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Development of ergonomics audits for bagging, haul truck and maintenance and repair operations in mining

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Abstract

The development and testing of ergonomics and safety audits for small and bulk bag filling, haul truck and maintenance and repair operations in coal preparation and mineral processing plants found at surface mine sites is described. The content for the audits was derived from diverse sources of information on ergonomics and safety deficiencies including: analysis of injury, illness and fatality data and reports; task analysis; empirical laboratory studies of particular tasks; field studies and observations at mine sites; and maintenance records. These diverse sources of information were utilised to establish construct validity of the modular audits that were developed for use by mine safety personnel. User and interrater reliability testing was carried out prior to finalising the audits. The audits can be implemented using downloadable paper versions or with a free mobile NIOSH-developed Android application called ErgoMine.

Practitioner Summary—The methodology used to develop ergonomics audits for three types of mining operations is described. Various sources of audit content are compared and contrasted to serve as a guide for developing ergonomics audits for other occupational contexts.

Keywords

Mining; audit; observational method; maintenance; haulage vehicles

1. Introduction

Auditing has roots in the financial and accounting contexts and involves an examination of a particular entity with a specific purpose. Ergonomics audits remain faithful to the concepts of checking, acceptable policies/procedures and consistency (Drury and Dempsey 2012), but

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the entity of interest is the workplace. An ergonomics audit provides a comprehensive measurement at a specific point in time of how well jobs and workplaces have been designed from an ergonomics standpoint (Koli, Chervak, and Drury 1998). In this context, we are not discussing audits of ergonomics programmes – rather audits of the actual work environment to provide a measurement of how effectively and comprehensively ergonomics has been applied. Although the results may have implications for assessing programme effectiveness, assessing ergonomics programmes is not a focus of this study. Auditing is used fairly extensively by safety professionals; however, surprisingly few ergonomics audits have been reported in the peer-reviewed literature (see Drury and Dempsey (2012) for a review).

The most detailed and rigorous ergonomics audit reported in the literature was developed for aircraft maintenance and inspection facilities (Chervak and Drury 1996; Drury 1998; Drury and Dempsey 2012; Koli 1994; Koli, Chervak, and Drury 1998) (for details of a computerised version of the same audit, see Meghashyam (1995)). The modular audit consisted of 23 modules cross-tabulated by maintenance phase (pre-maintenance, maintenance and post-maintenance) and human factors groupings (information requirements, environment, equipment/job aids and physical activity/workspace). A separate audit of visual inspection of aircraft was also reported by Koli et al. (1993).

Successful development and application of ergonomics audits have been carried out in underground coal. Simpson (1994a, 1994b) describes two ergonomics projects in underground coal mines in which a risk perception/hazard awareness questionnaire was developed. Simpson (1994a) focused on shafts, and identified a number of fall arrest hazards, issues with the choice of harness anchor points, control of hazards while working on top of the elevator cage and lifting hazards. Simpson (1994b) extended the development of the risk perception/hazard awareness questionnaire to the development of a human error audit grounded in the classic ergonomics framework of a human-machine system model. A typical human-machine model includes a machine that has displays to provide input (sensing) to the human for information processing, and subsequent human output to the machine controls, all occurring within the physical environment and influenced by work organisation. The audit was successfully applied to two underground haulage systems, and identified more than 40 potential errors and 9 latent failures (organisational influences that create unsafe conditions) involving equipment design, training, management actions and work organisation. One mine where the audit was applied went from having the highest accident rate from among 15 mines in a safety league to the lowest rate at the end of a 12-month period following the implementation (Simpson 1994b).

Ergonomics audits are an observational method that can be applied by a range of users if the users' capabilities and limitations are considered during design. For the audits developed here, the primary intended user population is safety professionals from the US mining industry. Since it is uncommon for these professionals to have formal ergonomics training, a decision was made at the outset that the audits would be designed for use by non-ergonomists. The audits therefore focused mainly on ergonomics issues that could be identified by observing and measuring workplace, equipment and task characteristics. Administrative and organisational issues were included to a lesser extent.

1.1. Choice of mining operations for audit development

Ergonomics audits were developed for three distinct types of mining operations: (1) small and bulk bagging operations, (2) haul truck operations and (3) maintenance and repair operations at coal preparation and minerals processing facilities. There were several influences on the decision of what types of operations to develop audits for with an underlying requirement that they apply to mining operations. First, previous collaborations with mines in the areas of ergonomics related to haul trucks and bagging operations identified problems without readily available context-specific tools to assist mines with addressing ergonomics issues. Small-bag filling and palletising operations had characteristics of production facilities, with frequent lifting and lowering of heavy bags. Previous haul truck research by the authors primarily considered vibration exposures, and slips and falls outside the cab during ingress or egress were among the types of injuries not necessarily related to vibrations that were known to occur.

In addition to the two types of operations mentioned, maintenance and repair operations were selected for several reasons. The main reason is that these operations continue to be a significant source of fatal and non-fatal injuries in mining. Also, very little ergonomics research has addressed maintenance and repair in mining or other industries. Aside from perhaps aircraft maintenance which has received considerable attention, research is sparse. This may be due to the difficult nature of studying irregular and often unplanned activities.

Given the limited research published on ergonomics audits, maintenance and repair operations provide a contrast with the more defined roles of bagging and haul truck operations, allowing us to judge the applicability and usefulness of audits across a range of mining activities. Haul truck operation often has several hours of uninterrupted driving interspersed with ingress/egress for fuelling, breaks and occasional light maintenance such as cleaning windows. Bagging operations typically involve repetitive tasks, with bag filling, palletising and preparation for shipment being the primary activities. Thus, the three types of operations chosen for audits were quite different from each other.

1.2. Desired audit characteristics

Before the project was initiated, the desired characteristics of the audit were defined. The requirements that Koli, Chervak, and Drury (1998) adapted from Koli (1994) were used as a starting point to create the following requirements for the audits reported here:

- **a.** Modularity: since not all aspects of ergonomics are relevant for all tasks or specific operations audited, the auditor needs the ability to choose appropriate modules for the current audit.
- **b.** Self-explanatory: the audit programme should be usable by non-specialists with a minimum of training. This is particularly important for most mines without onsite ergonomists.
- **c.** Content validity: modules must be applicable to the job or process being audited, and the data analysis must be based on recognised standards of good practice.

d. Observable: each measurement must be observable with a minimum of user judgement required and not require unusual equipment to measure.

e. Applicable: the whole programme should be equally applicable to many environments, e.g. the bagging audit should be applicable to many bagging facilities.

f. Solutions-oriented: although many audits simply identify issues or undesirable features of the audited entity, providing solutions or recommendations to remediate the problems was viewed as a key feature that would make the audits more useful and assist users with eliminating injury risks from workplaces.

1.3. Objective

The main objective of this manuscript is to describe the methodology used to develop three ergonomics audits. A secondary objective is to compare and contrast methods of generating audit content. Although the Koli, Chervak, and Drury (1998) audit provided the basic approach initially, several additional refinements and additions were added and are discussed. The approach and findings should be beneficial to others developing audits for additional applications.

2. Methods and findings

The methods summarised below represent research carried out over several years; therefore, where appropriate supporting literature is cited. Given the amount and diversity of information used to develop the audits, only summaries are practical for the constraints of a journal article.

2.1. Passive surveillance data

In the US, mining morbidity and mortality data is collected and made available to the public by the Mine Safety and Health Administration (MSHA) (see www.msha.gov). Data on fatalities and non-fatal injury cases with and without lost days between 2004 and 2008 were initially retrieved at the outset of the project. For each of the three types of operations, different classifications were used to help identify appropriate cases. For bagging operations, source of injury/illness ‘bags’ was used. For maintenance operations, regular job title of injured/ill miner of ‘mechanic/repairman/helper’ was used, as was a mine worker activity at time of injury/illness of ‘machine maintenance/repair’. For the haul truck analysis, mine worker activity at time of injury/illness of ‘operating haulage truck’ or regular job title of ‘truck driver’ were used for the initial selection. The latter were manually classified to determine if the truck was a haul truck.

The smallest data-set was that containing injuries associated with bagging operations, with 534 cases identified. Almost all of these injuries were related to overexertion associated with handling bags. ‘Sprain or strain’ was the nature of injury most frequently reported. The remaining injuries tended to be acute injuries relating to various aspects of bagging operations such as hand lacerations. No additional analyses (e.g. cross-tabulations) were done given the limited sample.

The initial case selection of injuries from the MSHA database for haul truck operations consisted of 1382 injury records (Santos, Porter, and Mayton 2010). Injury records with accident type classified as 'struck against moving object' and accident injury/illness classified as 'slip or fall of person (from an elevation or on the same level)' accounted for a large proportion (70%) of the total injuries during the five-year period from 2004 to 2008. These two classes were identified for more detailed analyses. No other individual subgroup (overexertion, handling materials, powered haulage or machinery) accounted for more than 12% of the data-set so those were not further stratified.

Based on manual coding of the narratives (Santos, Porter, and Mayton 2010), almost two-thirds of the 613 'struck against moving object' injuries occurred while the operator was driving (forward or backward), followed by loading (22%) and then unloading (8%). The majority of the 'struck against moving object' cases had 'sprain or strain' as nature of injury, and the back was the most frequently injured body part. About two-thirds of all the 'struck against moving object' injuries involved jarring and jolting of the operator.

More than 60% of the 359 total injuries related to 'slip or fall of person (from an elevation or on the same level)' occurred during egress and ingress, with the majority during egress. This concurs with previous work showing that a large proportion of falls from equipment injuries occurred during ingress or egress of large mining vehicles (Moore, Porter, and Dempsey 2009). The nature of injury most commonly reported was 'sprain or strain' (42%) followed by fracture/chip (24%). Overall, the results suggested that the audits and, therefore, the more detailed field studies would need to consider the entire operation of the haul truck, including those activities requiring the operator to operate the truck as well as those requiring the operator to be on the exterior of the truck.

Due to the widespread nature of maintenance and repair operations at coal preparation and minerals processing plants as well as the number of related injuries, the original analysis was expanded to include a ten-year sample of data (2002–2011) (Pollard, Heberger, and Dempsey 2014) as well as an analysis of lost days stratified by source of injury and body part. The sample included 21,799 cases of which 37 were fatalities. The numbers of incidents were highest for 'non-powered hand tools' (8669), 'handling material' (7989), 'powered tools and machinery' (2716) and 'slip/trip/fall' (2425). The total numbers of days lost were highest for 'handling material' (174,551), 'non-powered hand tools' (141,872), 'slip/trip/fall' (105,158) and 'powered tools and machinery' (51,817). These four categories were defined by Pollard, Heberger, and Dempsey (2014) and were studied further in field and laboratory studies, and are prominent in the audits through dedicated modules and questions. A separate, in-depth analysis of maintenance-related fatalities across all sectors and locations will be discussed in the next section.

2.2. Fatality report analysis

An analysis of fatal investigation reports produced by MSHA (reports can be downloaded at http://www.msha.gov/fatals/fab.htm) was performed for haul truck and also maintenance and repair operations (the researchers did not identify any fatalities during bag filling, sealing or palletising). The analysis was not initially planned as part of this study, but the availability of a significant number of relevant reports for haul truck and maintenance and repair operations permitted in-depth analyses for both classes. The analysis was undertaken to understand the types of task failures that can lead to fatal accidents. The identified underlying patterns with ergonomics implications were then used to develop specific audit items that identify the task or workplace features that contribute to task failures.

A sample of 40 MSHA fatality reports related to haul trucks was analysed for repeating patterns of accidents (20 from coal and 20 from metal/non-metal). An initial set of patterns was developed, and then these were refined following coding of the entire sample of 133 haul truck fatalities that occurred between 1995 and 2010 (Drury, Porter, and Dempsey 2012). The highest-level classification divided the fatalities into driving (first-level subcategories of 'loss of control', 'ground fails' and 'two-vehicle collision') and non-driving (first-level subcategories of 'unexpected movement', 'falls from vehicle' and 'hit by other vehicle'). The refined classifications and further sub-categorisation is discussed in more detail by Drury, Porter, and Dempsey (2012). Like the non-fatal analyses described above, the accident patterns discovered were used to develop audit items and modules intended to prevent similar occurrences in the future.

The analysis of maintenance and repair fatal accident patterns was conducted in a similar fashion (Reardon, Heberger, and Dempsey 2014). The 172 fatalities that occurred between 2002 and 2011 (47 from coal and 125 from metal/non-metal) were initially grouped by patterns identified from a sample of fatalities, and this grouping was refined while categorising the entire sample. The entire sample was then coded, which resulted in additional first-level categories being added. The set of fatalities was then coded by two researchers to ensure reliability of the classifications. The highest level of classification included 'potential energy', 'mechanical energy', 'electrical energy', 'thermal energy', 'pressure' and 'toxic vapors or substance'.

One noticeable difference between the distributions of fatalities in coal and metal/non-metal was that coal had a higher proportion of fatalities due to 'electrical energy' and metal/non-metal had a higher proportion of fatalities due to 'potential energy'. This is due to the fact that potential energy is limited in underground mines as opposed to surface facilities that can be several stories high, and electrical equipment and associated high voltage power centres and cables are more common in coal mines. Further analysis identified contributing factors (see Reardon, Heberger, and Dempsey (2014) for complete description) that were used to develop specific audit items and modules.

2.3. Field observations and studies

Data were collected from 73 total participants, with 26 performing bagging tasks across seven mine sites, 12 driving haul trucks at six different mine sites and 35 performing maintenance and repair tasks at seven different mine sites. Each data collection protocol was approved by the NIOSH Institutional Review Board. Subjects signed informed consents and participation ranged from being observed and video recorded to participating in the more detailed data collection protocols described below.

The bagging field observations focused on characterising the processes for small and bulk bag lines at seven mine sites (4 sand, 2 limestone, 1 mica). Observations from field visits conducted for a previous project and a pilot visit to a facility with small and bulk bagging lines (bentonite) were used to identify general ergonomics concerns and the types of tasks commonly performed. Parameters observed included the types of filling stations (small or bulk, level of automation), and where applicable the type of palletising, shrink wrap process, mobile equipment used for transporting, and truck or train loading method. Regular materials handling tasks were noted, including measurement of basic parameters such as starting and ending vertical locations, weights handled and carry distances. Examples include replenishing empty bags (small and bulk), manually weighing small bags and carrying propane cylinders to shrink wrap pallets. Manual palletising of small bags up to 45.4 kg (100 lb) was observed, and the pilot visit included a line where 45.4-kg bags were loaded directly from a flexible conveyor into a rail car. Basic environmental conditions were noted, including lighting and the potential for thermal stress.

In addition to the observation of bagging operations, field evaluations quantifying low back loading and the physiological costs of bagging tasks were performed at two bagging operations (Gallagher et al. 2011). A biomechanical model employing electromyography and goniometry was used to estimate lumbar compression (Adams and Dolan 1991; Dolan and Adams 1993), and a portable metabolic measurement system was used to record heart rate and oxygen consumption. Key findings included that the average oxygen cost for palletising (5.3 metabolic equivalents (METS)) indicated moderately intense physical activity. Bag filling resulted in lower physiological cost (3.2 METS), or a moderate level of energy expenditure. Use of a vacuum hoist resulted in a 39% reduction in the estimated peak compressive load on the worker’s spine compared to manual lifting without a hoist, supporting the use of hoists as a viable intervention for bagging palletising stations.

Field observation of haul truck activities was undertaken to characterise the tasks performed by haul truck drivers including ingress/egress, fuelling, pre-shift inspection and routine maintenance. The observations were conducted at six different mines/quarries of varying size (1 copper, 1 taconite (iron ore), 1 coal, 2 limestone and 1 sandstone), several of which were visited multiple times. During the visits the researchers discussed health and safety issues related to haul truck operations with mine management, mine safety and health personnel and haul truck operators to document concerns or to identify best operating practices. Additionally, the research team toured the mine site including the mine pit, haul truck-related maintenance facilities, haul roads and material dump locations. Scenes of interest were captured with photographs and video where appropriate to document best practices. Documentation that mines were willing to share with researchers, such as pre-shift inspection forms, were collected for later analysis.

In addition to mine visits, the research team contacted manufacturers and equipment dealers that manufacture, sell or lease varying sizes of haul trucks. During these interactions, researchers collected general information on the design of haul trucks used in mining, specific equipment operations manuals and manufacturer/dealer training products. Finally, the research team interacted with MSHA on best practices and other relevant information for operating haul trucks. Five coal and three Metal/Non-metal MSHA district offices were contacted to gain understanding of how MSHA inspectors approach and enforce haul truck health and safety related issues. The results of this evaluation were used to identify areas that needed to be addressed by the haul truck audit, and to identify best practices that could be used in the recommendation provided by the audit.

The maintenance and repair observations and data were collected at seven mine sites (three coal preparation plants, two sandstone processing plants and two limestone processing plants). Initially, researchers planned to conduct postural assessments of maintenance and repair workers while conducting tasks associated with injuries. Tasks of interest were those identified in the analysis of injury data (Pollard, Heberger, and Dempsey 2014). Researchers instrumented maintenance and repair employees with goniometers (DataLog, Biometrics Ltd., Ladysmith, VA, USA) and pressure-sensing boot insoles (Pedar-x, Novel, Munich, Germany). Goniometers were used to quantify shoulder, back, elbow and knee posture. The pressure-sensing insoles were used to measure steps and to estimate the weight of any items carried in the hands. The nature of mining plants made these systems impractical for use and this method was rejected after three field visits.

Field visits were conducted at one limestone mill, one sandstone mill and one coal preparation plant. Screen maintenance was observed at the coal preparation plant. For this process, workers had to stand inside the screen deck and remove build-up from the existing screen before it could be replaced. The wet, oily build-up made the goniometers start to drift and led to them coming off the workers. This made goniometer data unreliable. In the sandstone and limestone mills, the signal from the pressure sensing insoles was lost and showed frequent drops. This made the determination of steps and weight carried unreliable as well. In the end, researchers decided to do a purely video-based analysis of maintenance and repair tasks along with task analyses.

Because of the issues with instrumenting workers and the variability in exposure to numerous risk factors for a range of injuries (e.g. musculoskeletal disorders, acute traumatic injuries, slips and falls) during maintenance and repair work, a systematic, simulated, real-time video-based observation study was conducted (Heberger et al. 2012). The objective was to develop a methodology to quantify ergonomic and safety risk factors for maintenance and repair work in mills and prep plants. Observed maintenance tasks were recorded with video, and included screen maintenance, greasing, conveyor belt splicing, conveyor roller maintenance, crusher maintenance and rod mill maintenance. Repair tasks included centrifugal drier repair, heavy mobile equipment repair and emergency repair work on several motors and pumps. A detailed taxonomy of environmental factors and postural risk factors was developed using 41 video clips. Due to the time demands associated with coding (approximately 25–30 min per minute of video), the study was not as extensive as originally planned.

A field study was undertaken to measure vibration exposure during different stages of the haul truck cycle (loading, travelling full, unloading, travelling empty) and to examine the effect of vibration exposure on haul truck drivers from four mines/quarries. Whole-body vibration (WBV) and hand-arm vibration exposures were measured for seven drivers from four different surface quarry mine sites (2 limestone, 1 sandstone, 1 copper). Mayton et al. (2016) provide detailed findings of the exposure levels, but overall many of the measurements were below consensus standards with the exception of two mine sites where haul roads were rougher and led to higher vibration levels. Whole-body vibration levels were also higher when the trucks were traveling empty compared to traveling while loaded.

In addition to vibration exposure, Pollard et al. (2017) collected postural stability parameters as a measure of standing balance during one of two shifts. These data were collected pre-, mid- and post-shift using an AMTI AccuGait portable force plate system following standard testing procedures. Similarly, on the other shift, finger tactile sensation and grip strength measures were collected for the haul truck driver/operator, also for the pre-, mid- and post-shift using Touch-test Sensory Evaluators on the index and pinky fingers of the dominant hand. Grip strength parameters were collected using a Noraxon Myotrace 400 system following standard grip strength testing procedures. The vibration data were then compared with the postural stability parameters and the finger tactile sensation and grip strength measures collected pre-, mid- and post-shift to determine if any correlation could be identified between vibration exposure and a decrease in performance in postural stability or tactile sensitivity measures. This analysis showed no significant effects of the recorded vibration exposures on the dependent measures.

2.4. Laboratory studies

With few exceptions, small bags were palletised for shipment. Most observed palletising operations were manual, with some using scissor-lift tables as an aid to reduce bending. While automation is the ideal solution for manual palletising stations and mechanical aids such as vacuum lifts are secondary, the authors wanted to provide recommendations for palletising stations layouts to minimise biomechanical loading when palletising could not be automated or mechanised. To this end, a laboratory study was carried out to investigate the effects of operator and pallet positions relative to the conveyor belt on biomechanical loading of the low-back (Gallagher and Heberger 2015). Positioning the pallet at the end of the conveyor resulted in significantly lower forward bending moments as compared to pallets placed at the side of the conveyor. The 11.3-kg bag weight used resulted in mean estimated peak compression forces above the 3400 N limit suggested by Waters et al. (1993). Bag weights up to 45.4 kg (100 lb) were observed in the field, with 18–22.7-kg (40–50-lb) bags being common. These results suggest that automating or mechanising palletising stations should be strongly considered.

Bulk bags (or flexible intermediate bulk containers) are used to deliver large amounts of material. Although FICBs are not manually handled when full, they need to be manually closed and sealed. The terms used for closing (‘snaking’ and ‘flowering’) were used to describe commonly observed techniques used to close bulk bags. Snaking denoted the bag material being twisted and then folded over on itself, while the flowering denoted gathering the bag material at the centre. Tools available on the market to seal bags include strings that were tied in a knot or bow by hand, cable/zip ties that were fastened by hand or with cable tie guns (trigger gun or pneumatic gun) and wire ties that were twisted closed with the use of mechanical devices. However, the physical demands associated with using these tools have not been adequately assessed.

A laboratory study investigated physical demands associated with closing and sealing FICBs (Nasarwanji et al. 2016). Closing bags using the flowering method required, on average, 32% less muscle activity, 30% less perceived exertion and 42% less time than snaking, and was preferred by participants. In terms of sealing, no tool was significantly better across all measures; however, using a pneumatic cable tie gun consistently had the lowest muscle activity and perceived exertion ratings, with similar completion times to other tools. Sealing spout-top FICBs, with less bag material at the mouth, required on average 13% less muscle activity, 18% less perceived exertion, 35% less time and was preferred by participants compared to sealing a duffle top bag with more bag material at the mouth. Closing a spout-top bag using the flowering method and sealing the bag using a pneumatic cable tie gun installed with a tool balancer were recommended when practical.

Most surface mine facilities have extensive grated metal walkways both indoors and outdoors. Fairly extensive travel on these was observed during the maintenance and repair field visits, in particular. Inspection, maintenance and greasing of conveyors are examples of frequently performed activities that require such travel. Given the high frequency of trip and fall injuries during maintenance and repair operations (Pollard, Heberger, and Dempsey 2014), a laboratory study was carried out to investigate slip and fall potential of several types of walkway gratings observed at mine sites (Pollard, Heberger, and Dempsey 2015). Normalised coefficients of friction were calculated for three types of walkway materials at 0°, 5°, 10°, 15° and 20°, during both contaminated and dry conditions, and for uphill and downhill walking. The fewest slips occurred during trials for a diamond weave grating compared to serrated bar or perforated gratings, and these findings form the basis of walkway grating recommendations, since many sites occasionally replace old walkways or add new walkways.

2.5. Task analysis

Task analysis is one of the most widely used and robust ergonomics tools for systematically analysing work requirements and opportunities for error. Task analysis was especially helpful for studying maintenance and repair operations. Similar task elements across tasks such as tool use and poor postures became evident. Task descriptions of bagging operations were used as a means of describing processes in different plants. These descriptions were later used to formulate module names, since bagging operations can be followed from raw material to pallet fairly easily.

Researchers completed most of the task analyses undertaken from watching videos of task performance, particularly for the more complex maintenance tasks. An earlier generic task description of maintenance activities also helped to structure the observations (see Drury, Porter, and Dempsey (2012)). This allowed the hierarchical task descriptions to be formulated, often in conjunction with notes taken in the field. Note that task descriptions had been used to structure earlier audit developments, e.g. Koli, Chervak, and Drury (1998).

3. Audit development

It was mentioned earlier that one of the desired features of the audits was to have modular audits. For this reason, the starting basis for developing the audits was determining the module structures for each of the three audits. For each of the three audits, members of the project team with direct involvement in each of the three audits drafted lists of potential modules based on the combined information obtained from the project phases described earlier. It was desired to have module names that were self-explanatory. Figures 1–3 show the final structures of the bagging, haul truck and maintenance and repair audits, respectively – each reflecting the individual nature of the three types of operations.

The bagging audit structure was somewhat driven by the fact that not all facilities have small and bulk bagging operations, and also that the two types of bagging are fairly different in terms of ergonomics and safety issues. However, the facilities issues tend to be similar so common issues were grouped in modules under Facilities. The grouping in Figure 1 reflects these characteristics, and also has intuitive appeal for easy explanation to mine personnel.

The haul truck audit structure was influenced by the fairly diverse ergonomics and safety issues that impact the safety of haul truck operators. Figure 2 shows the haul truck audit organisation, which was driven by characterising the auditor interaction: the modules under Mine/Safety Manager are completed by interacting with mine management, the observation module is completed while observing different areas of the mine property and the remaining modules are completed while interacting with and observing the driver. The groupings are also intuitive and modules in each group can be conveniently conducted together. Training and policy features were found to provide the overall foundation for safety efforts, while the physical design and maintenance of the mine site such as roadways and berms influence the safety of the haul truck and driver throughout the operation cycle.

Figure 3 shows the maintenance and repair audit structure, which is the most complex due to the nature of the varied factors found to influence the safety and health of maintenance and repair workers. The administrative and facility level modules cover aspects of how maintenance jobs and associated safety components are managed as well as characteristics of the facilities in which they occur, respectively. The pre-maintenance and all maintenance tasks modules are carried out prior to and during maintenance processes. Finally, specific maintenance tasks modules were developed for maintenance tasks common to all types of preparation and processing plants and performed regularly by miners. For example, a number of plants were observed that required half or whole shifts of greasing performed by an operator.

It should be noted that two of the maintenance and repair audit modules utilised published checklists. The thermal stress questions from ISO Standard 15265 (ISO (2004)) were used for the thermal questions of the 'Environmental Factors' module. The 'Hand Tool Use' module was based on the hand tool use checklist provided by Hight et al. (2004). All other questions and modules were developed by the authors.

The recommendations were developed using several sources of information. The first source was good examples of ergonomics implementations that we observed during field visits. A simple example is a table crafted in a plant machine shop that was used to raise a scale from the floor to waist height. This eliminated the need to bend to place and remove bags that needed to be weighed. Other recommendations came from accepted ergonomics principles from texts or other publications, MSHA safety and training materials and results of laboratory and field studies described earlier.

Due to the length of the audits and recommendations, they cannot be included here but are available for download at http://www.cdc.gov/niosh/mining/works/coversheet1906.html. Appendix 1 gives an example of a representative module, as well as the recommendations for each of the questions the user would receive if they answer the questions as indicated in the first sentences of each recommendation. Alternately, a free NIOSH-developed Android app called ErgoMine can be downloaded on Android devices by searching the Google Play store for ErgoMine.

4. Audit testing

Once the audits were drafted, the authors reviewed those audits or audit modules that they did not write. Questions that were not clear were revised by the team in an iterative manner until there was consensus. Following these reviews, a colleague familiar with mining but not involved in the project was then asked to review the questions for clarity. Changes were made based on those recommendations.

Once a final internal review for clarity and grammar was completed, the audits were field tested with mine safety personnel at four mine sites (one graphite processing plant and three sandstone processing plants). One or two of the authors accompanied the auditor as he or she audited the operations. The authors asked auditors to make verbal comments about questions that were not clear, issues with answers such as missing response options (e.g. sometimes added to yes/no question) and any additional feedback. In general, the feedback was that the audits were relevant and detailed. Questions and answers were changed as appropriate based on the feedback.

Once the revisions were made, a reliability study similar to that conducted by Koli, Chervak, and Drury (1998) was carried out via a contract with The Ergonomics Center of North Carolina. Four Certified Professional Ergonomists completed the reliability study. It was not practical to have four persons observe mining operations simultaneously, so it was decided to use video of relevant operations to perform the testing. The authors had extensive video of the three types of mining operations, and representative videos were used. Audit content from Koli, Chervak, and Drury (1998) used for the current audits or the environmental questions from the ISO standard were not retested. All current questions could not be tested in this manner, such as policy questions asked of mine management, but most questions requiring observations could be tested with video. Fifty-three questions were tested for the bagging audit, 83 questions were tested for the maintenance and repair audit and 59 questions were tested for the haul truck audit.

Since the sample size was limited due to practical and financial constraints, the authors examined every question where all four reliability participants did not answer the question the same. The participants were also permitted to provide any written feedback if they felt it was warranted. All of the questions with discrepancies were examined by the authors, and changes were made to the questions or answers to address potential reasons for lack of reliability. For example, one question asked about the height of the hands during sealing bags. The question was clarified by asking for the highest height of the hands during sealing.

Twenty-two questions (42%) were retested for the bagging audit, two questions (2%) were retested for the maintenance and repair audit and seven questions (12%) were retested for the haul truck audit. The revised questions were then retested using the same videos and participants to determine if the issue was remedied, and in each case the reliability issues were resolved. For the bagging questions, three sets of answers had discrepancies but these were deemed to be at least partially attributable to the lack of three-dimensional information available from the video. For example, a question asked ‘Do workers ever slide bags while on the conveyor before they are lifted?’ and two responses were yes and two were No. The worker’s back was to the camera making the assessment difficult.

5. Discussion

The audits developed and described here represent a context-specific approach to developing tools that can assist those without significant formal training in ergonomics with identifying ergonomics deficiencies. The maintenance and repair and bagging audits, particularly, are examples of relatively simple semi-quantitative tools that can be used to allow mine safety personnel to perform risk assessments of manual tasks as advocated by Horberry, Burgess-Limerick, and Fuller (2013). A unique aspect of the audits is that recommendations are made for each audit item where a deficiency is noted, and the electronic version provides a tailored report with only those recommendations relevant to the particular site.

Overall, there has been little research reported in the literature on auditing as an ergonomics tool, although there is considerably more research on checklists (see Drury and Dempsey 2012). In fact, there is limited information on the development process for a number of tools in use. The research programme used to develop these audits was fairly diverse, and the auditing approach is an effective means of creating a tool that can be used in the field to identify and remediate ergonomics and safety deficiencies. A similar and successful approach was used by David et al. (2008) to create the Quick Exposure Check (QEC) for assessing exposure to musculoskeletal disorder risk factors by occupational safety and health practitioners. Although more general than the audits described here, they performed more extensive reliability, validity and usability testing. Functionally, the observations required by QEC and the audits reported here are very similar.

Observational methods are commonly used by ergonomists (Dempsey, McGorry, and Maynard 2005), and the authors feel that the auditing method was an appropriate choice for the intended population, which is often experienced at performing observations as part of the company’s or site’s safety and health process. Providing solutions to identified problems was also important, as the ultimate goal of the audits is to encourage mines to correct ergonomics and safety deficiencies. One of the findings of the survey of practitioners by David et al. (2008) was that the respondents felt that a scoring system was an essential requirement for an exposure tool. Although our audits are amenable to providing specific recommendations to identified problems, the more general QEC requires interpreting exposure values. In a sense, a scoring system interprets the response and provides guidance to the user. Future tool development should consider the importance of providing recommendations or interpretation to users.

Broadly speaking, the audits developed here, those developed by Koli et al. (1998), and the QEC (David et al. 2008) are examples of considering the requirements of the end user responsible for applying ergonomics to develop usable and useful tools for practitioners (the ergonomics of ergonomics?). Common to the three approaches was a primary consideration to understand the underlying ergonomics deficiencies of interest. Table 1 summarises our approach, but a main strength of this approach is that it can be modified and adapted to a wide range of human performance issues in other occupational or leisure pursuits. At this stage, significant ergonomics expertise is required to define those deficiencies and choose how to assess them with the eventual audit. Our approach was slanted towards occupational safety, and rather different approaches can be taken as required by the nature of the ergonomics deficiencies. Although some ergonomics issues are too complex for observational methods, the authors believe many contexts are amenable to auditing. Secondary to content was developing reliable and valid tools for practitioners. This stage requires effort to make sure the audits are developed considering the user requirements and expectations, as well as encouraging reliable observations. The three studies mentioned provide concrete examples and methodologies that can be adapted to other contexts.

5.1. Comparison of content sources

Comparing and contrasting the current audits with those developed by Koli, Chervak, and Drury (1998) illustrates how audit content can be developed with sources most relevant to the given context. The three audits reported here are rather different as illustrated in Figures 1–3, suggesting a certain amount of robustness of modular auditing as an ergonomics tool. The nature of the work being audited can be accommodated by developing modules specific to the ergonomics issues uncovered during data collection.

Although aircraft and mining plant maintenance appear rather different, there were quite a few commonalities between audits developed previously by Koli, Chervak, and Drury (1998) and those described here. Basic ergonomics issues such as handling materials, postural demands and hand tool design were the same, but identified deficiencies such as those associated with grated outdoor walkways were specific to mining. The modular design utilised in both efforts affords the ability to easily customise the audit structure to the requirements of the context under study.

Table 1 gives an overview of the sources of audit content discussed earlier, as well as a brief assessment of strengths and weaknesses of each approach. Although a number of the data sources were planned a priori, several others were opportunistic such as maintenance records provided by some collaborators. In each case, the source was determined to have information either about identifying ergonomics and safety deficiencies or about potential solutions to identified deficiencies. While several of the sources are more time- and resource-intensive (observation/interview, task analysis, laboratory studies and field studies), the remainder were not. One advantage of the audit approach is that these disparate sources of information can be neatly organised using the modular audit structure.

5.2. Limitations

The context-specific nature of the audits can be considered a limitation, but this also raises the interesting question of whether certain modules can be used outside of the intended mining operations. For example, a considerable overlap between the bagging audit palletising content and palletising issues in production environments exists. Before suggesting other uses, the authors recommend assessing content validity and modifying or adapting the audits content if warranted.

One difference in the development of the audits described here to the aircraft maintenance audit described by Koli, Chervak, and Drury (1998) is that the current audits were not tested for validity in the same manner. Koli, Chervak, and Drury (1998) compared the number of ergonomics issues identified by a completed audit compared to expert ergonomists performing ergonomics assessment unaided. The audits reported here also contain safety issues typically found in these contexts and therefore the audits were not strictly ergonomics in that some of the issues identified could be considered more in the occupational safety domain – particularly mining safety issues with which most ergonomists would not be familiar. Conversely, comparing the audits to the responses of participants drawn from the intended user population would not be appropriate either, since mine safety personnel rarely have formal ergonomics training. The audits would undoubtedly identify more ergonomics issues. That said, given the thoroughness of the audits and the amount of time spent and broad range of content that contributed to the content validity, the authors do not believe this is a significant limitation.

Although significant effort was made to uncover as many of the ergonomics and safety issues present in the different operations, the authors realise that the audits will not likely identify all issues in a relevant operation. However, we do feel that using the multiple, complementary methods to achieve content validity minimises the possibility of omitting important audit items.

The final limitation is that the reliability assessment and testing was conducted with a limited sample of field tests and formal interrater reliability tests. While this reliability testing was more substantial than reported testing for a number of observational ergonomics tools, the testing did not cover all potential mine sites or auditor characteristics.

5.3. Future research

As mentioned earlier, additional research will be needed if the audit content is extended to other types of environments such as manufacturing palletising operations, construction tasks with similar demands to maintenance and repair or other identified potential applications. In such a case, the amount of research required will be considerably less than what was reported here.

A second area of future research is investigating how users choose to implement (or not) the recommendations provided by the audits. Ultimately, the ability of the audits to identify issues that will then be resolved is the goal of the audits, and this can only be determined through planned studies. The recommendations are extensive, and few ergonomics tools include such detailed and comprehensive recommendations.

Finally, given the resources required to develop these audits, future research should be conducted to adapt or apply applicable content to work in other industry sectors. While the haul truck audit is fairly specific to mining, the bagging and maintenance and repair audits have content applicable to other industries. For example, the palletising-related modules could be easily modified to apply to palletising commonly found in manufacturing and related sectors. As long as the content validity can be established for existing modules for applicability outside of mining or for adaptations of existing modules, the utilisation of the audits can be extended.

6. Conclusions

Audits for three types of mining operations were developed using a broad range of content sources. The three types of operations were quite different, and the development process was robust to these differences. Taken together with the audit developed by Koli, Chervak, and Drury (1998), the results suggest that auditing has potential to be more widely used as a tool to implement ergonomics assessments to be completed by both ergonomists and non-ergonomists. While the audits reported here required considerable resources, the process can be scaled to ergonomics assessments of different types and applications.

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Appendix 1. Example Module and Recommendations

Module 9: Sealing

This module asks about characteristics of the sealing process such as methods and worker posture. This module should be completed for each small bag sealing station. This module requires a tape measure.

9.0 Input a name for the small bag sealing station you are currently evaluating:

____

9.1 How is the bag sealed?

- **a.** Manual process such as rolling or folding the top of the bag
- **b.** Semi-automatic process such as manually feeding the bag through the sealing machine or using a sealing machine that requires manual control

9.2 Part 1: Is sealing performed standing or sitting?

- **a.** Standing
- **b.** Sitting

Part 2: What is the highest height of the hands when sealing is performed (measured to the highest position of the middle knuckle, Figure 9.1). *If the worker is standing*, measure from the surface the worker is standing on (e.g. Figure 9.2); *if the worker is sitting*, measure from the seat of the chair.

Fill in the blank: Height: ___ in

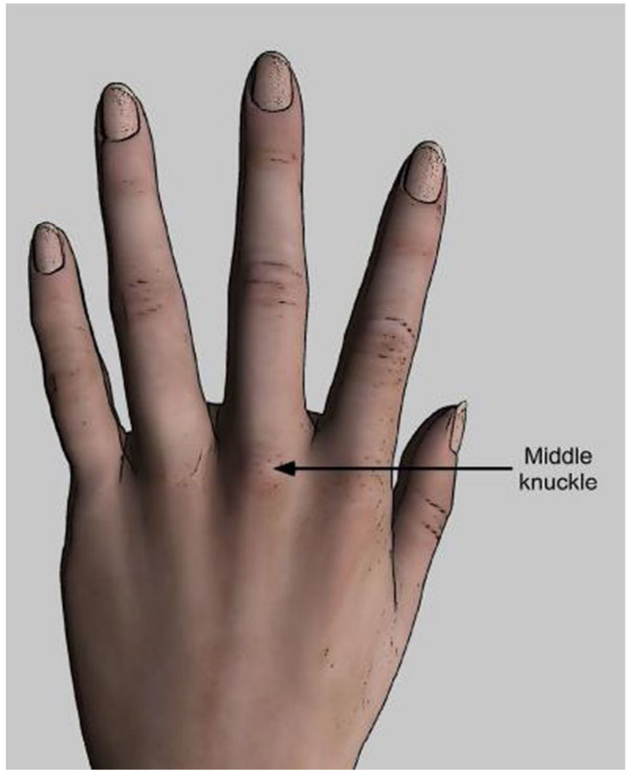

Figure 9.1.
The middle knuckle is the knuckle between the middle finger and the back of the hand.

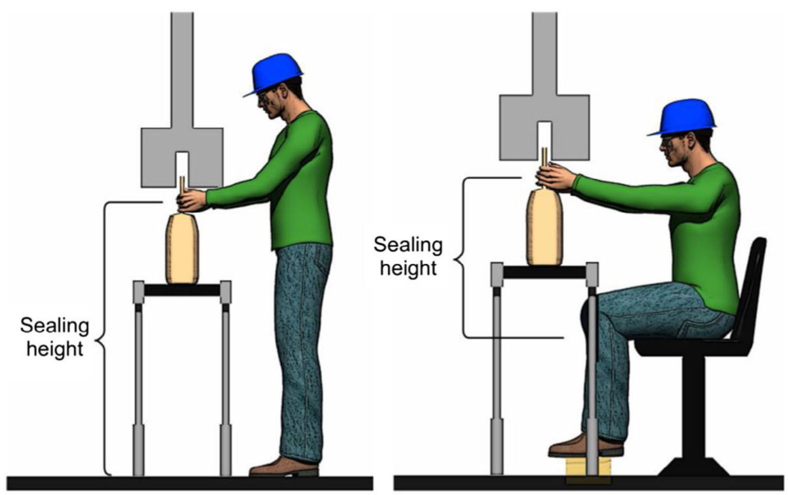

Figure 9.2.
When the worker is standing, the height of the hands is measured from the surface the worker is standing on to the highest position of the middle knuckle when performing the sealing task If the worker is sitting, the height is measured from the seat of the chair the worker is sitting on to the highest position of the middle knuckle.

9.3 Does the worker support the weight of the bag during the sealing process? **Yes / No**

9.4 How often is a pinch or wide finger grip observed during bag sealing (e.g. Figure 9.3)?

a. Rarely

b. Sometimes or Frequently

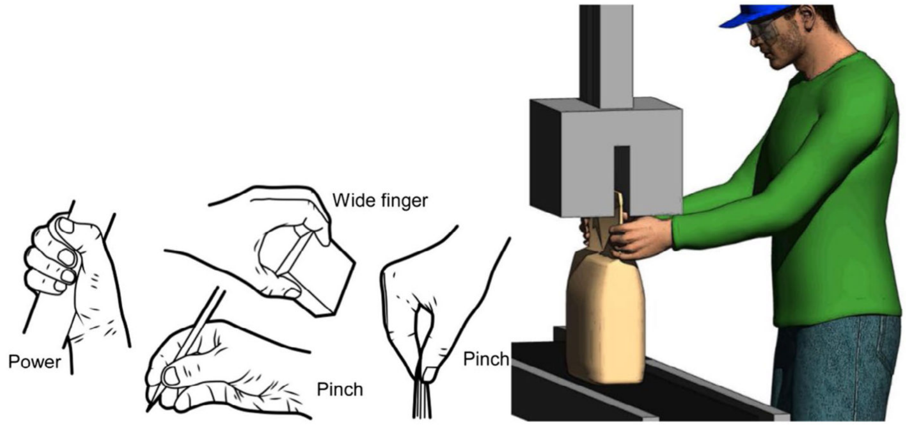

Figure 9.3.
Types of hand grips (left) and example of pinch grip during sealing (right).

9.5 How often is wrist bending or deviating observed during bag sealing (e.g. Figure 9.4)?

a. Rarely

b. Sometimes or Frequently

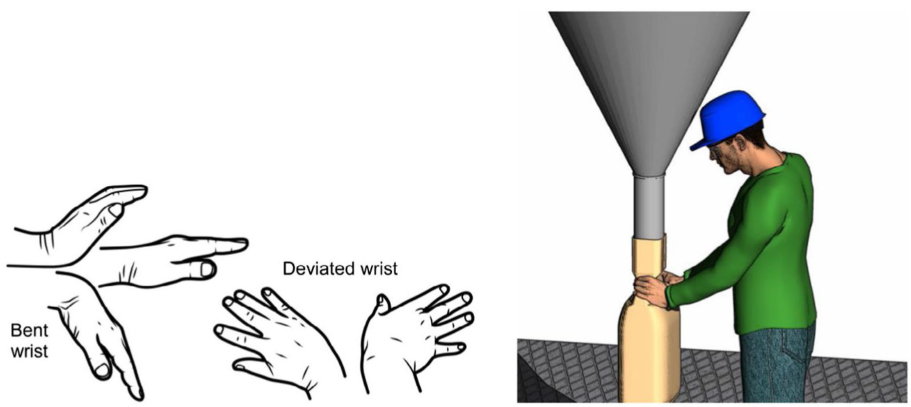

Figure 9.4.
Types of wrist postures (left). Wrist bending and deviating during sealing (right).

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Recommendations

(Q 9.1 a) You indicated that bags are sealed using a manual process. Consider using self-sealing bags or sealing the bags through semi-automatic sewing or heat sealing. This will reduce repetitive motions during manual sealing.

(Q 9.1 b) You indicated that bags are sealed using a semi-automatic process. Consider automating the process to feed the bags through the sealing machine (e.g. a system that closes the bag and feeds it through a sealing device). If a hand-held tool is used to seal the bags, the tool should be supported from beneath, suspended from above, or mounted to support its weight while in use and eliminate the need for repetitive lifting. Ensure that the tool is stored around 30 in from the floor to eliminate unnecessary bending to access the tool, and that it is counterbalanced.

(Q 9.2 part 1 is a and part 2 height ≠ 42 OR part 1 is b and part 2 height ≠ 9) You indicated that sealing is performed at a non-ideal height. To reduce the risk of injury, sealing should be performed at approximately elbow height (around 42 in above the ground when standing or 9 in above the seat of the chair when sitting).

(Q 9.3 yes) You indicated that the worker supports the weight of the bag during sealing. Supporting the bag can cause excessive strain on the hands and arms. Install a platform for the bags to rest on during the sealing process, or allow the sealing mechanism to move to the height of the supported bag.

(Q 9.4 b) You indicated that a pinch or wide finger grip occurs during sealing. Prolonged use of these postures can cause inflammation and pain in the hands/fingers. Ideally, the sealing process should be automated to eliminate the need for manual handling of bags. If this is not possible, encourage workers to hold the bags with a neutral hand posture (straight wrist) or use a tool that requires a power grip.

(Q 9.5 b) You indicated that wrist bending or deviating occurs during sealing. Prolonged wrist bending and deviation can cause inflammation and pain in the wrist, and may lead to repetitive trauma disorders such as carpal tunnel syndrome or tendonitis. Ideally, the sealing process should be automated to eliminate the need for manual sealing of bags. If this is not possible, encourage workers to maintain a neutral (straight) wrist whenever possible.

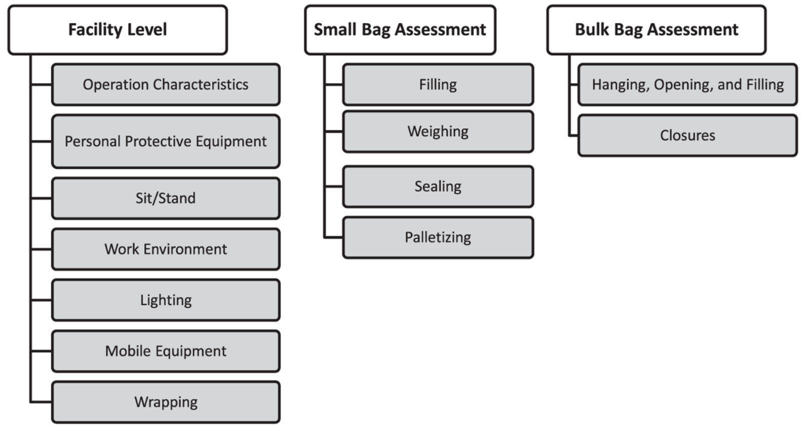

Figure 1.
Structure of bagging audit modules.

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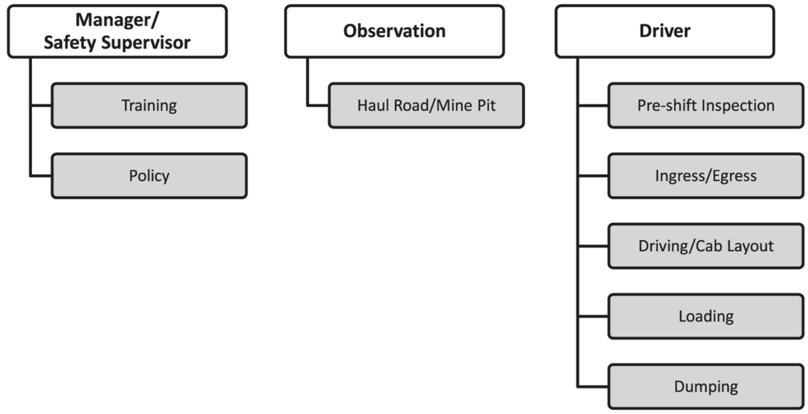

Figure 2.
Structure of haul truck modules.

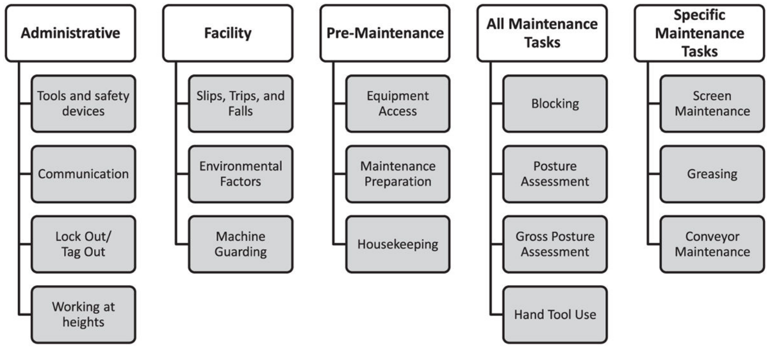

Figure 3.
Structure of maintenance and repair audit modules.

Table 1

Comparison of information sources used to develop audits (adapted and expanded from Dempsey et al. 2012).

Content Input	Strengths	Weaknesses
Surveillance data*	• Low cost and readily accessible • Easy identification of attributed causes of most frequent and severe injuries	• Ergonomics issues typically not identified • Potential for misclassification • Do not capture near misses or events without injuries or fatalities
Fatality/accident reports	• Often detailed descriptions of equipment, environment, operators and task(s) being performed at time of accident • Can be used to identify rare events that may not be captured by any of the other sources	• Typically not conducted by ergonomists which may limit reporting of and inference about ergonomics issues that contributed to accident
Observation/interview*	• Provide detailed user insight • Experienced operators can often quickly identify key ergonomics issues	• Operators may feel compelled to perform tasks in certain ways when observed • Some operators reluctant to be observed or interviewed
Task analysis*	• Task descriptions provide detailed structure and content of tasks • Level of detail can be tailored to the requirements of the analysis	• Time consuming • Can be difficult to observe all tasks • Maintenance tasks (other than preventive) in particular may be difficult to observe due to ad hoc timing
Field studies*	• Provide detailed information on ergonomics deficiencies and exposures	• Higher costs and time • May be biased due to potential observer bias • Must be tailored to the nature of the individual type of operation being studied
Laboratory studies*	• Highly specific results that provide detailed audit items or solutions to audited items • Allow for control rarely afforded by mining environments	• Higher costs and time • Narrow applicability of results (typically)
Laws/regulations	• May assist users with compliance	• Makes using audits in multiple jurisdictions (e.g. province or country) difficult
Consensus standards	• Content is often vetted by leading experts • Cost- and time-effective	• Content cannot be modified to fit situation, or if modified would no longer represent the standard
Maintenance records and production documentation	• Readily available • Allow trends to be quickly identified • Allow determination of frequently performed operations and tasks	• Content will vary considerably from company to company • Nomenclature often company-specific • Production documents have implications for ergonomics risk factors but do not provide documentation of them • Do not capture related injuries
Work documentation (training materials/	• Readily available	• Best case scenario

Content Input	Strengths	Weaknesses
standard operating procedures, etc.)	• Required by MSHA • Detailed description of 'safe' procedures	• Planned work may differ from how employees actually do work • May not be up to date

*Indicates items originally planned to be included.