# Ergonomics and Forensic Engineering

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**Abstract**

*In disputes, forensic engineers routinely investigate available hardware and software and may examine other engineering attributes and activities. Human factors and ergonomic (HF&E) aspects may be considered, but these tend to be more limited or overlooked. This paper discusses an HF&E framework for forensic analysis, including its four major subdisciplines (micro-, meso-, macro-, and mega-ergonomics), the role each plays throughout the product lifecycle, and examines their relationship to known and foreseeable use and misuse of a product or system. A taxonomy of errors, including distinguishing features of individual user errors versus system use errors, is presented and then used in a diagnostic rubric developed for forensic engineers to help identify HF&E issues as part of a forensic analysis. A health care setting case study is offered to demonstrate rubric use, but the rubric is generalizable to other domains.*

**Keywords**

Human factors, ergonomics, forensic engineering, rubric, use error, user error

## Introduction

Today, the terms "human factors" and "ergonomics" are used either interchangeably or in combination: human factors and ergonomics (HF&E). Historically, ergonomics was a term originating in Europe, whereas the term human factors originated in North America. HF&E spans the biological sciences and social sciences; ergonomics engineering is one of four industrial engineering subdisciplines.

The central objective of HF&E is to fit tools to the available humans in contrast to historical efforts to fit humans to whatever tools were available. This human-centered approach has been demonstrated repeatedly to reduce the probability of errors and increase safety[1]. Conversely, improper, defective, or nonexistent HF&E arguably increases the probability of errors and occurrence of incidents in all settings where humans engage in individual and team efforts.

In disputes, forensic engineers routinely examine available hardware, software, and other attributes and activities, such as quality engineering (e.g., design control, risk management). HF&E aspects may be considered, but this tends to be limited in scope (e.g., biomechanics only) or overlooked. The intent of this paper is to provide forensic engineers with a diagnostic rubric designed to detect the presence of HF&E flaws, defects, or concerns. The rubric consists first of classifying an identified human error proximate to the failure either as a system use error or an individual user error. Based upon that classification, the rubric leads the user through steps that facilitate analyzing the circumstances surrounding individual user(s) and associated organizations throughout the device or system lifecycle in search of both enabling and root cause(s). A simple illustrative example will be offered from the health care technology setting to demonstrate the rubric's use, but the basic principles are generalizable to other domains. Other case studies are readily available[2,3], which may be used for additional insight and/or practice employing the rubric.

This paper seeks to provide HF&E-related theoretical perspectives and diagrammatic tools so that the forensic engineers from other disciplines may better consider additional potential causes of failure in the case under analysis and help determine when specialized HF&E expertise in the root cause analyses may be warranted. When searching for HF&E experts, forensic engineers should consider the Board of Certification in Professional Ergonomics (www.bcpe.org), an internationally recognized, U.S.-based, non-profit organization analogous to the National Academy of Forensic Engineers (www.nafe.org).

## Theoretical Perspectives

*Human-Centered System Complexity Spectrum*

HF&E engineering is a subdiscipline of industrial engineering, but is also practiced by biologists, psychologists, sociologists, and others. The concept of "tools" is

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broadly construed to include just about any job aid. The HF&E system complexity spectrum[4] extends from using simple hand tools (physical ergonomics) to operating within a specific culture or subculture (e.g., nurses working with engineers within a hospital). The basic science disciplines involved range from biology to psychology to social psychology to sociology and political science. The spectrum encompasses four levels of complexity:

1) Micro-ergonomics (physical ergonomics) — involves human(s) operating with tools and considers anthropometry, biomechanical and sensory processes.

2) Meso-ergonomics (information ergonomics) — involves human(s) operating tools with automation and considers verbal and non-verbal, affective, cognitive, and physiological behaviors;

3) Macro-ergonomics (social ergonomics) — involves human(s) operating within organizations and considers communication, coordination, conventions, and expectations; and

4) Mega-ergonomics (cultural ergonomics) — involves human(s) operating within (sub-) cultures and considers language, artifacts, beliefs, customs, and morals.

## Overt and Covert Phenomenon

At each of the four levels identified above, there are both overt and covert phenomena. "Overt" in this context means detectable with one or more of our five senses; "covert" means additional instrumentation is required for detection. For example, at the micro-ergonomic level, the overt attribute is the range of physical dimensions of humans of differing ages, gender, ethnicity, etc.; the covert attributes include biomechanical and sensory attributes (including sensory-motor integration) of humans of varying genders, ages, etc.

These overt and covert human attributes underpin the Needs, Wants, and Desires (NWDs)[5,6] of tool users, ranging, for example, from size of display fonts to ensure enhanced readability for most users (micro-ergonomic) to language of instruction manuals that corresponds with users own preferences (mega-ergonomic). They can also elucidate sources (root causes) of potential problems, if these and other user NWDs are not adequately addressed. **Figure 1** (adapted from Reference #5) summarizes examples

| Ergonomics | Factor | Example(s) |
|---|---|---|
| Micro- | Overt: | Static size & fit of an individual (range of adjustment of operating table) |
| | Covert: | Biomechanical – weight & balance of individual surgical tools<br>Sensory – multiple alarms interfering with high priority alarm recognition.<br>Sensory-motor Integration – hand/eye coordination fidelity |
| Meso- | Overt: | Verbal/Non-verbal information management behaviors – verbalization & trackball operations while using computerized system |
| | Covert: | Affective – frustration with simultaneous alarms<br>Cognitive – difficulty recognizing highest priority alarm.<br>Physiological - ↑ Heart rate/respiration rate due to time pressure & alarm recognition issues |
| Macro- | Overt: | Communication – 2 nurses verifying drug & dosage setting for device.<br>Coordination – equipment buyer not coordinating with nurse end users |
| | Covert: | Conventions – buyer ignores nurse users' preference; buyer uses "preferred" vendors.<br>Expectations – buyer expects clinicians will "safely & effectively" use any device |
| Mega- | Overt: | Language – clinicians & engineers do not use/understand same language.<br>Artifacts – devices familiar to clinicians unfamiliar to engineers & vice-versa |
| | Covert: | Shared values, such as beliefs, customs, ethics, & morals, differ between clinicians and others (engineer, legal, business, etc.) |

**Figure 1**
Examples of factors (overt and covert) by ergonomic level.

of overt and covert factors by ergonomic level that warrant consideration by the forensic engineer.

At the physical (micro-) ergonomic level, the overt factors relate to anthropometry issues, such as the size of an individual's hand (e.g., to grasp a tool), a comfortable working height of a task surface (e.g., the adjustment range of an operating table), and easily accessible placement of operating controls (e.g., the distance required to reach a knob or switch). The covert micro-ergonomic factors include biomechanical issues (e.g., expected grip strength), sensory issues (e.g., expected visual, auditory, or tactile acuity), and the related sensory-motor integration capabilities expected of humans of differing ages, gender, ethnicity, (dis)abilities, etc.

At the information management (meso-) ergonomic level, the overt factors are both verbal and nonverbal (e.g., gesture) behaviors required to interact with automated or partially automated tools (e.g., voice-controlled devices, swiping on a screen, etc.). The degree to which those overt factors are non-intuitive, difficult to understand, or poorly designed or implemented, engenders user difficulties that engage the covert meso-ergonomic factors, such as affective (e.g., feelings and emotions) behaviors, cognitive behaviors, and psychophysiological behaviors.

At the social (macro-) ergonomic level described above, the overt factors are communication and coordination among team members or other stakeholders (e.g., end-users, manufacturers, clients, or any individual or entity with a "stake" in the device or system) working toward a putatively agreed-upon objective. The covert macro-ergonomic factors are conventions (e.g., roles and norms, especially among individuals with varying gender, age, education, organizational position, etc.) and expectations, which are often misplaced or unreasonable[5].

Finally, at the cultural (mega-) ergonomic level, the overt factors are linguistics and tangible artifacts. These include jargon and use of tools familiar to members of one subculture, but foreign to another (e.g., a stethoscope and a multimeter for nurses and engineers, respectively). Additionally, broader cultural issues may be at work, such as overall workplace "safety" culture (or lack of), perception/reality of fairness, diversity, and the like. Underlying — and intimately connected to — these overt factors are the mega-ergonomic covert factors: beliefs, customs, ethics, and morals, many of which vary by training, profession, upbringing, and other human attributes.

While these four discrete ergonomic levels may appear, at first, to be disparate and unrelated, this is incorrect. Generally, there is significant interconnectivity and interaction between discrete levels. For example, consider a simple set of operating instructions (i.e., the ubiquitous "user manual"). The correct choice of wording and sentence construction to yield acceptable domestic readability statistics (e.g., English language, >70% reading ease, and <8th grade reading level) are overt mega-ergonomic factors. Typography (e.g., font size, etc.) and graphics (e.g., size, contrast, complexity, etc.) manifest overtly, but involve covert elements of micro-ergonomic factors (i.e., required visual acuity and contrast sensitivity). The medium on which the manual is presented (i.e., hardcopy or electronic) has elements of both micro- and meso- ergonomic overt factors. The presentation and subsequent evaluation of comprehension of the user manual include both overt and covert macro-ergonomic factors. This reflects merely a partial analysis of a simple user manual when considered across the full range of human-centered system complexity.

## Taxonomy of Errors

HF&E is ubiquitously relevant to forensic engineering analyses because human users are invariably involved in all human-built systems (with their concomitant flaws). Even in completely autonomous systems, we have developers and manufacturers prior to system installation, installers prior to deployment, and service personnel after deployment.

Root causes of incidents are human errors insofar as, at some point, somewhere, a human took or omitted an action that initiated the chain of events. But, unlike attempts to always blame the operator (often cited as a proximal "cause"), HF&E recognizes that human work occurs within one or more socio-technical systems. Socio-technical systems can be understood to be systems resulting from the intersection of tangible infrastructure (hardware and software) and human social systems (strengths and limitations). These socio-technical systems directly impact the probability of human error; depending upon the system design, it can increase or decrease the frequency of human errors. **Figure 2** provides a taxonomy of human error[4]; errors are jointly dependent on error type and error category.

**Figure 2** illustrates the four basic types of error behavior: expected, unexpected, misguided, and malicious. But the underlying source also depends on the primary error category — is it a system use error, or is it an individual user error? System use errors are the result of the actions and decisions of the development, deployment, maintenance, or disposal organizations. Individual user

| ERROR TYPE | ERROR CATEGORY: SYSTEM USE ERROR | ERROR CATEGORY: INDIVIDUAL USER ERROR |
|---|---|---|
| EXPECTED BEHAVIOR | ACTIVE (KNOWN BUGS) | ROUTINE USE |
| UNEXPECTED Behavior | LATENT (UNKNOWN BUGS) | NOVEL USE |
| MISGUIDED Behavior | DRIFT (BEYOND DESIGN ENVELOPE) | MISUSE |
| MALICIOUS Behavior | SABOTAGE | ABUSE |
| | **LOCUS OF CONTROL:** *DEVELOPMENT, DEPLOYMENT,& MAINTENANCE ORGANIZATIONS* | **LOCUS OF CONTROL:** *INDIVIDUAL HUMAN(S)* |

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**Figure 2**
Human error taxonomy.

errors are the result of actions and decisions of individual users, who may be end-users or members of the stakeholder organizations. These two primary error categories can exist at every phase of the product lifecycle (e.g., pre-launch, deployment, end-user, and/or service and disposal). System use errors involve organizational issues of engineering design, development, deployment, maintenance, and disposal (referred to as 3DMD), which are ultimately traceable to the organization's personnel and management errors, including internally codified standard operating procedures (SOPs).

Unlike identifying operator errors, system use errors can be more subtle and difficult to diagnose. Products and systems are the resultant of processes; defective products and systems are the resultant of defective processes. The system use error types are active ("known bugs or operation") and latent ("unknown bugs or operation")[7], drift ("operation beyond the design envelope")[8], and sabotage. So, the forensic analysis of system use errors requires an investigation of the organizational 3DMD processes. The best starting point for this analysis is the lifecycle design/deployment control and risk management processes. It is virtually guaranteed that a defective product or system may be traced back to a defective design or deployment control or a defective risk management process. That defective process then adversely impacts personnel selection and training — and the proper user focus[9]). Combined with the above, these distinctions form the basis for organizing data collected for inclusion in the proposed diagnostic HF&E rubric.

## The Human Factors & Ergonomics Rubric

The proposed diagnostic rubric, entitled "Human Factors and Ergonomics Rubric," is comprised of **Figures 3, 4,** and **5**. **Figure 3** provides the "big picture." It describes the life cycle phases that the investigator selects from (all that apply) of: 1) pre-launch (or pre-market); 2) deployment; 3) end-user; and 4) service and disposal phases. This is followed by a diagrammatic prompt to "Go To B: Individual User Errors" (**Figure 4**) and then to "Go To C: System Use Errors" (**Figure 5**) for further illumination of those respective errors by phase. Finally, it guides the investigator to report on the categories and types of HF&E issues uncovered. **Figure 4** is essentially an inset of **Figure 3**, which expands upon on the primary, secondary, and tertiary individual user errors that the investigator may encounter. **Figure 5** is a companion inset expanding upon the primary, secondary, and tertiary system use errors.

To navigate the rubric:

- Start in **Figure 3** by recognizing which of the following users may be involved: e.g., pre-launch, deployment, end-user, and/or service and disposal.

- Next categorize and elucidate the error category

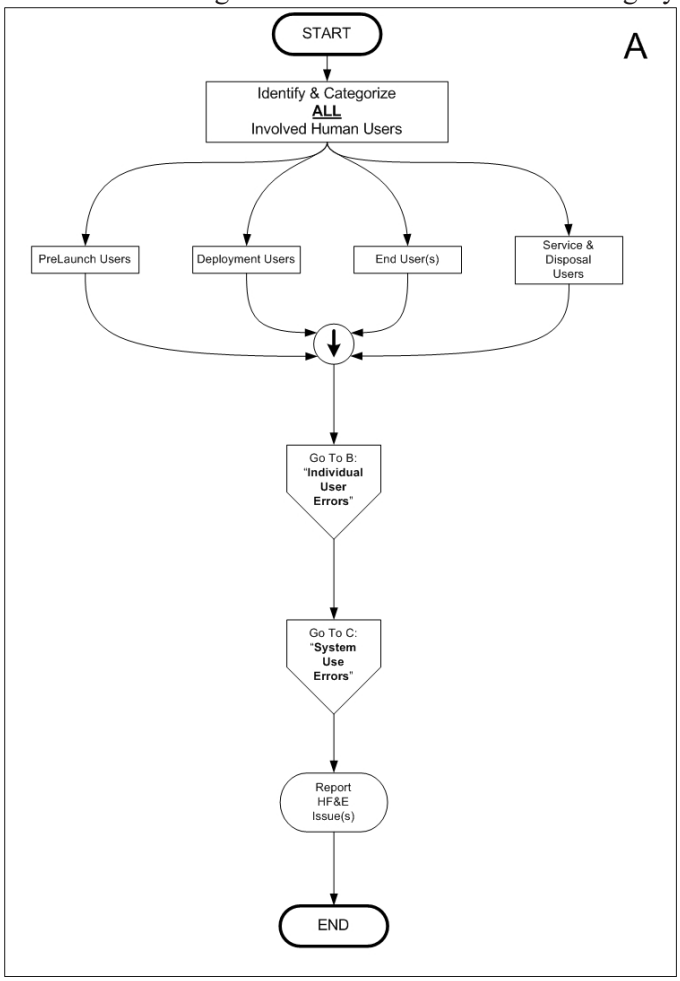


**Figure 3**
Human factors and ergonomic rubric.

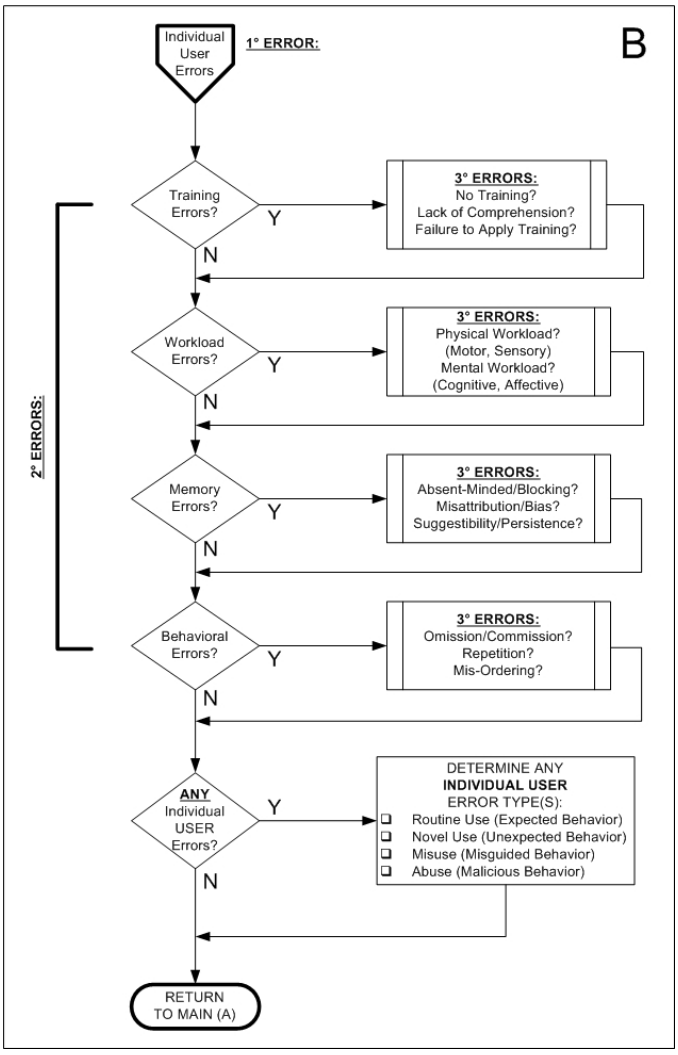


**Figure 4**
Human factors and ergonomic rubric.

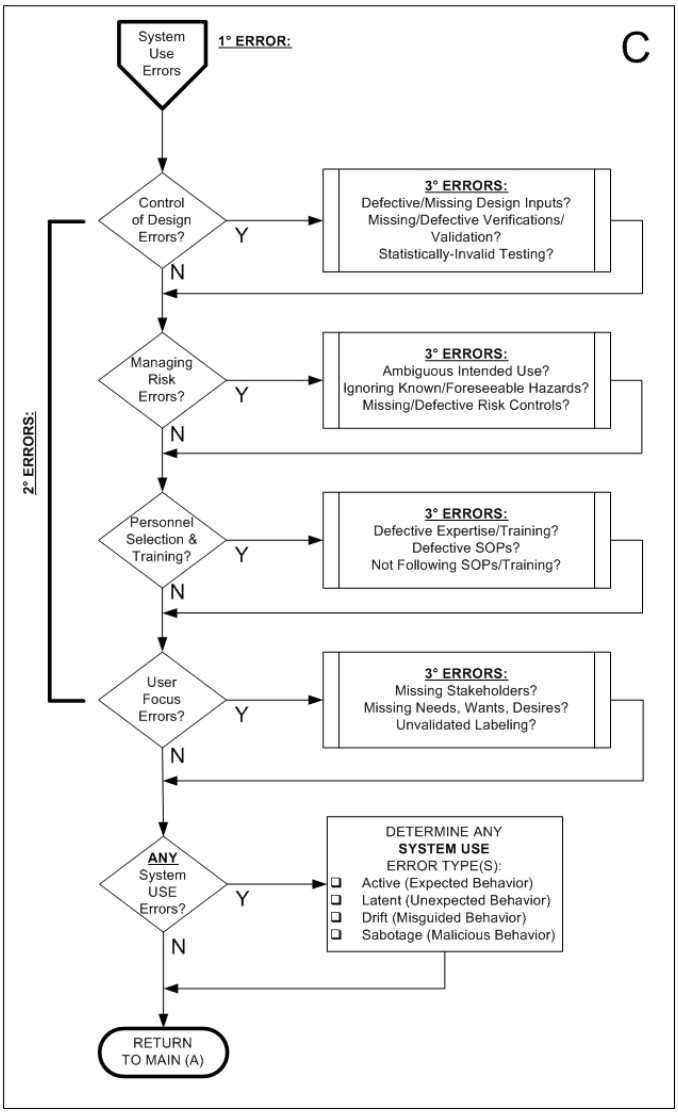


**Figure 5**
Human factors and ergonomic rubric.

for each user group selected above. If individual user errors are recognized as potential factors, go to **Figure 4**. Then choose which secondary individual user errors of training/expertise, workload (both physical and mental), memory, and the objective behaviors of the individual(s) may be involved in the incident (e.g., the operator) and identify their associated tertiary errors. If system use errors are likely factors, as well, proceed to **Figure 5** and identify which of secondary errors in control of design, managing risk, personnel selection and training, and user focus may be factors; subsequently, identify which of their associated tertiary errors may be contributory.

- Next determine the respective associated error type. In the case of a system use error, the error type will be identified as either active or latent[7], drift[8], or sabotage; in the case of an individual user error, the error type will be identified as routine use, novel use, misuse, or abuse (as described earlier in **Figure 2**).

- Finally, return to **Figure 3,** and report all the HF&E issue(s) uncovered by the rubric in the forensic analysis.

A practical example will illustrate this is neither complex nor onerous, until you get down deep into the HF&E details, at which point you should consult an expert in one of the specific subdisciplines of HF&E, if needed.

## Practical Application: Case Study

Consider the following scenario. A gastroenterologist

(a physician specializing in digestive tract illness) is about to do a procedure on a patient in the hospital. The patient is anaesthetized and prepared for the procedure. The physician arrives in the operating room where the patient and an endoscope system await him.

Because his iPhone battery is nearly depleted, the physician plugs the iPhone into the USB port on the endoscope equipment rack front panel, so that the battery will charge while he is treating his patient. Unfortunately, the endoscope refuses to operate, even though it was working properly for the previous procedure just 30 minutes ago. Fortunately, neither the patient nor the iPhone were injured. This is colloquially known as a near miss, although it is more correctly termed a near hit; missing is not always the case and such events, in slightly different circumstances, may result in serious injuries or even deaths.

A forensic engineer is asked to conduct an analysis by hospital management and to report on the problem and possible solutions. The investigator uses the steps and information diagrammed on the "Human Factors and Ergonomic Rubric" as demonstrated in **Figures 3, 4**, and **5,** to organize the inquiry and categorize and report on the findings. Following the first task diagrammed in the rubric in **Figure 3**, the investigator identifies all involved human users and subsequently categorizes them as: Prelaunch Users (e.g., manufacturer personnel); Deployment Users (hospital personnel); and End-User (gastroenterologist). The Service & Disposal Users were not considered to be factors in this case study investigation and are not discussed.

In this case, the forensic engineering investigator initially visits the deploying organization (the site of the reported incident), and conducts interviews with the physician, surgical staff, risk managers, and others. The investigator also requests production of various documents from the endoscope manufacturer and the hospital. Following the diagnostic rubric, the forensic investigator uncovered multiple HF&E failures and documented errors made by the various categories of identified human users. The following narratives (with corresponding summary tables) illustrate many, but not all, of the reported findings:

### *A. End-User(s) (Gastroenterologist)*

The gastroenterologist committed several individual user errors. These were recognized as secondary errors of training, workload, memory, and behavior. The physician denied receiving any training regarding the fact that the USB port was solely for use by service personnel and would automatically force the equipment into a system diagnostic mode. This error type was unexpected and constituted a novel use of the endoscope system.

The investigator determined the physician had made a behavioral error because the USB port was positioned in the surgical room at chest height, easily seen and readily accessible; using a USB port for iPhone charging is a normal and customary activity, so it was deemed a routine type error for iPhone users.

Workload errors were also considered factors as the user was a highly trained, busy physician under constant time pressure focused on the specifics of the patient; this was noted by the investigator as increased mental workload. The physician user plugged the iPhone into the port without taking the time to consider whether that action was appropriate, which constituted misuse. Workload issues may have further contributed to memory errors, which manifested in the tertiary error of absent-mindedness, when plugging his personal iPhone into a readily accessible USB port. This was consistent with secondary behavioral and tertiary repetitive errors identified in the rubric and frequently emitted in other settings.

The physician's action (plugging his iPhone into the endoscopy system) was deemed the proximate cause of the equipment failure; it was not the root cause. In summary, the investigation uncovered primary, secondary, and tertiary error categories and types found among End-User(s) as follows in **Figure 6**:

| 1° ERROR CATEGORY | 2° Error Category | 3° Error Category | ERROR TYPE |
|---|---|---|---|
| ***Individual User(S)Errors*** | ***Training*** | No Training | Novel Use (Unexpected) |
| | ***Workload*** | Mental Workload | Misuse (Misguided) |
| | ***Memory*** | Absent-Minded | Misuse (Misguided) |
| | ***Behavior*** | Repetition | Routine Use (Expected) |

**Figure 6**
Summary of end-user(s) category errors and types.

### *B. Deployment User(s) (Hospital Personnel)*

Hospital staff were found to be involved in system use errors, which were exacerbated by individual user errors (that have some systems features). A deployment user error occurred as one of the surgical technicians was aware of the problem with use of the prominent USB port (having made the error previously, but not having reported it). This was deemed a behavioral error of omission and a failure to apply training; it was a misuse error type.

That same technician was working during the case procedure but had a family emergency the previous night and was sleep deprived. This resulted in secondary user

errors, such as elevated workload (both mental and physical) and memory errors (failure to remember problem with port) as well as not noticing the physician plugging into the USB port, as the technician was properly focused on attending to their specific duties. This was deemed a novel use error type, in that staff were not expected to operate under those conditions.

There were also system use errors, uncovered by employing the rubric, specifically those associated with managing risk. The hospital risk manager had not identified the prominent, front-facing USB port as a potential hazard and, therefore, had not engaged in effectively managing risk errors by ignoring known/foreseeable hazards. This resulted in missing/defective risk controls, such as a failure to block the port or train clinicians (including surgical staff) on the risk of unauthorized use. These were considered latent error types. The biomedical equipment personnel were equally unaware of the potential hazard, even though they were aware of the purpose of the device's diagnostic port. The system use error is associated with an unexpected, latent error type insofar as it involved an equipment defect (identified as a control of design secondary error) that the hospital organization was generally unaware, even though it was known by the manufacturer, but not recognized as a "defect."

The errors identified above further indicated defects in proper user identification, defects in communication and coordination within the hospital organization, and a need to alter conventions and expectations among different subgroups (biomedical equipment technicians, surgical staff, hospital management, and potentially attending physicians). This evidenced secondary system use errors involving user focus errors insofar as there were missing stakeholders and invalidated (or missing) labeling. These were also deemed latent error types from the hospital's perspective, even though they were or should have been known from the manufacturer's perspective.

The hospital organization's socio-technical system design and management was reported as an intermediate and enabling cause, not the proximate cause or the root cause. In summary, the investigation uncovered primary, secondary, and tertiary error categories and types found among Deployment User(s) as follows in **Figure 7**:

| 1° ERROR CATEGORY | 2° Error Category | 3° Error Category | ERROR TYPE |
|---|---|---|---|
| ***Individual User(S) Errors*** | ***Training*** | Failure to Apply Training | Misuse |
| | ***Workload*** | Mental & Physical Workload | Novel Use |
| | ***Memory*** | Absent-Minded | Novel Use |
| | ***Behavior*** | Omission | Misuse |
| ***System Use Errors*** | ***Managing Risk*** | Ignoring Known/Foreseeable Hazards<br>Missing/Defective Risk Controls | Latent |
| | ***User Focus Errors*** | Missing Stakeholders<br>Unvalidated Labeling | Latent |

**Figure 7**
Summary of deployment user(s) category errors and types.

*C. Pre-Launch User(s) (Manufacturer Personnel)*

Pre-Launch users (manufacturer personnel) were involved in both individual use errors and system use errors; only the system user errors are identified here.

The investigator reviewed the documented risk analysis and discovered the front panel USB port was identified as a "hazard," but only from the perspective of the service personnel not being able to work with the equipment if the port malfunctioned. This was deemed an active error type insofar as the equipment defect was a known "feature," but not recognized as a use hazard; this is in contrast to it being deemed a latent error for the hospital. There were also secondary errors associated with user focus. The investigator discovered that there was virtually no user focus — all foreseeable users were not identified, no effort was made to determine their NWDs, and use hazards were not (and could not be) systematically identified; this was deemed a latent error type.

The risk analysis falsely reduced the estimated risk priority by including detectability[10]. Once the equipment leaves the plant, the manufacturer has no control over whether users will: (a) detect a specific risk; (b) attend to that risk, if they detect it; (c) remember what action to take for that specific risk, if they attend to it; and (d) have the time or other resources necessary to implement an effective risk mitigation strategy. As a result, managing risk secondary errors also occurred as the use hazard was not understood, the resultant risk control(s), such as blocking or labeling, could not be incorporated in the equipment product design requirements, and no verification or validation[11] could be executed to address the hazard to users.

Examination of post market complaint documentation indicated that the problem had occurred prior to this incident. However, given the failure to identify it as a use hazard in the risk management process, it was not recognized as a problem requiring corrective or preventive action. These missing/defective risk controls constitute latent error types, as the users were unaware of the defects in their internal processes.

Secondary system use errors in personnel selection and training were also found. Examination of the manufacturer's standard operating procedures (SOPs) indicated they were generic and not specifically tailored to the unique

products being manufactured (defective SOPs). Therefore, these were not adequate to inform the employees of their specific duties and responsibilities. No documented evidence was found of personnel training that mitigated these shortcomings and that was supported by the engineering flaws identified in risk management and control of product design (defective training). These were deemed drift error types, as the SOPs and expertise/training were outside the design envelope required for the organization's product development efforts.

The management of the manufacturer's organization was identified as the root cause of the incident. In summary, the investigation uncovered primary, secondary, and tertiary error categories and types found among Pre-Launch User(s) as follows in **Figure 8**:

| 1° ERROR CATEGORY | 2° Error Category | 3° Error Category | ERROR TYPE |
|---|---|---|---|
| ***System Use Errors*** | ***Managing Risk*** | Ignoring Known/Foreseeable Hazards<br>Missing/Defective Risk Controls | Active<br>Latent |
| | ***User Focus Errors*** | Missing Stakeholders<br>Missing, Needs Wants, Desires | Latent<br>Latent |
| | ***Personnel Selection & Training*** | Defective SOPs<br>Defective Expertise/Training | Drift<br>Drift |

**Figure 8**
Summary of pre-launch user(s) category errors and types.

## Conclusion

Forensic engineering in disputes routinely examines available hardware engineering, software engineering, and quality engineering (e.g., design controls and pre- and post-market risk management) attributes and activities. HF&E expertise should no longer be relegated to an afterthought or footnote, but rather must become an integral element in forensic investigations. Use of the Human Factors and Ergonomics Rubric, within the context of some of the underlying HF&E theoretical perspective presented here, offers forensic engineers, regardless of discipline, a structured, systematic approach to analyzing and exposing a wider breath of HF&E failures and human errors related to an ongoing incident investigation.

Even though reasonable investigators may make different judgements and thus arrive at different conclusions, the use of this diagnostic rubric promotes identification of both individual and organizational errors that provide a more balanced explanation of the underlying causation. Approaching forensic investigations using these tools also arguably fosters better mitigation efforts aimed at problems found at all levels. While beyond the scope of this paper, "closing the loop" by reporting identified problems to relevant regulatory agencies may be indicated. Rigorously validating interventions aimed at resolving problems identified during these HF&E oriented forensic investigations will likely do much to forward the goal of prevention of future adverse events.

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