
University of Calgary
3280 Hospital Drive NW
Calgary, Alberta
Canada T2N 4Z6
E-mail: peronksl@ucalgary.ca

REFERENCES

1. Barton NJ. Fractures of the phalanges of the hand in children. *Hand*. 1979;11:134–143.
2. Cooper C, Dennison EM, Leufkens HG, et al. Epidemiology of childhood fractures in Britain: a study using the general practice research database. *J Bone Miner Res*. 2004;19:1976–1981.
3. Hastings H II, Simmons BP. Hand fractures in children. *Clin Orthop Relat Res*. 1984;188:120–130.
4. Landin LA. Fracture patterns in children. *Acta Orthop Scand*. 1983;202:3–109.
5. Mäyränpää MK, Mäkitie O, Kallio PE. Decreasing incidence and changing pattern of childhood fractures: a population-based study. *J Bone Miner Res*. 2010;25:2752–2759.
6. Hartley RL, Todd AR, Harrop AR, et al. Pediatric hand fracture referring practices: a scoping review. *Plast Surg (Oakv)*. 2019;27:340–347.
7. Leonard MH, Dubravcik P. Management of fractured fingers in the child. *Clin Orthop Relat Res*. 1970;73:160–168.
8. Mahabir RC, Kazemi AR, Cannon WG, et al. Pediatric hand fractures: a review. *Pediatr Emerg Care*. 2001;17:153–156.
9. Nofsinger CC, Wolfe SW. Common pediatric hand fractures. *Curr Opin Pediatr*. 2002;14:42–45.
10. Young K, Greenwood A, MacQuillan A, et al. Paediatric hand fractures. *J Hand Surg Eur Vol*. 2013;38:898–902.
11. Lindley SG, Rulewicz G. Hand fractures and dislocations in the developing skeleton. *Hand Clin*. 2006;22:253–268.
12. Bhende MS, Dandrea LA, Davis HW. Hand injuries in children presenting to a pediatric emergency department. *Ann Emerg Med*. 1993;22:1519–1523.
13. Liu EH, Alqahtani S, Alsaaran RN, et al. A prospective study of pediatric hand fractures and review of the literature. *Pediatr Emerg Care*. 2014;30:299–304.
14. Stanton JS, Dias JJ, Burke FD. Fractures of the tubular bones of the hand. *J Hand Surg Eur Vol*. 2016;32:626–636.
15. Worlock PH, Stower J. The incidence and pattern of hand fractures in children. *J Hand Surg*. 1986;11:198–200.
16. Holm AG, Lurås H, Randsborg PH. The economic burden of outpatient appointments following paediatric fractures. *Injury*. 2016;47:1410–1413.
17. Morris MW, Bell MJ. The socio-economical impact of paediatric fracture clinic appointments. *Injury*. 2006;37:395–397.
18. Berry WD, Feldman S. *Multiple Regression in Practice (Quantitative Applications in the Social Sciences)*. Thousand Oaks, Calif.: Sage; 1985.
19. Harrell FE Jr, Lee KL, Mark DB. Multivariable prognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors. *Stat Med*. 1996;15:361–387.
20. Sullivan LM, Massaro JM, D'Agostino RB Sr. Presentation of multivariate data for clinical use: The Framingham Study risk score functions. *Stat Med*. 2004;23:1631–1660.
21. Maguire JL, Kulik DM, Laupacis A, et al. Clinical prediction rules for children: a systematic review. *Pediatrics*. 2011;128: e666–e677.
22. Stiell IG, Wells GA. Methodologic standards for the development of clinical decision rules in emergency medicine. *Ann Emerg Med*. 1999;33:437–447.
23. Al-Qattan MM, Al-Qattan AM. A review of phalangeal neck fractures in children. *Injury*. 2015;46:935–944.
24. Moons KG, Altman DG, Reitsma JB, et al. Transparent reporting of a multivariable prediction model for individual prognosis or diagnosis (TRIPOD): explanation and elaboration. *Ann Intern Med*. 2015;162:W1–73.
25. Lamraski G, Monsaert A, De Maeseneer M, et al. Reliability and validity of plain radiographs to assess angulation of small finger metacarpal neck fractures: human cadaveric study. *J Orthop Res*. 2006;24:37–45.
26. Sletten IN, Nordsletten L, Hjorthaug GA, et al. Assessment of volar angulation and shortening in 5th metacarpal neck fractures: an inter- and intra-observer validity and reliability study. *J Hand Surg Eur Vol*. 2013;38:658–666.