A scoping review of knowledge authoring tools used for developing computerized clinical decision support systems

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ABSTRACT

Objective: Clinical Knowledge Authoring Tools (CKATs) are integral to the computerized Clinical Decision Support (CDS) development life cycle. CKATs enable authors to generate accurate, complete, and reliable digital knowledge artifacts in a relatively efficient and affordable manner. This scoping review aims to compare knowledge authoring tools and derive the common features of CKATs.

Materials and Methods: We performed a keyword-based literature search, followed by a snowball search, to identify peer-reviewed publications describing the development or use of CKATs. We used PubMed and Embase search engines to perform the initial search (n = 1579). After removing duplicate articles, nonrelevant manuscripts, and not peer-reviewed publication, we identified 47 eligible studies describing 33 unique CKATs. The reviewed CKATs were further assessed, and salient characteristics were extracted and grouped as common CKAT features.

Results: Among the identified CKATs, 55% use an open source platform, 70% provide an application programming interface for CDS system integration, and 79% provide features to validate/test the knowledge. The majority of the reviewed CKATs describe the flow of information, offer a graphical user interface for knowledge authors, and provide intellisense coding features (94%, 97%, and 97%, respectively). The composed list of criteria for CKAT included topics such as simulating the clinical setting, validating the knowledge, standardized clinical models and vocabulary, and domain independence. None of the reviewed CKATs met all common criteria.

Conclusion: Our scoping review highlights the key specifications for a CKAT. The CKAT specification proposed in this review can guide CDS authors in developing more targeted CKATs.

Key words: Clinical Knowledge Authoring Tools, Clinical Decision Support, decision support rule authoring, scoping review of literature, knowledge engineering

INTRODUCTION

Clinical Decision Support (CDS) is a key component of healthcare transformation to achieve the Quadruple Aim. Computerized clinical decision support systems enable the wide and fast adoption of CDS among health systems. Once integrated with the clinical workflow, CDS systems provide users with targeted information that is intelligently filtered to assist clinicians at the point of care. To achieve a successful CDS system in clinical practice, several factors...
need to be in place such as having the right information represented in the CDS, CDS producing the right intervention format, using CDS through the right channels, deploying the CDS in the right clinical workflow, and the CDS system being used by the right person. Development and maintenance of CDS knowledge, also known as Computable Biomedical Knowledge (CBK), is a major challenge in healthcare. Dissemination of CBKs, which are almost always published as narrative text and diagrams, requires transformation into a computable format, yet such transformation is a tedious process taking time and resources to ensure currency.

Clinical Knowledge Authoring Tools (CKATs) are used to generate accurate, complete, and reliable digital knowledge artifacts in a relatively efficient and affordable manner. Fast and efficient CKATs are increasingly needed for CBK development since: (1) CDS systems are quickly becoming an essential tool for healthcare providers; (2) EHRs are ubiquitously used in most inpatient and outpatient settings in the United States; (3) regulators and clinical quality officers have established metrics motivating health care institutions to use CDS; and (4) practitioners, being members of the Internet generation, expect their computer-based tools to provide decision support. CKATs range from simple text editors to complex software solutions such as the Arden Syntax editor.

Continuously assessing and updating CBK is crucial to make the CDS process effective and timely. However, the volume of available clinical evidence is increasing at a rapid pace, thus requiring tools, such as CKAT, to frequently update and adjust the CBK. To address this challenge, CKATs are increasingly connecting the Knowledge Engineering and Knowledge Use components of a CDS system. Hence, CKATs can reduce the overall cost of CBK development by (1) taking the anticipated clinical workflow into account and (2) continuously improve and deploy CBK models into clinical settings (Figure 1).

A comprehensive CKAT is responsible for authoring, reviewing, testing, certifying, publishing, and assessing CDS models. Several different types of users collaborate in the process of a CBK model development life cycle driven by the CKAT, such as subject matter experts, clinical experts, developers, data scientists, clinical champions, and administrators.

CKAT systems have increasingly incorporated knowledge extraction mechanisms in addition to knowledge authoring tools. In such a hybrid approach, CKATs not only enable the knowledge curators to translate CPGs and other medical evidence into CBK but also enable end-users to generate de-novo knowledge from a clinical data repository (eg, generating a statistical model that can be integrated into a CDS system). Thus, knowledge curators are gradually incorporating statistical and machine learning tools (eg, Orange, RapidMiner, Weka, KNIME) in parallel with the CKAT systems. These model-authoring tools help knowledge engineers to extract, validate, and author CBK at once. Since statistical and machine learning tools are not primary CKATs, those tools are not included in this scoping review.

Even though extensive review studies have been conducted on CDS systems (eg, types and effectiveness of such systems), research is lacking on the types and specifications of CKATs. Given the variety and variability across CKATs, this study aims to address the following questions: (1) what are the widely published CKATs? and (2) what are the salient features of those CKATs?

MATERIALS AND METHODS

Eligibility criteria

Our criteria for inclusion of reviewed papers are as follows: (1) Quantitative and qualitative articles that focused on clinical knowledge authoring. (2) Studies on the use of ontology and standard models as part of CDS authoring. (3) Studies published in peer-reviewed journals or conference proceedings (ie, editorials, commentaries, letters, reviews, and opinion articles were excluded). (4) Articles published in English. (5) Published after 2000, as our screening query found few publications mentioning computerized CKATs prior to 2000.

Information sources and search strategy

Search strategies were constructed to identify (1) peer-reviewed, published literature addressing the role of rule authoring environment, and (2) additional snowball searches to identify prominent tools currently used in the CDS systems.

Our primary literature search used PubMed and Embase search engines. PubMed was searched for relevant articles using the keyword “Clinical Decision Support Knowledge Authoring,” which resulted in 1467 records. This initial search strategy was then developed iteratively for the PubMed database, and once all authors were satisfied with both the breadth and specificity of the results, this strategy was translated for the other databases. The final PubMed search strategy, conducted on the legacy PubMed interface, included

Figure 1. Knowledge authoring tool transforming the knowledge into an actionable clinical decision support format and continuously improving its quality and performance.
the following combination of key terms: (“decision support systems, clinical” [MeSH Terms] OR “clinical decision support” [All Fields] OR “clinical guideline” [All Fields]) AND “author*” [All Fields] AND Data range: Publication date from 2000/01/01.

This report fulfills the PRISMA checklist items for scoping reviews. 

Search results were downloaded into reference management software to facilitate the removal of duplicate citations, and the resulting unique set of citations underwent title/abstract and full-text screening. During the review process, features articulated by manuscripts were abstracted and encoded in spreadsheets. Shortlisting the features was accomplished by applying the thematic analysis approach to the abstracted data.

RESULTS

Our search strategy returned 1579 publications, 1494 from PubMed and 85 from EMBASE. We removed 9 duplicates, 1157 nonrelevant abstracts, and 366 articles lacking CKAT details. We included 47 articles in our final review (Figure 2). These articles included 33 unique CKATs. We used the reviewed papers to compose the list of criteria for CKAT, which included topics such as simulating the clinical setting, validation/testing details, compliance, transparency, intellisense (i.e., usability features for coding), standard clinical models and vocabulary, and domain independence.

The final list of articles and CKATs included in those studies were populated. Several articles used the same CKAT; however, only a few papers analyzed more than 1 CKAT (Table 1).

Technical aspects of the CKATs were extracted and merged, if needed, from the identified articles (Table 2). To review the development platform characteristics, we analyzed the supported operating systems, the type of the application, and the programming languages used. Most of the CKATs are web-based applications requiring only a web browser, hence independent from the operating systems. Java and JavaScript are the major programming languages used. Among the reviewed CKATs, 55% are open source, letting others further expand on the existing knowledge authoring core. The majority of the CKATs are using, either directly or indirectly through a programming interface, medical terminology standards such as SNOMED-CT.

Figure 2. Article-flow diagram based on the PRISMA guideline.
| No. | Author(s)         | Year | Article title                                                                 | CKAT                          |
|-----|-------------------|------|--------------------------------------------------------------------------------|-------------------------------|
| 1   | Kerexeta et al    | 2020 | Adaptive clinical decision support system using machine learning and authoring tools | KGT (EXCON)                   |
| 2   | Richardson et al  | 2020 | Building and maintaining trust in clinical decision support: Recommendations from the Patient-Centered CDS Learning Network | CDS Connect                   |
| 3   | Torres et al      | 2020 | A domain-independent semantically validated authoring tool for formalizing clinical practice guidelines | Authoring Tool                |
| 4   | Lomotan et al     | 2020 | To share is human! Advancing evidence into practice through a national repository of interoperable clinical decision support | CDS Connect                   |
| 5   | Heen et al        | 2020 | A framework for practical issues was developed to inform shared decision-making tools and clinical guidelines | MAGICapp                     |
| 6   | Fox et al         | 2020 | OpenClinical.net: Artificial intelligence and knowledge engineering at the point of care | OpenClinical                  |
| 7   | Totten et al      | 2019 | Improving access to and usability of systematic review data for health systems guidelines development | MagicApp                     |
| 8   | Zhang et al       | 2018 | Using systematic reviews in guideline development: The GRADE approach | GRADEpro                      |
| 9   | Choi et al        | 2018 | Artificial intelligence clinical decision supporting system for diagnosis of heart failure: Concordance with expert decision | I-KAT                         |
| 10  | Piovesan et al    | 2018 | GLARE-SSCPM: an intelligent system to support the treatment of comorbid patients | GLARE                         |
| 11  | Alkasab et al     | 2017 | Creation of an open framework for point-of-care computer-assisted reporting and decision support tools for radiologists | Marval                        |
| 12  | Ali et al         | 2017 | Multi-model-based interactive authoring environment for creating shareable medical knowledge | I-KAT                         |
| 13  | Zini et al        | 2017 | An environment for guideline-based decision support systems for outpatients monitoring | Alium                         |
| 14  | Zhang et al       | 2016 | A concise drug alerting rule set for Chinese hospitals and its application in computerized physician order entry | Drug alerting rule authoring tool |
| 15  | Lin et al         | 2015 | Design, development, and initial evaluation of a terminology for clinical decision support and electronic clinical quality measurement | OpenCDS                       |
| 16  | Khodambashi et al | 2015 | Filling the gap between guideline development and formalization process—a requirement analysis | GRADEpro                     |
| 17  | Zhang et al       | 2015 | Mobilizing clinical decision support to facilitate knowledge translation: a case study in China | Knowledge authoring web portal |
| 18  | Kristiansen et al | 2015 | Development of a novel, multilayered presentation format for clinical practice guidelines | MagicApp                      |
| 19  | Ali et al         | 2014 | Arden syntax studio: Creating medical logic module as shareable knowledge | Arden syntax studio           |
| 20  | Ali et al         | 2014 | Customized clinical domain ontology extraction for knowledge authoring tool | I-KAT                         |
| 21  | Sottara et al     | 2014 | The health eDecisions authoring environment for shareable clinical decision support artifacts | HeD Editor                    |
| 22  | Ali et al         | 2013 | Authoring tool: acquiring sharable knowledge for Smart CDSS | Smart CDSS Authoring tool     |
| 23  | Kim et al         | 2013 | Design of shareable and interoperable clinical decision support system architecture | SAGE Authoring Environment    |
| 24  | Pasche et al      | 2013 | Assisted knowledge discovery for the maintenance of clinical guidelines | KART                          |
| 25  | Colantonio et al  | 2012 | A knowledge editing service for multisource data management in remote health monitoring | Knowledge Editing Service (KES) |
| 26  | Shiffman et al    | 2012 | Building better guidelines with BRIDGE-Wiz: Development and evaluation of a software assistant to promote clarity, transparency, and implementability | BRIDGE-Wiz                    |
| 27  | Kim et al         | 2011 | Implementation of guideline-based CDSS | SAGE Authoring Environment    |
| 28  | Song et al        | 2011 | A multi-classifier based guideline sentence classification system | Clinical process modeling toolkit | (continued)
Nomenclature of Medicine—Clinical Terms), LOINC (Logical Observation Identifiers Names and Codes), UMLS (Unified Medical Language System), ICD (International Classification of Diseases), and RxNORM (Medication Normalized Naming System). Of the reviewed CKATs, 70% support application programming interface (API) integration with other information system platforms such as EHRs (eg, CKAT authorizing the EHR systems to submit assessment values and then pulling different CDS scenarios synchronously). Among the analyzed CKATs, all but one (Rule Editor) support some version of a graphical user interface (GUI), which facilitates the knowledge authoring and review process by clinicians and informatics experts.

Different authoring environment characteristics of the CKATs were extracted from the reviewed articles (Table 3). Of the 33 CKATs, 27 support at least 1 standard language for knowledge encoding. Some CKATs went through multiple revisions using different programming languages. Moreover, 36% of the CKATs have a built-in version control feature. Of the CKATs, 28 support CDS authoring independent of any domain/use case. Even though 97% of the CKATs support GUI, only 70% facilitates collaborative knowledge authoring; 67% of the CKATs support simulating the clinical setting to ensure CDS works as expected at the point of care. Only 18% of the CKATs support grading the evidence, while 79% of them support testing all possible scenarios. As part of the knowledge base updating cycle, CKATs assess the knowledge deployed by receiving feedback from the CDS system. Among the reviewed CKATs, 61% support this surveillance feature. And, 97% of CKATs support intellisense features to help the authors while encoding the knowledge (eg, automatically pulling the values from a terminology standard system, and color coding the scenarios not reachable); 48% of the CKATs support automated CDS content publishing, facilitating the content deployment to CDS systems, especially when multiple users collaborate in the CDS generation process (Figure 3).

The reviewed articles included different user types of CKATs. After reviewing all CKATs, the following types of users were identified as potential CKAT users: (1) Subject Matter Experts: SMEs are CDS experts who know the best practices and the clinical setting. SMEs are typically a qualified healthcare informatics person specializes in CDS. (2) Clinical Experts: CEs have in-depth clinical knowledge...
| CKAT no. | CKAT                      | Paper no. | Developers and funders                                                                 | Development platform | Open source | Medical terminology standards | API | Inform flow | GUI |
|---------|---------------------------|-----------|--------------------------------------------------------------------------------------|----------------------|-------------|-------------------------------|-----|-------------|-----|
| 1       | KGT (EXCON)               | 1         | Basque Government’s ELKARTEK 2017 program under EXCON project                        | Web based            | R           | No                            | Yes | Yes         | Yes |
| 2       | ACE Authoring Tool        | 32        | National Library of Medicine and the Agency for Healthcare Research and Quality (AHRQ) | Web based            | JavaScript  | Yes                           | UMLS SNOMED LOINC | No  | Yes         | Yes |
| 3       | Authoring Tool            | 3         | eHealth and Biomedical Applications, ViconTech, Donostia-San Sebastian, developed by Deontics Ltd (London, UK) | Desktop              | Unk         | No                            | Unk | Yes         | Yes |
| 4       | Alium                     | 13        | Dalhousie University DaYi hospital                                                   | Web based            | JavaScript  | No                            | ICD SNOMED           | Yes | Yes         | Yes |
| 5       | BRIDGE WIZ                | 26        | National Library of Medicine and the Agency for Healthcare Research and Quality       | Desktop              | Java        | No                            | No  | Yes         | Yes |
| 6       | CDS Connect               | 2, 4      | AHRQ funded                                                                         | Web based            | Unk         | Yes                           | UMLS ICD SNOMED UMLS ICD | Yes | Yes         | Yes |
| 7       | CPG-EX Knowledge-authoring web portal | 37, 39 | Dalhousie University DaYi hospital                                                   | Web based            | Java        | Yes                           | Yes | Yes | Yes |
| 8       | Guideline Markup Tool     | 43        | Austrian Science Fund, European Commissions IST program                             | Web based            | Unk         | No                            | No  | Yes | Yes |
| 9       | GLIF3 Authoring Tool      | 45        | National Library of Medicine and by the Telemedicine, U.S Army medical research      | Web based            | Unk         | Yes                           | Unk | Yes | Yes |
| 10      | GrADEpro                  | 8, 16     | WHO, McMaster University                                                             | Web based            | Unk         | No                            | Unk | Yes | Unk |
| 11      | Guideline Markup Tool     | 43        | Austrian Science Fund, European Commissions IST program                             | Web based            | Java        | No                            | No  | Yes | Yes |
| 12      | HeD Editor                | 21        | U.S. Office of the National Coordinator for Health Information Technology, SHRPC project 2B | Web based            | JavaScript, AngularJS, d3js | Yes | SNOMED LOINC S NORM          | Yes | Yes | Yes |
| CKAT no. | CKAT | Paper no. | Developers and funders | Development platform | Open source | Medical terminology standards | API | Information flow | GUI |
|---------|------|-----------|------------------------|----------------------|-------------|-----------------------------|-----|-----------------|-----|
| 13      | I KAT | 9, 12, 19, 20 | Ministry of Knowledge Economy, Korea, under the ITRC, National Library of Medicine | Web based | Java | Unk | SNO MED | Yes | Yes | Yes |
| 14      | KAT   | 40 | HUG—Hospital of Geneva | Web based | Java | No | SNO MED | Yes | Yes | Yes |
| 15      | KART  | 24, 29 | Unk | Unk | Unk | Yes | SNO MED | Yes | Yes | Yes |
| 16      | KA-Tool | Unk | Unk | Unk | Unk | Yes | SNOMED | Yes | Yes | Yes |
| 17      | KES   | 46 | European Union Information Society Technologies Project | Web based | Java | Yes | SNOMED | Yes | Yes | Yes |
| 18      | MAGICapp | 5, 7, 18 | MAGIC evidence ecosystem foundation | Web based | JavaScript | Yes | ICPC, ICD, SNOMED-CT, ATC, RxNORM, MeSH | Yes | Yes | Yes |
| 19      | CAR/DS Authoring Tool | 11 | American College of Radiology | Web based | JavaScript | Yes | RadLex, LOINC, SNOMED, RAEle-ments CDE | No | Yes | Yes |
| 20      | SmartCare | 36 | Canadian Institute of Health Research | Web based | Java | Yes | SNO MED | Yes | Yes | Yes |
| 21      | PROforma Authoring Tool | 47 | Royal Hospital London, NHS | Unk | Unk | Yes | Unk | No | Yes | Yes |
| 22      | OpenCDS | 15 | National human genome research institute and University of Utah Department of Biomedical Informatics | Web based | Java | Yes | SNO MED, ICD, RxNORM | Yes | Yes | Yes |
| 23      | OpenClinical | 6 | Cancer Research U.K. and later at Oxford University and UCL/Royal Free Hospital in London | Web based | Unk | Yes | Unk | Unk | Yes | Yes |

(continued)
| CKAT no. | CKAT                          | Paper no. | Developers and funders                                                                 | Development platform | Open source | Medical terminology standards | API      | Inform flow | GUI |
|---------|-------------------------------|-----------|----------------------------------------------------------------------------------------|----------------------|-------------|-------------------------------|----------|-------------|-----|
| 24      | Rule Editor                   | 35        | Partners HealthCare                                                                    | Web based            | No          | Unk                           | Unk      | Yes         | No  |
| 25      | SAGE Authoring Environment    | 23, 27, 31| SAGE project partners are: Apelon Inc., IDX Systems, Intermountain Health Care, Mayo Clinic—Rochester, Stanford Medical Informatics, and the University of Nebraska Medical Center | Web based            | No          | SNOMED                        | Unk      | Yes         | Yes |
| 26      | SAGEDesktop                   | 42        | SAGE project partners are: Apelon Inc., IDX Systems, Intermountain Health Care, Mayo Clinic—Rochester, Stanford Medical Informatics, and the University of Nebraska Medical Center | Web based            | No          | SNOMED                        | Unk      | Yes         | Yes |
| 27      | SAGE                          | 30, 38    | National Research Foundation of Korea                                                  | Web based            | No          | Unk                           | Yes      | Yes         | Yes |
| 28      | Smart CDSS Authoring tool     | 22        | Ministry of Knowledge Economy, Korea                                                   | Web based            | Yes         | SNOMED                        | Yes      | Yes         | Yes |
| 29      | Protégé                       | 44        | Knowledge Modeling Group at Stanford Medical Informatics                               | Web based            | Yes         | SNOMED                        | Yes      | Yes         | Yes |
| 30      | Internet Portal               | 33        | German Association of the Scientific Medical Associations                             | Web based            | Yes         | SNOMED                        | Yes      | Yes         | Yes |
| 31      | GEM Cutter                    | 34        | Mayo Clinic, Yale School of Medicine                                                  | Web based            | Yes         | SNOMED                        | No       | Yes         | Yes |
| 32      | GLARE                         | 10        | Universita del Piemonte Orientale                                                     | Web based            | No          | SNOMED                        | Yes      | Yes         | Yes |
| 33      | SmartCare                     | 36        | Canadian Institutes of Health Research                                                | Web based            | Yes         | SNOMED                        | Yes      | Yes         | Yes |

Abbreviations: API: Application Programming Interface; ATC: Anatomical Therapeutic Chemical Classification System; CKAT: Clinical Knowledge Authoring Tool; GUI: Graphical User Interface; ICD: International Classification of Diseases; ICPC: International Classification of Primary Care; Indep: Independent; LOINC: Logical Observation Identifiers Names and Codes; MeSH: Medical Subject Headings; OS: Operating System; RAE: Radiology Elements; RAO: Radiology Lexicon; RxNORM: Medication Normalized Naming System; SNOMED: Systematized Nomenclature of Medicine; Unk: Unknown; UMLS: Unified Medical Language System.
| CKAT no. | CKAT name | Knowledge authoring language | Version control | Domain and specialty | Collaboration authoring | Use cases | Simulate clinical setting | Grading evidence | Validation and testing | Surveillance and assessing | Intellisense | Continuous deployment |
|----------|-----------|------------------------------|-----------------|---------------------|------------------------|-----------|--------------------------|-----------------|--------------------------|-----------------------------|-------------|---------------------|
| 1        | KGT (EXCON) | Unk                          | Unk             | Domain Indep        | Unk                    | Readmission of diabetic patients | No            | Yes                      | Yes                          | No          | No                  |
| 2        | ACE Authoring Tool | ACE, Arden Syntax, SWRL | No              | Pediatric           | No                     | Initial Urinary Tract Infection in Febrile Infants and Young Children | Yes           | No                       | No                           | No          | No                  |
| 3        | Authoring Tool (TORRES et.al) | Arden syntax, RDF, OWL | No              | Domain Indep        | Unk                    | Gestational diabetes, current physical activity level | Unk           | Yes                      | No                           | No          | Yes                 |
| 4        | Alium      | PROforma                     | Yes             | Domain Indep        | Unk                    | Prevention, diagnosis and treatment of therapy side effects, head and neck cancer mobile devices support | Yes           | Yes                      | Yes                          | Yes         | Yes                 |
| 5        | BRIDGE WIZ | GEM GLIA                     | Yes             | Domain Indep        | Yes                    | Diabetes type II          | Unk           | Yes                      | Yes                          | Yes         | Yes                 |
| 6        | CDS Connect | CQL                           | Yes             | Domain Indep        | Yes                    | CVD, chronic pain management | No            | No                       | No                           | Yes         | Yes                 |
| 7        | CPG-EX     | Jena CPG syntax, OWL         | No              | Domain Indep        | Unk                    | Radiology—according to the EU radiation protection 118 | Yes           | No                       | Yes                          | Yes         | Yes                 |
| 8        | Knowledge-authoring web portal | GEM GLIA         | No              | Domain Indep        | Unk                    | Pharmacy drug override, drug check use | No            | No                       | Yes                          | No          | Unk                 |
| 9        | GLIF3 Authoring Tool | GLIF3             | Unk             | Domain Indep        | Unk                    | Migraine headache         | Yes           | No                       | No                           | No          | Yes                 |
| 10       | gRADEpro   | Unk                          | Unk             | Domain Indep        | Yes                    | WHO Interim policy guidance on the use of medication in the treatment of tuberculosis | No            | Yes                      | Yes                          | Yes         | Unk                 |
| 11       | Guideline Markup Tool | Asbru             | No              | Domain Indep        | No                     | Unk                      | No            | No                       | Unk                          | Yes         | Yes                 |
| 12       | HeD Editor | HeD expression language, OWL2-DL | Unk             | Domain Indep        | Yes                    | Antithrombotic therapy on discharge adapted from MQF-00685 quality measure | Yes           | Unk                      | Unk                          | Yes         | Yes                 |
| 13       | IKAT       | Arden syntax                 | Unk             | Domain Indep        | Yes                    | Head and neck cancer     | Yes           | Unk                      | Unk                          | Yes         | Unk                 |
| 14       | KAT        | Arden syntax                 | Unk             | Domain Indep        | Yes                    | POE                      | Yes           | Unk                      | Unk                          | Yes         | Unk                 |

(continued)
| CKAT no. | CKAT name | Knowledge authoring language | Version control | Domain and specialty | Collaboration authoring | Use cases | Simulate clinical setting | Grading evidence | Validation and testing | Surveillance and assessing | Intellisense | Continuous deployment |
|----------|-----------|------------------------------|-----------------|---------------------|------------------------|-----------|-------------------------|-----------------|------------------------|--------------------------|-------------|----------------------|
| 15       | KART      | RDF, Query Language (SPARQL) | Unk             | Domain Indep        | Yes                    | Antibiotic prescribing and many more | Yes           | Unk                    | Yes                       | Unk          | Yes                  | Yes         | Unk               |
| 16       | KA-Tool Knowledge Editing Service (KES) | GLIF3 | Yes             | Domain Indep remote monitoring | No | ICU based COPD, diabetes | No | No                  | Yes                       | Unk          | Yes                  | Yes         | Yes               |
| 17       | MAGICapp | Unk                          | Unk             | Domain Indep        | Yes                    | Various – 1.5 BMJ guidelines, COVID-19 | Unk           | Yes                   | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 18       | CAR/DS Authoring Tool | CAR/DS | Yes             | Radiology           | Yes                    | Lung-RADS, BI-RADS, LI-RADS, Incidental Findings Monitoring | Yes           | No                    | Yes                       | No           | Yes                  | No          | No               |
| 19       | SmartCare | OWL                       | Yes             | Anesthesia          | Yes                    | Physiological monitoring | Yes           | No                    | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 20       | PROforma Authoring Tool | PROforma, GLIF | Unk              | Domain Indep        | Yes                    | Routine prescribing system, pain control system, a system for advising medication for patients | Yes           | No                    | Yes                       | Unk          | Yes                  | Unk         | Unk               |
| 21       | SAGE      | SAGE                        | Unk             | Domain Indep        | Yes                    | Hypertension guideline | Yes           | Unk                   | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 22       | SAGEDesktop | SAGE                      | Yes             | Domain Indep        | Yes                    | Immunizations, diabetes | Yes           | No                    | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 23       | SAGE      | OWL                         | Unk             | Domain Indep        | Unk                    | Computerized physician order entry (CPOE) | Yes           | Unk                   | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 24       | Rule Editor | Unk                       | Unk             | Domain Indep        | Yes                    | Head injury, COVID 19, Stroke | Yes           | No                    | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 25       | Smart CDSS Authoring tool | Arden Syntax                   | Yes             | Domain Indep        | Yes                    | Head and Neck Cancer diagnosis and treatment recommendations | Yes           | No                    | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 26       | Protégé   | OWL                         | Yes             | Domain Indep        | Yes                    | Unk | Yes                       | Yes          | Yes                  | Yes                       | Yes          | Yes                  | Yes         | Unk               |
| 27       | Internet Portal | Unk                    | Unk             | Domain Indep        | Yes                    | Unk | Yes                       | Yes          | Yes                  | Yes                       | Yes          | Yes                  | Yes         | Unk               |

(continued)
Table 3. continued

| CKAT no. | CKAT name | Knowledge authoring language | Version control | Domain and specialty | Collaboration authoring | Use cases | Simulate clinical setting | Grading evidence | Validation and testing | Surveillance and assessing | Intellisense | Continuous deployment |
|----------|-----------|-------------------------------|-----------------|---------------------|------------------------|-----------|--------------------------|-----------------|------------------------|--------------------------|--------------|---------------------|
| 31       | GEM Cutter | OWL, GLIF                    | Yes             | Domain Indep        | Yes                    | CPOE, asthma, obesity | Yes        | No                       | Yes             | Unk                    | Yes                       | Yes          | Yes                 |
| 32       | GLARE     | OWL                           | Yes             | Domain Indep        | Yes                    | Different phenomena, including bladder cancer, reflux esophagitis, heart failure, and ischemic stroke. | Yes        | No                       | Yes             | Yes                    | Yes                       | Yes          | Yes                 |
| 33       | SmartCare | OWL                           | Yes             | Anesthesia          | Yes                    | Physiological monitoring | Yes        | No                       | Yes             | Yes                    | Unk                       |              |                     |

Abbreviations: ACE: Attempto Controlled English; CAR/DS: Computer-Assisted Reporting and Decision Support; CKAT: Clinical Knowledge Authoring Tool; CQL: Clinical Quality Language; GEM: Guideline Elements Model; GLIF: Guideline Interchange Format; HeD: Health eDecisions; OWL: Web Ontology Language; PROforma: Proformalisation (of medical knowledge); RDF: Resource Description Framework; SAGE: Standards-based Sharable Active Guideline Environment; SPARQL: SPARQL (Simple) Protocol and RDF Query Language; SWRL: Semantic Web Rule Language; Unk: Unknown.
about the subject on which CDS is authoring. CEs are typically the
CPG authors. (3) Developers/Data Scientists: Technical experts who
know how to encode the knowledge into a machine-readable format
with assistance from SMEs and CEs. (4) Clinical Champion: CCs
are the lead clinical experts in charge of the CBK model and CDS
governance. (5) Guideline Developer: Technical developers convert-
ing CBK into knowledge base artifacts. (6) Administrators: Persons
responsible for publishing and validating the CBK model in the clini-
cal setting. The administrator is also in charge of data capture to as-
serve the impact and performance of the CDS system.

The reviewed studies included different approaches to integrate
CKATs in the CDS development workflow. After merging work-
flows of CKATs described in different articles, we identified the fol-
lowing shared components of knowledge management across
CKATs: assembling, authoring, reviewing, testing, publishing, vali-
dating, and assessing the knowledge (Figure 4).

DISCUSSION

CKATs are integral to the development and maintenance of CDS
systems. CKATs enable authors to generate accurate, complete, and
reliable digital knowledge artifacts in a relatively efficient and af-
fordable manner. Although extensive studies have reviewed the ef-
fectiveness of CDS systems, research is lacking on the types and
specifications of CKATs. To address the need for a list of CKAT features, this study aimed to review and compare knowledge authoring tools and derive the common features of CKATs that are published in peer-reviewed publications.

We identified 33 unique CKATs across 47 publications. More than half of published CKATs use open source software and close to 70% use a standardized API, hence providing an opportunity to integrate CKATs in various CDS systems. Most CKAT developers have attempted to increase the usability of their applications, with 94% describing the information flow, 97% providing a graphical user interface, and 97% offering intellisense features for coding knowledge models.

CKATs assessed in peer-reviewed publications are still immature in supporting enterprise level features that are needed for healthcare settings to develop, maintain, and deploy knowledge models over an extended period. For example, only 48% of the CKATs have been continuously deployed and assessed in clinical settings. Furthermore, team-based knowledge management, key for deployment in healthcare settings, is still lacking among published CKATs with only 36% of them offering a knowledge version control and 18% providing an approach to grade the knowledge, despite the fact that 70% of them are providing collaborative tools for knowledge authoring. These challenges have led most peer-reviewed CKATs to remain in limited use within academic settings. Moreover, additional work is needed to develop CKATs that can be seamlessly integrated with rapidly evolving health IT platforms such as EHRs.

Given the frequent changes of clinical practice guidelines, especially during public health emergencies such as the COVID-19 pandemic, CKATs should also offer more automated features to incorporate up-to-date knowledge from both clinical and public health sources. Although public health decision support systems are differentiated from CDS systems, CKATs are needed to author, revise, maintain, and update population-level knowledge models. Additionally, primary care settings, which often use preventative CDS systems, will benefit from merging existing public health guidelines into local CDS systems, especially when dealing with public health emergencies. Consequently, CKATs should support not only the curation and maintenance of clinical knowledge but also the creation and management of population and public health knowledge models.

Several ongoing and significant health informatics challenges were not addressed in the reviewed CKAT publications. None of these publications explained how CKATs, and their knowledge models, handle the data quality issues with EHR data. Using alternative or additional clinical data sources such as insurance claims, and how such data sources may affect the knowledge models, was also absent in the CKAT publications. For example, medication records in EHRs are prescriptions while insurance claims include medication refills thus conveying different meanings for knowledge models using such information. Another important issue not mentioned in the CKAT publications was the incorporation of non-clinical data sources such as social determinants of health (SDOH) in knowledge models. Individual and neighborhood level SDOH data are increasingly used in the clinical decision-making process to improve outcomes and reduce utilization. However, none of the reviewed CKATs mentioned how such unstandardized information would be encoded and integrated into the knowledge creation process.

Future research and development in CKATs should address multiple dimensions of the knowledge authoring process. CKATs should ease the authoring and reviewing of the knowledge rules. CKATs should further facilitate multiuser collaboration for knowledge development. Automating the CDS testing process and supporting standardized terminology systems are also essential for future CKAT development. CKATs should continue offering intellisense features for knowledge coding and providing a clinical simulation environment to increase the usability of such tools. CKATs should also offer continuous deployment and publishing capabilities while increasing/improving knowledge management features. Finally, CKATs should be assessed and validated along with CDS systems so that their effectiveness can be measured in the larger context of decision support. See the Supplementary Appendix for additional recommendations generated based on our review to enhance future research and development in CKATs.

Despite our valuable findings, this review has several limitations. First, we conducted a scoping review of literature, and not a systematic review, hence some CKATs may have been missed. Second, the review only included published peer-review publications. Therefore, CKATs lacking such publications (eg, commercial CKATs) are not presented in this review. Third, all CKAT features extracted and presented in this review are limited to information included in the peer-reviewed publications. The actual CKATs were not downloaded and assessed separately. Accordingly, features that may exist in a CKAT, but not reported in the publications, are not listed in this review. Finally, this review was limited to systems primarily designed as CKATs; and excluded tools that are primarily designed for analytical or machine learning purposes. As the gap between knowledge generation and knowledge authoring is closing by such tools, additional reviews are needed to assess the role of analytical tools as CKATs.

CONCLUSION

CKATs play an integral role in improving CDS systems. Our scoping review highlights the key specifications for a CKAT. The CKAT specification proposed in this review can guide CDS authors in developing more targeted CKATs.

AUTHOR CONTRIBUTIONS

SSN, PN, HL and HK designed the study. SSN, CL, and RD conducted the study including data collection and data analysis. HK led the review strategy, and guided the study team during the preparation of this manuscript. SSN prepared the manuscript draft which got reviewed and revised with important intellectual input from PN, HL, and HK. All authors have complete access to the study data.

SUPPLEMENTARY MATERIAL

Supplementary material is available at JAMIA Open online.

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CONFLICT OF INTEREST STATEMENT

None declared.

DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.
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