Technology-induced Errors
The Current Use of Frameworks and Models from the Biomedical and Life Sciences Literatures

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Framework, model, theory, technology-induced error, unintended consequences, e-iatrogenesis, technology facilitated error, human factors, sociotechnical, organizational, software engineering

Summary
Objective: The objective of this paper is to examine the extent, range and scope to which frameworks, models and theories dealing with technology-induced error have arisen in the biomedical and life sciences literature as indexed by Medline®.

Methods: To better understand the state of work in the area of technology-induced error involving frameworks, models and theories, the authors conducted a search of Medline® using selected key words identified from seminal articles in this research area. Articles were reviewed and those pertaining to frameworks, models or theories dealing with technology-induced error were further reviewed by two researchers.

Results: All articles from Medline® from its inception to April of 2011 were searched using the above outlined strategy. 239 citations were returned. Each of the abstracts for the 239 citations were reviewed by two researchers. Eleven articles met the criteria based on abstract review. These 11 articles were downloaded for further in-depth review. The majority of the articles obtained describe frameworks and models with reference to theories developed in other literatures outside of healthcare. The papers were grouped into several areas. It was found that articles drew mainly from three literatures: 1) the human factors literature (including human-computer interaction and cognition), 2) the organizational behavior/sociotechnical literature, and 3) the software engineering literature.

Conclusions: A variety of frameworks and models were found in the biomedical and life sciences literatures. These frameworks and models drew upon and extended frameworks, models and theoretical perspectives that have emerged in other literatures. These frameworks and models are informing an emerging line of research in health and biomedical informatics involving technology-induced errors in healthcare.

1. Introduction
The evaluation of health information systems (HIS) is becoming increasingly more important. Over the past decade, we have seen the number of HISs implemented in healthcare settings grow exponentially. HISs have the potential to greatly streamline healthcare and reduce the chance of human error [1]. However, with the rapid growth in the deployment of HIS, there has been a rise in the number of medical errors that have their origins in HIS being reported in the health and biomedical informatics literatures. Indeed a growing body of research is showing that when HIS are not developed, designed, implemented and/or maintained adequately, they may increase the possibility of an error arising from the complex interaction between clinician (e.g. physician, nurse) and HIS [2–4]. These publications first emerged in the early 2000’s with the publication of several seminal works by health and biomedical informatics researchers (e.g. [2, 5–7]).

In these influential works a number of terms were used to describe HIS related errors. They included: “unintended consequences”, “e-iatrogenesis”, “technology facilitated errors”, and “technology-induced errors” [2, 6–8]. Each of these terms has its own definition. For example, “unintended consequences” refers to unexpected results that arise from the use of technology that “lack a purposeful action or causation” ([6] p 415). Unintended consequences can be desirable, undesirable or unanticipated [6]. E-iatrogenesis refers to “patient harms caused in part by the application of health information technology” ([8] p 388)), whereas technology facilitated errors refer to those errors that are made possible by HIS [7]. Lastly, technology-induced errors have been defined as those sources of error that “arise from: a) the design and development of technology, b) the implementation and customization of a technology, and c) the interactions between the operation of a technology and the new work processes that arise from a technology’s use” ([4] p 154). Although each of these terms differ qualitatively, their focus is a new and emerging line of research in the biomedical and life sciences area – research that focuses upon medical error that involves HIS and manifests itself during the complex interactions between HIS and health profes-
specific user interface features and functions [2], HIS database content [2, 6] and undesirable changes to workflow emerging from interactions between HIS software, devices and the organizations where the software has been implemented [6, 8]. Differing researchers have also been able to use these evaluation methods to identify specific types of technology-induced errors at key points: a) during HIS software development [2], b) prior to organizational HIS implementation [8], and c) after a HIS has been implemented in an organization [4, 6]. It is interesting and worthy to note that researchers have been able to identify the same medical errors involving HIS using a variety of evaluation methodologies at differing points in the software development lifecycle (SDLC) (e.g. [2, 4, 6]).

As noted above, work is underway in the identification of specific technology-induced errors [2, 7]. However, there is a need for a systems level understanding of the origins of technology-induced errors and their propagation throughout a healthcare system [4]. Such a systems level understanding could be developed by examining the frameworks, models and theories that have been used to inform the literature about errors involving HIS. A systems level perspective would help health and biomedical informatics practitioners to understand where errors come from and how errors could be prevented using the evaluation methods at their disposal before an error occurs at point of care [2, 4, 8].

Some researchers have suggested that error frameworks, models and theories can be imported from other areas or domains (i.e. aviation, banking, nuclear power) [2, 6]. Other researchers such as Brender [10] and Shortell and Kaluzny [11] have indicated that healthcare work has unique characteristics that do not allow for frameworks, models and theories developed for other industries to be easily applied without some modification, extension or adaptation. These researchers have suggested healthcare work is unique for varying reasons. For example, healthcare work is variable, dynamic and complex. Healthcare work is also emergent in nature, involves a high degree of ambiguity and uncertainty, requires a high degree of coordination and is not easily deferred (unlike work undertaken in other industries such as banking and mining) [11]. Furthermore, some researchers have found healthcare places additional pressures upon its workers (e.g. physicians and nurses) to provide continuity of care while at the same time responding to the emergent needs of each patient [11]. The question remains, however, as to whether error frameworks, models and theories may be imported, modified, extended or adapted for application in health (i.e. in identifying and preventing medical errors involving HIS use) [11–13].

3. Methods

To better understand the state of work in the area of technology-induced error involving frameworks, models and theories (undertaken by researchers in the biomedical and life sciences areas), the authors of this paper conducted a search of Medline®. Initially, the authors began their search by reviewing Medline® MeSH terms [9]. Terms such as “technology-induced error” have only appeared in the literature in the last few years [2]. Therefore, they are not currently listed as pre-existing MeSH terms (in addition “unintended consequences” [6], “technology facilitated” [7] and “e-iatrogenesis” [8] have not yet been incorporated as MeSH terms). In conducting reviews, the NLM encourages the use of emergent terms by researchers where there are new lines of research and literature [9]. Therefore, as our objective was to determine if frameworks, models and theories that have appeared in the biomedical and life sciences literatures aligned with concepts such as “technology-induced error”; we used the following search terms: “technology induced error” and “framework”; “technology induced error” and “model”; “technology induced error” and “theory”; “technology-induced error” and “framework”; “technology-induced error” and “model”; “technology-induced error” and “theory”; “unintended consequences” and “framework”; “unintended consequences” and “model”; “unintended consequences” and “theory”; “e-iatrogenesis” and “framework”; “e-iatrogenesis” and “model”; “e-iatrogenesis” and “theory”; “technology facilitated error” and “framework”; “tech-
nology facilitated error” and “model”, “technology facilitated error” and “theory”. These terms were initially selected from the reading of key published works in this area [i.e. 2, 6–8] (as the NLM suggests should be done when no specific MeSH terms exist) [9].

Two researchers holding PhD’s reviewed each of the titles of the published articles and proceedings that were returned from each of the searches involving the above outlined search terms. If the title or abstract of the article or proceeding referred to a framework or model or theory in the context of technol-

ogy-induced error, technology facilitated error, unintended consequence or e-iatro-
geny, then the full article was reviewed by two authors to determine if a framework, model or theory was described (as outlined in [14, 15]). To inform the searches and reviews of the articles the authors first defined: theory, model and framework [12]. A theory can be defined as an idea or system of ideas that can be used to explain behaviours. A theory consists of: 1) a set of concepts and 2) a set of propositions. In order for a theory to exist, it must state “a relationship between the concepts” in the form of propositions. Lastly, “propositions must be contingent – they must be amenable to some form of em-

pirical test” ([12] p 30). Models have their origins in the experiences, reflections and insights of scholars and practitioners. Models help such individuals to “understand key concepts, their relationships and systems” ([16] p 16). Some scholars believe “models are testable partial theories” ([12] p 31). In contrast, frameworks are simply considered to be organizing structures and may be developed into models or theories over time [17].

4. Results

All articles from Medline® from its incep-
tion to April of 2011 were searched using the above outlined strategy (see Methods section above). Two hundred and thirty-nine citations were returned. Each of the abstracts for the 239 citations were reviewed using the above outlined criteria by the two researchers. Eleven articles met the criteria based on abstract review. These 11 articles were downloaded for further in-

depth review by the two researchers who hold PhDs (see [14, 15]). The majority of the articles obtained in the search (Table 1) describe frameworks and models that draw on theories from other domains. Although new theories developed explicit-

ly for studying technology-induced error were not found in the literature, the frame-
dworks and models that were identified did draw on a number of theoretical perspec-
tives from the error and other literatures (e.g. Reason’s work [20]). The researchers developed a summary table (Table 1) with the following headings: author names, year of publication and reference, name of framework/model, potential causes of error, strengths and weaknesses of the frameworks/models, literatures of origin, and state of current application (i.e. has the model/framework been tested for its ability to predict or identify medical errors invol-

ving HIS as indicated by the framework/model developers).

Several themes emerged from a review of these works. For example, although the articles describe frameworks and models published in the biomedical and life sciences literatures, and draw on theoreti-
cal perspectives from other domains (e.g. psychology, sociology and organization behavior), the authors of these works do not identify them as full theories (i.e. they do not meet the definition of a theory as out-
lined in the Methods section of this paper). The frameworks and models do, however, draw on numerous theories from other liter-

atures. The majority of the articles in Table 1 draw on the human factors, human-computer interaction and cogni-
tive literatures, followed by the socio-tech-
nical, organizational behavior and sociol-
y literatures. Lastly, a few of the articles draw primarily on the software engineering literature. It must be noted that in many cases each of these domains have theories that have been used to inform the develop-
ment of these models and frameworks. For example, Roger’s Innovation Diffusion Theory [18] has been used to inform Ash et al.’s Thematic Hierarchical Model of Con-
sequences of CPOE [6]. As well, many of the works draw on more than one domain and base literature. For example, Sittig and Singh’s Socio-technical Model for Studying Information Technology, draws upon the human factors, socio-technical and soft-
ware engineering literatures [19]. Many of these authors have developed such multi-
disciplinary frameworks and models due to the complexity of errors resulting from HlSs. It is worthy to note that theories, models and frameworks from other litera-
tures are not typically imported and tested “as is” for their applicability, rather models and frameworks are being modified, ex-
tended or adapted specifically for health-
care and are being tested for their ability to identify and explain technology-induced errors. Some of these researchers have suc-
cessfully demonstrated the applicability of the models in identifying and explaining technology-induced errors. Several of the authors of these new models or frame-
works have indicated there to be successful empirical testing of some components of these models while others are currently undertaking testing to determine their model’s or framework’s applicability to medical error involving HIS (e.g. [19, 21]).

From a further detailed review of the re-
sulting papers in Table 1, it was found that the papers could be organized into sev-
eral main groups based on the literatures and theoretical works from which they emerged from and draw on. They include: 1) the human factors literature (including human-computer interaction and cognition), 2) the organizational behavior/socio-
technical literature, and 3) the software en-
gineering literature. The remainder of the paper will discuss the papers in terms of these groupings.

5. Human Factors Models and Frameworks

The majority of the papers (i.e. 7 of the 11) contained references to the human factors literature (which in this paper is considered broadly to include human-computer interaction and cognitive science applied to user interface design) (see [4, 19, 21–22, 24, 30, 32, 35] in Table 1). These works can be readily employed in healthcare and are spe-
cific to the unique types of information sys-
tems that are designed and developed for healthcare (e.g. physician order entry). For example, Zhang, Patel, Johnson and Short-
liffe [22] describe a cognitive taxonomy of
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<td>Bloomrosen, Starren, Lorenzi, Ash, Patel and Shortliffe, 2011 [32]</td>
<td>Input-output model of unintended consequences</td>
<td>Interface design, implementation, poor training/support, poor fit with workflow, poor fit with decision making, interoperability, legislators and regulatory changes, data accuracy</td>
<td>Strengths: based on expert consensus and recommendations. Weaknesses: provides a research agenda but not specific techniques</td>
<td>Organizational/Fiscal/Policy and Regulation/Cognitive and Human Factors</td>
<td>Proposes a research agenda</td>
</tr>
<tr>
<td>Borycki and Keay, 2010 [30]</td>
<td>Continuum of methods for diagnosing technology-induced errors</td>
<td>Interface design, poor system organization fit, poor workflow</td>
<td>Strengths: can be used to design a strategy for addressing technology-induced errors across the Software Development Life Cycle. Weaknesses: requires further testing.</td>
<td>Software Engineering/Sociotechnical/Human Factors</td>
<td>Parts have been used in healthcare organizations (cites multiple empirical works in its development – e.g. Ash et al., 2007)</td>
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<tr>
<td>Kushniruk, BeuscCart-Zephir, Grzes, Borycki, Wabbledand Kannry, 2010 [29]</td>
<td>Framework for selecting health information systems to prevent error</td>
<td>Poor system-organization fit, poor procurement processes</td>
<td>Strengths: can be used for system selection. Weaknesses: difficult to change &quot;conventional&quot; methods currently used for system procurement</td>
<td>Software Engineering/Project Management/Sociotechnical Design/Risk Management</td>
<td>Has been applied in various hospital settings</td>
</tr>
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<td>Sittig and Singh, 2010 [19]</td>
<td>Eight-dimensional model of sociotechnical challenges involved in design, development, implementation, use and evaluation of HIT in healthcare</td>
<td>Poor system design, system development, or configuration</td>
<td>Strengths: considers multiple dimensions of safe and effective HIT use. Weaknesses: primary focus is not on errors</td>
<td>Human Factors/Diffusion of Innovations/Organizational Behaviour/Technology Acceptance Model/Cognitive Theory/Human Error/Workflow/Sociotechnical/Software Engineering/Emotional Aspects</td>
<td>Has been applied and is undergoing further testing (See Sittig &amp; Singh, 2010)</td>
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<tr>
<td>Borycki, Kushniruk, Keay, Nicoll, Anderson and Anderson, 2009 [24]</td>
<td>Framework for integrating clinical and computer based simulations to predict technology induced errors.</td>
<td>Poor interface design, incorrect content displayed to user</td>
<td>Strengths: predictive, can be used by decision-makers to forecast and address potential issues before deployment using computer-based simulations. Weaknesses: need to confirm that predicted errors would occur in the real world.</td>
<td>Human Factors/Medical Simulations/Computer based Simulations/Operations Management</td>
<td>Applied in study of pervasive devices in health care (See Borycki et al., 2009)</td>
</tr>
<tr>
<td>Borycki, Kushniruk, Keay and Kuo, 2009 [21]</td>
<td>Framework for considering the origins of technology induced error</td>
<td>Sources of errors ranging from government policy, model organizations, vendor organizations, local health care organizations, and the individual</td>
<td>Strengths: allows one to look at potential sources of errors and how the sources interact at multiple levels. Weaknesses: needs to be tested</td>
<td>Human Factors/Organizational Behaviour/Computer-Based Simulations</td>
<td>Not yet validated</td>
</tr>
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Table 1 Summary of articles (continued)

<table>
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<tr>
<th>Authors/Year of Publication/Reference Number</th>
<th>Framework/Model</th>
<th>Potential Causes of Errors</th>
<th>Strengths and Weaknesses of the Frameworks/Models</th>
<th>Literatures of Origin</th>
<th>State of Current Application</th>
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<td>Harrison, Koppel &amp; Bar-Lev. 2007 [36]</td>
<td>Interactive sociotechnical analysis framework and typology</td>
<td>Elimination of informal social interactions, elimination and redundant checks, poor interface design, poor representation of workflow, poor communication of information, loss of feedback</td>
<td>Strengths: draws on differing areas of research. Weaknesses: needs to be tested.</td>
<td>Sociotechnical/Ergonomics/Construction of Technologies/Technology in Practice/Social Informatics</td>
<td>Not yet validated</td>
</tr>
<tr>
<td>Borycki &amp; Kushniruk, 2005 [4]</td>
<td>A methodological framework for describing how to use simulations to identify and predict technology-induced error</td>
<td>Interface design, incorrect content displayed to user</td>
<td>Strengths: predictive, can identify specific problem areas before release of the system. Weaknesses: need to confirm that predicted errors would occur in the real world</td>
<td>Human Factors/Medical Simulations</td>
<td>Has been applied internationally (Japan, US). Method used in Kushniruk et al., 2005, 2006</td>
</tr>
<tr>
<td>Zhang, Patel, Johnson &amp; Shortliffe, 2004 [22]</td>
<td>Theoretical and conceptual cognitive taxonomy of medical errors</td>
<td>Errors resulting from execution, evaluation, goal, intention, action specification, action execution, perception, interpretation, action evaluation</td>
<td>Strengths: focus on underlying cognitive aspects of errors. Weaknesses: requires further testing</td>
<td>Human Error/Action Theory/Cognitive Science/Human Factors</td>
<td>Has been applied, and is undergoing further testing (see Zhang et al., 2004)</td>
</tr>
<tr>
<td>Horsky, Kaufman, Oppenheim &amp; Patel, 2003 [35]</td>
<td>Multifaceted cognitive methodology for characterizing cognitive demands of systems</td>
<td>Heavy cognitive demands on users, especially those who lack a robust conceptual model of the system</td>
<td>Strengths: builds on cognitive task analysis to provide insights into interactive strategies and patterns of associated errors. Weaknesses: further testing needed</td>
<td>Cognitive Science/Human Factors/HCI/Distributed Cognition</td>
<td>Has been applied, and is undergoing further testing (see Horsky et al., 2003 for details)</td>
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medical errors involving individuals and their interactions with technology (Table 1). Their framework borrows from the work of Reason in defining human error in terms of “slips” and “mistakes”. Their work also incorporates cognitive theory and Norman’s Action Theory which describes seven stages in the interaction of users with systems and provides a framework for considering at what stage errors may occur [22].

A second paper by Borycki et al. [21] also referred to Reason’s influential model of human error (Table 1). Reason’s [20] approach distinguishes between a “sharp end” and a “blunt end” where error may arise in complex human-computer interaction. It is at the sharp end that errors are made by humans; however, the origins of such errors (their ultimate causes) may be at the blunt end of the continuum, that is, at the end involving the complex organizational processes, policies and environments that may eventually lead to error at the sharp end. In this work, Borycki et al. [21] extend and elaborate upon Reason’s model to include the consideration of healthcare specific sources of technology-induced error (e.g. from healthcare legislation to user training and implementation). The work blends the human-computer interaction and human error literatures with theory from the organizational behaviour literature in healthcare [21]. In related work, Horsky et al. describe the development of a framework for analyzing the cognitive complexity of computer-assisted clinical
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ordering (Table 1). The approach provides a methodology for characterizing the cognitive demands of users of interactive HISs and is based on a framework that provides insights into clinicians’ strategies in using systems and the errors that arise from them [35].

In another line of publications, several researchers describe frameworks that can be used to identify and predict technology-induced errors (i.e. using clinical simulations and computer based simulations). For example, Borycki and Kushniruk [4] describe a methodological framework for designing and conducting clinical simulations that can be used to identify and predict technology-induced errors. They follow this work by combining clinical simulations and computer based simulations. In this paper the researchers extend their original methodological framework to describe how clinical and computer based simulations can be combined and used to: 1) predict a health information system’s error rates and 2) project those error rates over time (if the HIS is widely implemented). Computer based simulations can be used to forecast the long term effects of specific technology features and functions upon error rates (once HIS have been implemented). Clinical simulation results (e.g. data about observed error rates) can be used as inputs to computer based simulations, allowing healthcare administrators to make decisions about what technology features and functions to address in order to make HIS safer. This methodological framework has been used by Borycki, Kushniruk, Key, Nicoll, Anderson and Anderson (Table 1) to study and prevent technology-induced errors and mitigate risks associated with implementing HIS [24].

Human factors models and frameworks offer a significant contribution to the study of technology-induced errors. The strengths of such models include their ability to predict technology-induced errors so they can be addressed prior to HIS implementation. A weakness of these models is their inability to take into account all aspects of organizational context in causing errors involving HIS. In summary, a number of frameworks and models published and indexed by Medline® in the biomedical and life sciences literature draw on work from the human computer interaction and cognitive research. This work has been used to inform development of models and frameworks that are specific to the healthcare domain and work that focuses upon identifying and describing medical errors involving HIS.

6. Organizational Behavior and Sociotechnical Models and Frameworks

Theories related to diffusion of innovation have been a source of inspiration for many researchers from several domain areas (e.g. management, health/biomedical informatics) (see paper by Ash et al. in Table 1). Roger’s text entitled “Diffusion of Innovations” [18] has provided insights to some researchers as to the varying factors that affect a technology’s diffusion [6, 18]. For example, Rogers [18] provides an overview of how communication channels influence an innovation, and identifies the main attributes of an innovation that influence its diffusion through a social system. Ash et al. [6] have extended work documented in Roger’s text [18] to healthcare. Ash and colleagues have documented the intended and unintended consequences associated with using a physician order entry system and have developed the Thematic Hierarchical Network Model (including those consequences that are desirable and undesirable using Physician Order Entry). The researchers use ethnographic observational and interview data and derive their model from the qualitative findings of their study [6].

Sociotechnical theory has also been a source of inspiration for the development of many models and frameworks [19, 29, 36]. Sociotechnical theory has its origins in work conducted by researchers at the Tavistock Institute in London who identified that there is a need for a fit between technical (i.e. tools, devices and techniques) and social sub-systems (i.e. employees knowledge, skills, values and needs) in organizational workplaces (including organizational authority structures and systems of rewards) [25, 26]. This work was later extended to the health informatics domain by researchers such as Berg [27, 39], Aarts [28, 39] and Breder [38] who have focused on the importance of task-technology fit involving HIS. Sittig and Singh [19] (Table 1) draw their inspiration for their Socio-technical Model for Studying Health Information Technology in Complex Adaptive Healthcare Systems from the sociotechnical theory literature. Sittig and Singh’s model identifies eight dimensions of “safe and effective HIT use” ([19] p. 73). The dimensions include: 1) hardware and software, 2) clinical content, 3) human-computer interface, 4) people, 5) workflow and communication, 6) organizational policies, procedures and culture, 7) external rules, regulations and pressures, and 8) system measurement and monitoring. The authors argue that aspects of each of their model’s dimensions interact and may influence the occurrence of errors. The authors describe their model as having a sociotechnical focus, even though the model borrows some of its underpinnings from the human factors and software engineering literatures. The model has been applied to the study of HIS and is currently undergoing further empirical testing [19]. In related work that draws on the sociotechnical, social construction and social informatics research and theory, Harrison, Koppel and Bar-Lev [36] (Table 1) propose the Interactive Socio-technical Analysis (ISTA) framework. The work is significant as it focuses upon the: 1) importance of studying actual use of health information technology; 2) the impact of health information technology upon technical and physical settings of work (i.e. organizations), 3) users’ renegotiation and reinterpretation of health information technology features and 4) the interactions between and interdependence among sociotechnical systems in the workplace. The strengths of this work lie in the recognition that tool design alone is not the sole contributor to medical errors involving HIS and health information technology. When a new HIS or health information technology is introduced, sources of error may include inadvertent changes in tasks health professionals perform, changes in workflows and communication patterns, as well as changes in interactions among health
professionals resulting from implementation of the HIS. A weakness of this work is the need for more research that documents the effects of HIS (within the context of a social and organizational system) upon medical error rates. In another work, Bloomrosen, Starren, Lorenzi, Ash, Patel and Shorlifke [32] (Table 1) describe an input-output model that identifies the unintended consequences arising from technology use. The model includes technological, organizational, fiscal, policy, regulatory and cognitive factors that affect health information technology design. The health information technology’s design leads to care processes, cognitive, organizational, social/legal, fiscal and technology-related consequences that affect stakeholders such as patients, providers, organizations, vendors, payers and governments. It is interesting to note that the model considers the range of unintended consequences – anticipated, unanticipated, desirable and undesirable [32]. In summary, researchers such as Ash et al. [6] have extended Roger’s work by focusing upon the intended and unintended (e.g. medical errors arising from interactions with HIS) consequences of using HIS (Table 1). Other researchers have developed models and frameworks that draw their inspiration from both the sociotechnical literature (e.g. [36]) first conceptualized by researchers at the Tavistock Institute and later introduced to the biomedical and health informatics literature by authors such as Berg [27, 39] and Aarts [28, 39].

7. Software Engineering Models and Frameworks

Software engineering has a long and established tradition of research that includes the development of frameworks that can be used to test software applications, devices and interactions [4] among these applications/devices for their effects on worker error rates [19, 29, 30]. For example, one framework which borrows from the software engineering literature considers technology-induced errors in terms of where in the System Development Life Cycle (SDLC) they arise from (ranging from inadequate or inappropriate requirements specification, system design, programming, customization to testing and implementation) (see article by Borycki and Keay in Table 1). Many publications and texts from the general software engineering literature provide details about differing types of software engineering approaches at each of these phases – arguing for the need to use frameworks that can be used to guide requirements specification, design, programming, testing and procurement of software as early as possible in the software development process to reduce costs associated with addressing software errors after an application has been implemented and widely deployed (i.e. the later an error is discovered in the SDLC, the higher the costs associated with correcting the error(s) that arise from the software once it has been implemented). Along these lines, a recent paper by Kushniruk and colleagues (Table 1) emerged in the search that describes a framework for improving the safety of HIS by focusing on the analysis of the fit of a system with the purchasing organization during the system selection process [29]. The framework considers a continuum of evidence for assessing HIS-organization fit, from weak evidence for fit obtained from conventional selection processes (such as vendor demonstrations) to strong evidence of fit obtained from in-depth analysis of system features (e.g. obtained from in-situ testing of candidate systems in organizational settings).

In a related recent paper Borycki and Keay have reviewed and grouped a range of evaluation methods that have been used in detection of technology-induced error in terms of whether they can be applied before or after the time of system deployment [30] (Table 1). Recent work in ensuring safer health systems through more rigorous processes throughout the SDLC has also begun to appear. This work focuses on more rigorously testing systems for their technology-organization fit as part of system selection, requirements gathering, design and testing of systems such as electronic health records (EHRs) [29, 30].

It must be noted that the strengths of the frameworks emerging from software engineering have their basis in the empirical research from the general software engineering literature that supports their use. As well, the breadth and the applicability of these approaches to many industries where software/devices have been used to improve the effectiveness of work processes is also a strength of these models [4]. The strengths of the frameworks emerging from the software engineering literature are also their weakness. Much of the literature is based on research that has been conducted in industries where user transactions are less complex in nature (as compared to healthcare) and where there are few urgent or life threatening decisions that have implications for individuals (i.e. patients). Additionally, user requirements are often tacit in nature and users’ beliefs about their work practices are not easily elicited during the requirements specification process. For example, findings from the empirical literature indicate that: a) a work process does not always occur in the way that users think it occurs, b) the way users carry out activities may vary by user, and c) rules and procedures that involve an application/device may not be followed or may be “broken” by users [10, 31, 38, 39]. In summary models and frameworks that draw their inspiration from the software engineering literature have focused upon identifying and preventing technology-induced errors across the SDLC. Such work will be necessary to prevent technology-induced errors.

8. Discussion

In this paper we have described a number of frameworks, models and underlying theoretical perspectives (that the frameworks and models have drawn from) published in Medline®. HIS differ from information systems in other domains (e.g. nuclear power and aviation) in terms of their functions, use and application to the work setting (see [1]). Models and frameworks for considering technology-induced error have begun to be practically employed in the prediction and prevention of such error. Recent work in predicting and preventing technology-induced error in healthcare has blended the use of many models and frameworks as described above [2, 4, 7, 8]. Some researchers have also conducted preventative analyses of error, by starting at the blunt end of Rea-
son's model to consider policy and organizational factors (using the framework outlined by Borycki et al. [21] that extends Reason's work to healthcare informatics) and then moving to the sharp end to assess the potential impact of system design and implementation choices on error at the human-system interface. Likewise, Reason's model of error has led some researchers to conduct analyses targeted at both the sharp and blunt ends of the error continuum. Using one strategy some researchers have first started with the occurrence of an error (at the sharp end) and then traced the error back to possible blunt end causes (see [35]). However, there are a few publications that have specifically focused their work upon identifying the root causes of errors after an error involving a HIS has occurred [4, 21]. It can be argued that there is need for more work in this area as we continue to see publications that are documenting new types of errors emerge [3, 6, 7]. Although the review did not identify new theories specifically for technology-induced error in healthcare, many of the frameworks, models and theoretical perspectives that have been discussed in this literature draw on work in other domains. Furthermore, it can be concluded that existing frameworks, models and theories developed outside of health informatics have informed and inspired (e.g. have been adapted, modified and extended) health and biomedical informatics research that has focused on understanding technology-induced errors in healthcare.

Future work could involve using models such as Leavitt’s diamond [37] as pointed out by Brender [38]. Leavitt’s model may allow one to track the trajectory of accident opportunities. More importantly, Leavitt’s work could be useful in exploring the events of an accident and how they propagate through an organizational system in order to trace out the root causes of errors (i.e. in terms of task, actors, structure, technology, and organizational environment) as there are few models or frameworks to guide this type of work in identifying the root causes of technology-induced errors in health informatics at present. In addition to this work there is a need to undertake further testing of these models and frameworks to determine their ability to predict potential technology-induced errors. Some of the models and frameworks in this work have only recently been adapted or proposed. Therefore, there is a need for a research agenda in the area involving empirical testing or extension of these frameworks and models involving technology-induced errors. The models and frameworks outlined in this work are only beginning to be tested in real world settings to determine their value in describing technology-induced errors and their sources. There is a significant need to continue testing these models and frameworks in future work – eventually this may lead to the development of full theories of error in healthcare.

A limitation of the review reported in this article is that the authors used Medline® to conduct their searches. Medline® was used by the authors as many of the journals that are considered influential to the biomedical and health informatics literature are indexed by Medline®. Our intent was to document this literature from a biomedical and health informatics perspective so we limited our search to Medline® for this reason. Health informatics is an emerging discipline and with its development into a science, it has begun to create its own body of literature that is specific to the healthcare domain [1].

9. Conclusion

We must ensure that HIS do not inadvertently add new forms of error. However, due to the complexity of healthcare processes and work activities, the potential for HIS to cause technology-induced error is an ever growing concern. In this paper we examined the extent, range and scope to which frameworks, models and theories have been developed or applied in research in the biomedical and life sciences literature focusing on technology-induced errors. More specifically, the authors identified and described several models and frameworks that draw on a range of theories from varying disciplines. It is hoped that consideration of this literature will lead to a more principled and effective deployment of applications/devices and thereby reduce the number of technology-induced errors that arise from use of health information technology.

References