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Ergonomics Issues in Mining

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106.1   Introduction

It was not too long ago that coal and ore from underground mines were shoveled or manually loaded onto carts drawn by horse or mule (Sanders and Peay, 1988). As recently as the mid-1950s, almost a third of all coal produced in the U.S. was still hand-loaded. In the years prior to the introduction of mechanization, mining was truly backbreaking work. The principal tools of the miner were the pick and shovel, powered solely by raw muscle. Figure 106.1 illustrates a common task of the underground miner of this period: undercutting a coal face in preparation for blasting. As shown in Figure 106.1, this task was performed while the miner was lying on his side, using a pick to hew the coal and a shovel to support the body. Miners could spend three to six hours undercutting a coal face, using their picks to make a one meter deep horizontal incision at the base of the mineral seam.
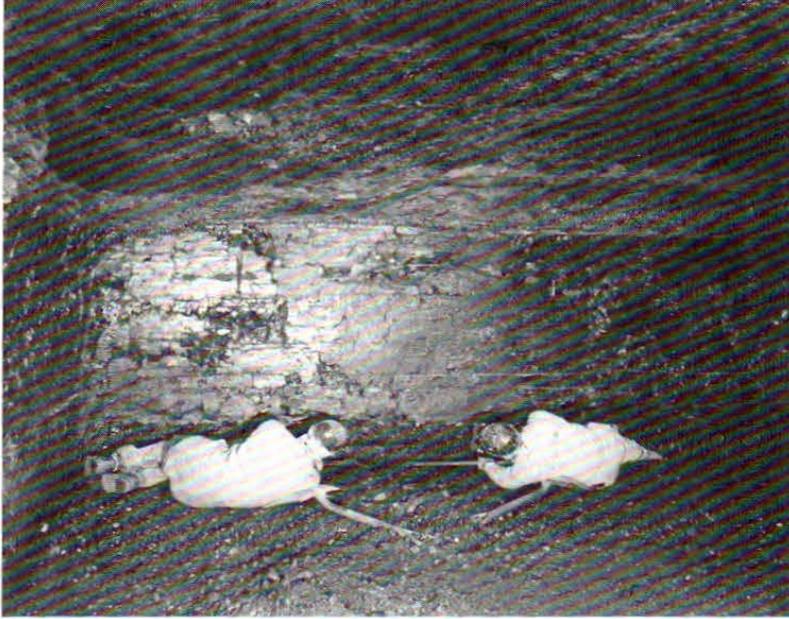
FIGURE 106.1   Miners undercutting a coal face prior to mechanization. (From National Archives. With permission)

Advances in mechanization in the second half of the 20th century have greatly reduced physical demands on the mine worker. Even so, mining remains among the most physically demanding occupations. While the overall magnitude of physical work performed by the miner has been reduced, many unique physical and environmental demands remain. For example, miners may have to deal with restricted workspace, less than desirable illumination, muddy or wet floor conditions, high levels of whole-body vibration, and considerable heavy lifting. Of the stressors listed above, the most demanding environmental characteristic of underground mines is undoubtedly the limited vertical workspace in which many miners must function. The impact of this single factor on human-centered design is extraordinary. The significant injury experience in the mining industry is undoubtedly the consequence of the multiplicity of risk factors present in this environment.

106.2   Epidemiology of Work-Related Musculoskeletal Disorders (WMSDs) in Mining

There is compelling evidence that work-related musculoskeletal disorders (WMSDs) affect mineworkers to a greater degree than workers in other industries (Lockshin et al., 1969). For example, studies have shown that miners experience more disability from knee and back pain (Lawrence, 1955; Lawrence and Aitken-Swan, 1952), more absenteeism (Duthie and Anderson, 1962), more osteoarthritis (Kellgren and Lawrence, 1952; Schlomka et al., 1955), and more disk degeneration (Kellgren and Lawrence, 1952) than comparison industrial populations. Back injuries emerge as a particularly serious problem in mining. A study by Klein et al. (1984) reported that the mining industry had the second highest incidence ratio for back injuries (1.5 claims/100 workers), trailing only the construction industry (1.6 claims/100 workers). Such injuries are consistently the single leading cause of lost-time injuries in U.S. coal mines (Peay, 1983), an experience shared by their international counterparts (Leigh et al., 1991). These injuries typically result from overexertion during the performance of manual materials handling tasks (Peters, 1983).

Manual handling of heavy materials is a pervasive activity in mining, and has been identified as a major contributing factor to sprain and strain injuries (Peay, 1983). The combination of heavy lifting and punishing environmental constraints has been linked to spinal changes in some studies. Lawrence (1955) examined British coal miners to identify factors related to degenerative disk changes, and found that injury, duration of heavy lifting, duration of *stooping*, and exposure to wet mine conditions were

the factors most associated with spinal changes. Another study investigating spinal changes in miners was reported by MacDonald et al. (1984). These investigators used ultrasound to measure the spinal canal diameter of 204 coal miners and found that those with the greatest morbidity had significantly narrower spinal canals. The study by Lawrence (1955) and other evidence suggests that the seam height of the mine has a marked influence on the incidence of low back disorders. In general, compensation claims appear to be highest in seam heights of 0.9 to 1.8 meters (where stooping is prevalent). Claims are slightly lower in seams less than 0.9 meters (where kneeling and crawling predominate), and are substantially reduced when the seam height is greater than 1.8 meters. The finding of increased low back claims in conditions where stooping predominates is in concert with other evidence relating non-neutral trunk postures to low back disorders (Punnett et al., 1991). It is not surprising, given the physical demands and environmental constraints, that a field survey performed by the National Institute for Occupational Safety and Health (NIOSH) found that exposure to ergonomic hazards for miners was high compared to nonmining industries (Winn and Biersner, 1992).

While back injuries are more frequent in mining than in other industries, upper extremity CTDs do not appear as severe. This should not be too surprising since mining does not typically require highly repetitive or forceful exertions by the hands. As a result, the incidence rate of carpal tunnel syndrome is relatively small in mining (Hudock and Keran, 1992); however, it must be noted that a steady increase in the number of reported cases has been observed in recent years (MSHA, 1991). It is not clear whether this increase is due to changes in workplace factors (i.e., increasing use of remote controls or repetitive exertions in *roof bolter*'s tasks), or is a reporting artifact resulting from increased media attention given the disorder during this period.

# 106.3   Characteristics of the Underground Mining Workforce

Demographics

In 1986, the U.S. Bureau of Mines conducted a probability sample survey, the Mining Industry Population Survey (MIPS), to assess demographic characteristics of the United States mining workforces (Butani and Bartholomew, 1988a, 1988b). While the MIPS is by now somewhat dated, it remains our most recent look at the U.S. mining population, and contains several notable demographic findings. One finding that stands out is the almost exclusive dominance of male workers in the coal mining workforce. Ninety-eight percent of the coal workforce is male, and of the 2% that are female, only half work underground. Almost as dramatic is the dominance of Caucasians, comprising 94% of the total coal workforce. The cultural makeup of metal and nonmetal mines was a bit more varied, with whites, blacks, and Hispanics representing 82, 7, and 8% of the workforce, respectively. The difference in cultural makeup between coal and metal/nonmetal mines may be largely the result of the geographic location of the various types of mines. At the time of the survey, the average age of the coal workforce was 39; however, recent anecdotal evidence suggests that the mean age of the coal miners is now well into the 40s. Thus, ergonomics researchers and industry committees must consider the physical and cognitive effects of an aging workforce when carrying out ergonomics interventions.

Anthropometry

Physical characteristics of the underground mining population have been reported by several authors (Moss, 1934; Gary et al., 1955; Humphreys and Lind 1962, Ayoub et al., 1981b; Ayoub et al. 1984; Gallagher and Hamrick, 1992). By far the most in-depth studies (in terms of measures taken and sample size) are those by Ayoub and colleagues (Ayoub et al., 1981; Ayoub et al. 1984). These authors collected a battery of 42 anthropometric measurements for two major segments of the mining population: (1) low coal miners, and (2) non-low coal miners. Data for each of these populations were compared with those of other occupational groups to detect whether significant differences were evident. Comparison of the anthropometry of low coal miners vs. comparison industrial groups showed that miners were heavier,
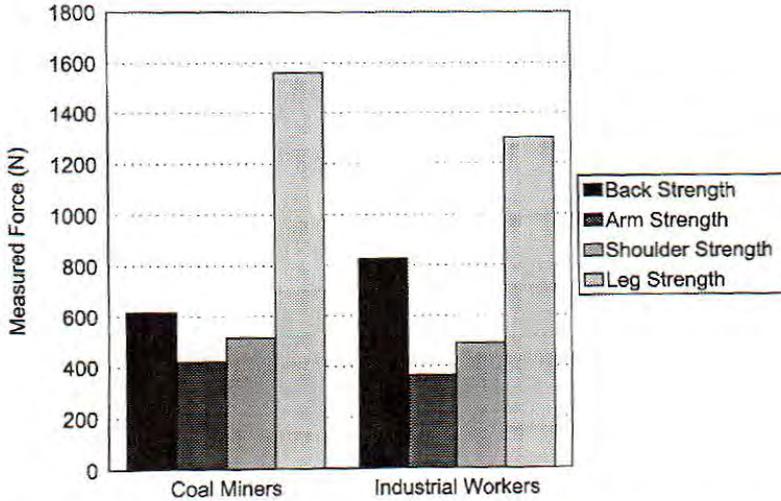
FIGURE 106.2 Comparison of strength measurements between low-seam coal miners and a traditional industrial population. (From Ayoub, M. M., Bethea, N. J., Bobo, M., Burford, C. L., Caddel, K., Intaranont, K., Morrissey, S., and Selan, J. 1981a. *Mining in Low Coal. Volume 1: Biomechanics and Work Physiology.* Final Report — U.S. Bureau of Mines Contract No. HO3087022. Texas Tech University, Lubbock, TX.)

and exhibited a related increase in the circumferences of the torso, arms, and legs (Ayoub et al., 1981b). Male low coal miners were also somewhat heavier than miners not working in low coal; however, the opposite trend was observed with female miners. Females working in non-low coal were also larger in all measures of circumference. This difference may be attributed to tasks performed, and varied geographical and ethnic makeups of the two groups.

Strength Characteristics of Miners

Various measures of isometric strength of underground miners were also obtained by Ayoub et al. (1981a) and Ayoub et al. (1984). These included back strength, shoulder strength, arm strength, sitting leg strength and standing leg strength. When compared with a sample of industrial workers (Ayoub et al., 1978), low-seam coal miners were found to have significantly lower back strength, but much higher leg strength (Figure 106.2). The authors ascribed the decrease in back strength to unspecified factors related to the postures imposed by the low-seam environment. Indeed, there is evidence to support this position. Low coal miners may be obliged to work in a stooping posture for extended periods. In this posture, the spine is largely supported by ligaments and other passive tissues, "sparing" the use of the back muscles. Studies of lifting in the stooping posture suggest that the gluteal muscles and hamstrings provide a large share of the forces in this position (Gallagher et al., 1988). The results of Ayoub et al. (1981a) may be due to a relative deconditioning of back muscles when stooping (due to relative inaction), and an increased reliance on the leg and hip musculature to perform underground work tasks (producing an increase in leg strength).

Aerobic Capacity

Several studies have investigated the maximal aerobic power of underground miners, using estimation techniques (Ayoub et al., 1981; Ayoub et al., 1984) or direct measurement (Kamon and Bernard, 1975; Kamon, Doyle, and Kovac, 1983). Most studies appear to agree that underground miners are inclined to have lower than average aerobic capacity compared with population norms and to comparison groups. The trend is evident for both genders (Ayoub et al., 1981a; Ayoub et al., 1984), and might be related to the finding, reported above, that underground miners exhibit increased body weight when compared with other groups. Kamon and Bernard (1975) found a steeper drop in maximal oxygen uptake and

heart rate with age in miners than in other published data. However, it should be noted that other data has not shown as steep a decline (Ayoub et al., 1984).

106.4 Demands of Physical Work in Underground Mining

Imagine arriving at work one day to find that the ceiling of your workplace had been inexplicably lowered to 120 cm (approximately 4 ft.) above the floor. The impact of this restriction in workspace on the ability to perform normal work functions becomes immediately apparent. What once were routine tasks (for example, simply walking down the hall) suddenly become enormously demanding. Instead of walking erect, one is forced to walk fully bent over at the waist. Imagine further that part of your job for the day required considerable manual handling of heavy materials, for example, lifting or carrying 23-kg bags from one end of the hall to the other. As this scenario is contemplated, one can begin to get a picture of the unique physical demands that are present in the coal mining environment. As difficult as it may be to believe, the environmental restrictions described above might seem luxurious to some miners. Occasionally, miners perform physical work in vertical space restrictions so severe that crawling is not even possible. While this represents an extreme case, it is not at all uncommon for the mine to be any higher than 1.2 meters. In fact, about half of all coal mines in the U.S. fit this category. As will be discussed in this section, the physiological and biomechanical demands of doing manual work in such an environment are much greater than if this constraint were not present.

Daily Energy Expenditure of Miners

Before mechanization, the energy expenditure of underground coal miners remained relatively high throughout the workday. A study by Moss (1934) showed that the average daily energy expenditure for a coal miner before mechanization was approximately 4500 kilocalories per day. Rest periods were not of sufficient length to bring the oxygen consumption back down to a normal resting level. Modern mining, on the other hand, is characterized by short bursts of high energy expenditure tasks, interspersed with periods of rest or lower energy tasks. Figure 106.3 illustrates the ventilation volume and oxygen uptake for a roof bolter helper in a low-seam environment (Ayoub et al. 1981a). As can be seen in this figure, the roof bolting cycle contains periods where the energy expenditure is greater than 2 liters/min, and other periods where recovery is possible. The introduction of more frequent rest breaks from increased mining mechanization appear to be reflected in the reduction in shift energy expenditure of the coal miner. Depending on the specific job title of the miner, shift energy expenditures for miners in the late 1970s were found to range between 2100 and 2800 kcals (Ayoub et al., 1981a). However, it should be noted that these values are still at or above proposed maximum permissible limits for daily energy output for men (Banister and Brown, 1968; NIOSH, 1981).

Energy Expenditure for Specific Mining Tasks

Several studies have examined the energy expenditure of performing specific underground mining tasks (Ayoub et al., 1981a; Ayoub et al., 1984; Durnin and Passmore, 1967; Moss, 1934; Gary et al., 1955). Table 106.1 provides a summary of energy expenditure data for mining tasks from these sources. As can be seen from this table, many mining tasks fit into the category of heavy work (5.0 to 7.5 kcals/min), or very heavy work (7.5 to 10.0 kcals/min), based on the classification suggested by Astrand and Rodahl (1977). The table presented here is not exhaustive. Additional data on energy expenditure requirements for mining tasks are available (Durnin and Passmore, 1967; Ayoub et al., 1984).

Effects of Posture on Metabolic Cost

The posture adopted in the performance of a work task has a decided influence on the metabolic demands incurred by an individual. Nowhere is this more evident than in the evaluation of metabolic demands of working in constricted mining workspace (Moss, 1934; Bedford and Warner, 1955; Humphreys and
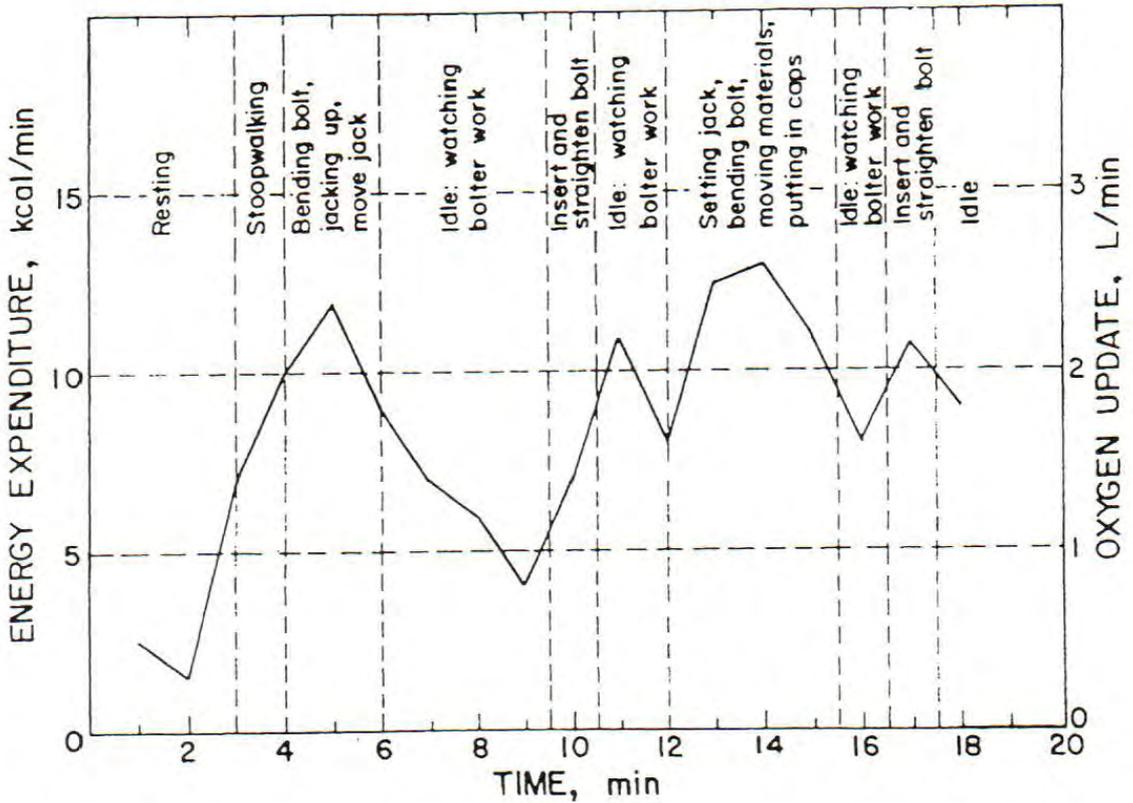
FIGURE 106.3 Energy expenditure and activity profile for a roof bolter helper. (From Ayoub, M. M., Bethea, N. J., Bobo, M., Burford, C. L., Caddel, K., Intaranont, K., Morrissey, S., and Selan, J. 1981a. *Mining in Low Coal. Volume 1: Biomechanics and Work Physiology.* Final Report — U.S. Bureau of Mines Contract No. HO3087022. Texas Tech University, Lubbock, TX.)

TABLE 106.1   Energy Expenditure for Selected Mining Tasks

Activity	Mean Energy Expenditure (kcal/min)	Standard Deviation	Range
Shoveling Coal			
Durnin and Passmore (1967)	7.0	—	5.1–9.4
Ayoub et al. (1981)	9.3	3.0	—
Garry et al. (1955)	6.9	0.9	—
Erecting Roof Supports	5.7	—	4.2–10.1
Helping			
Low Coal (Ayoub et al., 1981)	7.2	1.7	—
Non-Low Coal (Ayoub et al., 1984)	5.7	2.1	—
Roof Bolting			
Low Coal (Ayoub et al., 1981)	4.9	1.5	—
Non-Low Coal (Ayoub et al., 1984)	5.6	1.5	—
Timbering			
Ayoub et al. (1981)	6.0	2.4	—
Garry et al. (1955)	5.7	1.5	—
Humphreys and Lind (1952)	6.0	—	—
Scaling Roof (Ayoub et al., 1984)	8.5	—	—
Rock Dusting (Ayoub et al., 1984)	7.6	—	—
Moving Cables (Ayoub et al., 1984)	7.1	—	—
Jackleg Drilling (Ayoub et al., 1984)	7.1	—	—
Machine Maintenance (Ayoub et al., 1984)	6.2	—	—
Track Maintenance (Ayoub et al., 1984)	7.2	—	—

TABLE 106.2   Physiological Cost of Erect Walking, Stoopwalking, and Crawling

Task	Sex	Heart rate (beats/min)	Ventilation volume (L/min)	Percent Work Capacity	Oxygen uptake ($ml * kg^{-1} * min^{-1}$)
Normal Walk	Male	89.2 (5.4)	10.6 (0.4)	10.9 (0.9)	5.0 (0.9)
	Female	89.7 (3.6)	9.6 (0.7)	11.6 (2.2)	4.4 (0.6)
90% Stoopwalk	Male	96.0 (9.3)	12.8 (0.9)	12.5 (2.0)	5.7 (1.4)
	Female	107.5 (6.8)	12.4 (1.8)	15.3 (2.9)	5.8 (0.4)
80% Stoopwalk	Male	86.8 (15.8)	13.9 (1.8)	14.7 (2.3)	6.8 (1.5)
	Female	92.0 (12.7)	12.0 (0.6)	15.2 (2.2)	5.8 (0.2)
70% Stoopwalk	Male	82.2 (7.2)	13.2 (1.7)	15.1 (4.1)	6.8 (1.5)
	Female	89.9 (11.1)	11.0 (1.2)	15.7 (3.5)	6.0 (1.0)
60% Stoopwalk	Male	88.5 (7.2)	17.0 (2.3)	18.1 (1.4)	8.3 (1.0)
	Female	100.5 (21.6)	16.2 (5.3)	21.3 (5.0)	8.1 (1.8)
Crawling	Male	81.3 (11.3)	12.5 (1.3)	15.5 (2.3)	7.0 (0.5)
	Female	87.4 (7.8)	10.3 (1.0)	14.8 (2.7)	5.7 (1.8)

Numbers in parentheses represent the standard deviation.

Source: Ayoub, M. M., Bethea, N. J., Bobo, M., Burford, C. L., Caddel, K., Intaranont, K., Morrissey, S., and Selan, J. 1981a. *Mining in Low Coal. Volume 1: Biomechanics and Work Physiology.* Final Report — U.S. Bureau of Mines Contract No. HO3087022. Texas Tech University, Lubbock, TX.

Lind, 1962; Ayoub et al., 1981; Morrissey et al., 1985). Moss (1934) examined the physiological cost associated with normal walking, a "half-stoop" (80% of full stature), a "full-stoop" (60% of full stature), and walking on "all-fours" (50% of full stature) for eight experienced mining subjects. His finding showed that the half-stoop, full-stoop, and all-fours conditions increased the metabolic demands of walking 3.5 mph by 21%, 65%, and 73%, respectively. Similar trends were shown by Humphreys and Lind (1962), while the data from Bedford and Warner (1955) showed much higher increases in metabolic cost with *stoopwalking*. The most thorough experiment of the effects of stoopwalking and crawling was done by Ayoub et al. (1981a) and also reported by Morrissey et al. (1985). This study illustrated a progressive trend toward increasing metabolic cost as stooping becomes more severe (Table 106.2). Not only is the metabolic cost increased as stooping becomes more severe, the maximum speed attainable by subjects is reduced, particularly in stoopwalking at 60% stature and in crawling tests.

The metabolic cost of manual materials handling in restricted postures (stooping and kneeling) has also been studied (Gallagher and Bobick, 1988; Gallagher et al., 1988; Gallagher and Unger, 1990; Gallagher, 1991; Freivalds and Bise, 1991; Gallagher and Hamrick, 1992). These studies suggest that the metabolic cost of manual materials handling is not predominantly influenced by posture, but by an interaction between the posture adopted and the task being performed. For example, the kneeling posture is more costly than stooping when a lateral transfer of materials is done (Gallagher and Bobick, 1988; Gallagher et al., 1988; Gallagher and Unger, 1990). However, other studies have illustrated that kneeling can be more economical when the task requires increased vertical load displacement (Gallagher, 1991; Freivalds and Bise, 1991; Gallagher and Hamrick, 1992). A study of shoveling tasks in different postures by Morrissey et al. (1983) found no difference in energy expenditure in standing, stooping, and kneeling postures; however, only five subjects participated in this study and it may suffer from a lack of sufficient power to detect differences.

Manual Materials Handling in Restricted Postures

Mining is essentially an exercise in materials handing, some of which has been automated (especially the revenue-producing mineral extraction and transport segment), but much of which has not (movement of mining supplies, maintenance work, etc.). The amount of manual work that must be done in underground mines would be demanding enough without imposing restrictions in vertical workspace. As discussed below, such restrictions influence human strength capabilities, psychophysically acceptable workloads, and lifting biomechanics.

Effects of Restricted Postures on Strength

Studies examining static or dynamic strength capabilities in unusual or restricted postures are relatively rare. Haselgrave et al. (1987) reported results of isometric strength tests in kneeling vs. standing postures. These authors reported that lateral exertions were weaker when kneeling; however, pushing forces were equivalent in both postures. Pulling and lifting forces in the kneeling posture exceeded those in the standing position, by 25% and 44%, respectively. Results obtained by Gallagher (1989) were similar; however, this author reported higher pushing forces when kneeling on two knees than when standing. This study also studied a maximum upward push (with the force exerted upon a lifting handle at eye height), for which strength was not dependent on posture.

A study by Gallagher (1997) investigated trunk extension strength and electromyography of eight trunk muscles in standing and kneeling postures. Findings of this study showed that trunk extension strength is reduced by 16% in the kneeling posture in comparison with standing. However, normalized trunk muscle EMG was not significantly different between the two postures. Gallagher (1997) speculated that the reduction in trunk extension strength in the kneeling posture may be the result of a reduced capability to perform a strong rotation of the pelvis when the kneeling posture is adopted.

Psychophysically Acceptable Loads in Restricted Postures

Several studies of psychophysical lifting capacity in restricted postures have been done. Ayoub et al. (1987) reported psychophysical limits for a variety of unusual lifting postures including kneeling, sitting, lying down, and others. These data were collected with the assumption that atypical postures would be used only infrequently, for example, a one-time lift. Unfortunately, such postures may be used by miners for more prolonged bouts of manual lifting. As a result, the U.S. Bureau of Mines has examined the lifting capacity of underground miners in a variety of postures and vertical space constraints for tasks of longer duration (Gallagher et al., 1988; Gallagher and Unger, 1990; Gallagher, 1991; Gallagher and Hamrick, 1992). These investigators particularly wanted to quantify lifting capacity in the two most common postures used for lifting in *low-seam mines* — stooping and kneeling on both knees (Bobick, 1987). Results of these studies showed a significant decrease in lifting capacity in the kneeling posture, ranging from 8 to 18% (Gallagher et al., 1988; Gallagher and Unger, 1990; Gallagher, 1991; Gallagher and Hamrick, 1992). This deficit may be due to restrictions in the forces provided by the powerful hip and leg musculature in the kneeling posture, as compared with standing or stooping. In the stooping posture, the hamstrings and gluteal muscles appeared to provide a great deal of the force for the lifting tasks. Subjects consistently identified these muscle groups as those most sore after periods of lifting in the stooping posture (Gallagher et al., 1988). However, the effects of posture can be overridden by other MMH variables. For example, lack of a good handhold may reduce the acceptable load to a point that the differences related to posture are no longer evident (Gallagher and Hamrick, 1992).

A surprising, and somewhat disturbing, result of these studies is that psychophysically acceptable loads in prolonged stooping were generally on par with that achieved in the unencumbered standing position (Gallagher and Hamrick, 1992). Given the association of trunk flexion and incidence of low back disorders (Punnett et al., 1991), one would envision reduced load acceptability in this posture. However, as Snook (1985) has noted previously, the psychophysical approach does not seem sensitive to bending and twisting motions often associated with low back pain. Results of psychophysical studies in restricted postures seem to confirm this assessment. Further, these studies raise the issue of what drives subjective assessments of acceptable loads. Such assessments might be largely based on strength capabilities and physiological workload, rather than responses to the strain experienced by the low back. It may be advisable to base lifting limits for the stooping posture on biomechanical parameters, rather than relying on psychophysical estimates.

Biomechanics of Restricted Postures

Several methodologies have been employed to evaluate the biomechanical strain experienced during manual work in restricted postures. These have included use of intra-abdominal pressure (IAP),
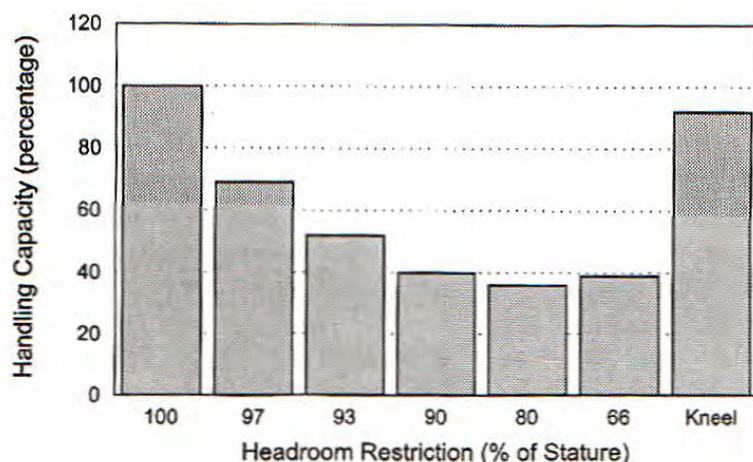
FIGURE 106.4 Handling capacity for stooping (percentages of full stature) and kneeling postures according to the IAP criterion. (From Ridd, J.E. 1985. Spatial restraints and intra-abdominal pressure. *Ergonomics*, 28(1): 149-166. With permission.)

electromyography (EMG), and estimations of L_5-S_1 moments. Because of their unique features, the restricted postures employed in underground mining have been found to present challenges to many traditional biomechanical models. As discussed in the following sections, there are often serious concerns whether certain ergonomic models are valid tools for the analysis of atypical postures.

Intra-abdominal Pressure (IAP)

Evaluation of spinal loading using the IAP criterion has been described by several authors (Davis and Troup, 1966; Davis and Ridd, 1981; Ridd, 1985; Sims and Graveling, 1988). Ridd (1985) found an almost linear decrement in lifting capacity with progressively lower vertical workspace up to 90% of stature, after which the decrement began to level off (Figure 106.4). At standing positions ranging from 66 to 90% of stature, the decrease in lifting capacity was 60%, according to the IAP criterion. The kneeling posture was found to incur only an 8% decrease in lifting capacity where the space restriction was equivalent to 75% of stature, according to Davis and Ridd (1981). Ridd (1985) also described the effects of asymmetric lifting activities on IAP. There was some indication that lifting asymmetrically is less stressful than sagittal plane activities in restricted postures. This result is in accord with psychophysical data showing that subjects were willing to accept greater loads asymmetrically in restricted postures (Gallagher, 1991). The reason may be that sagittal plane motions are precisely those most inhibited by vertical space constraints. Asymmetric motions are less affected by this restriction, leading to increased lifting capacity and decreased IAP responses.

There is currently much controversy regarding the role of IAP in spinal biomechanics. The original belief that IAP reduces the compressive loading on the lumbar spine has been disputed recently by many authors (Grillner et al., 1978; McGill and Norman, 1985; Nachemson et al., 1986). A particular concern is that the increase in IAP requires higher abdominal muscle activity, resulting in an additional compression penalty on the lumbar spine. Furthermore, the IAP does not always appear to respond to situations where spinal loading is known to be high, for example, when the spine is loaded asymmetrically (Andersson, 1982). In fact, IAP does not always produce consistent results with flexed postures (Sims and Graveling, 1988). At any rate, our understanding of the role of IAP in spinal biomechanics seems far from complete. As a result, some have recommended caution in using this mechanism to establish safe handling limits (Andersson, 1982; Ayoub and Mital, 1989).

Biomechanical Modeling

As mentioned previously, the robustness of many traditional biomechanical models may be put to the test in the analysis of atypical postures. As an example, while the spinal muscles provide the majority of

lumbar support when the trunk is erect or moderately flexed, the spine employs a distinct "passive" mechanism of support when the trunk is fully flexed (Floyd and Silver, 1951; Floyd and Silver, 1955; Silver, 1954). While progress has been made in our understanding of this passive loading in recent years (Dolan et al., 1994), there remains a great deal to learn about this spinal support mechanism. Similarly, the kneeling posture is atypical of the type of lifting posture for which many biomechanical models have been formulated, most of which assume the feet constitute the base of support. Adopting a kneeling position changes a great deal regarding lifting biomechanics; for example, reducing leg muscle contributions to the lift. This may result in an increased agonist role for the erectores spinae.

An analysis reported by Gallagher and Unger (1988) illustrates some typical problems encountered with use of traditional biomechanical models in the analysis of restricted postures. These authors used the optimization model developed by Schultz and Andersson (1981) to estimate the compressive and shear loading in stooping and kneeling positions. The validity of this model in restricted postures was suspect, as model estimates of muscle forces contradicted EMG responses in the two postures. The analysis done in this study was admittedly beyond the scope of the validation performed by Schultz et al. (1982), where the most severe trunk flexion angle was 30 degrees. However, this example points out the problems run into repeatedly by the author. Many models available simply have not been validated for the analysis of unusual or atypical lifting postures.

Similar problems exist with the use of EMG-assisted biomechanical models with restricted postures (Gallagher et al., 1994). EMG-assisted models are greatly advancing our knowledge of trunk muscle responses and loading on the lumbar spine to manual materials handling activities (Marras and Sommerich, 1991a; Marras and Sommerich, 1991b). However, such models are generally valid under conditions where trunk muscles are the structures called upon to provide a restorative moment. However, the reliance on passive mechanisms (as opposed to muscles) in the stooping posture make it less amenable to such an approach. Use of an EMG-assisted model to evaluate restricted postures has uncovered complex muscle recruitment patterns (Gallagher et al., 1994); however, the issue of the passive component, estimated to account for 16 to 31% of the extensor moment in full flexion (Dolan et al., 1994) still needs to be resolved when using EMG-assisted models in the stooping posture.

A recent study of the mining task of handling heavy electrical cables examined the estimated peak L5-S1 moments resulting from hanging the cable under a variety of postures and vertical space limitations (Gallagher et al., 1995). The major finding of this study was that the peak moment when hanging cable was more highly related to the restriction in vertical space than to the posture employed. As can be seen in Figure 106.5, the greater the restriction in vertical space, the higher the peak moment experienced by the subject. It should be noted that this trend is evident even in the face of a contrary trend. That is to say, the higher the cable is lifted off the ground, the more weight is handled. Thus, lower moments were experienced with greater vertical space, though more weight was lifted under these conditions. Contrasts examining differences in peak moment in stooping and kneeling postures showed no difference in peak loading between these postures.

106.5   Summary of Physical Work in Restricted Postures

From the literature reviewed above, we can begin to develop an understanding of the stresses associated with working in restricted postures. Clearly, working in such postures exacts many tolls, including increased metabolic demands, decreased lifting capacity, and increased loading on the lumbar spine. What should also be clear, however, are some limitations of the parameters that we rely upon to provide insight regarding physical capabilities of workers. As discussed above, some of our parameters may disagree about which posture has the greatest limitation in handling capacity. If one were to look only at IAP data, we would conclude that handling capacity is only slightly reduced when kneeling. A different conclusion is reached when the psychophysical approach is used. Similarly, examination of the stooping posture using psychophysics may not suggest a deficit in acceptable workloads compared with standing, whereas biomechanical measures display increased strain on the low back. Clearly, reliance on only one measure or technique may not be sufficient to develop a full appreciation of the capabilities and/or
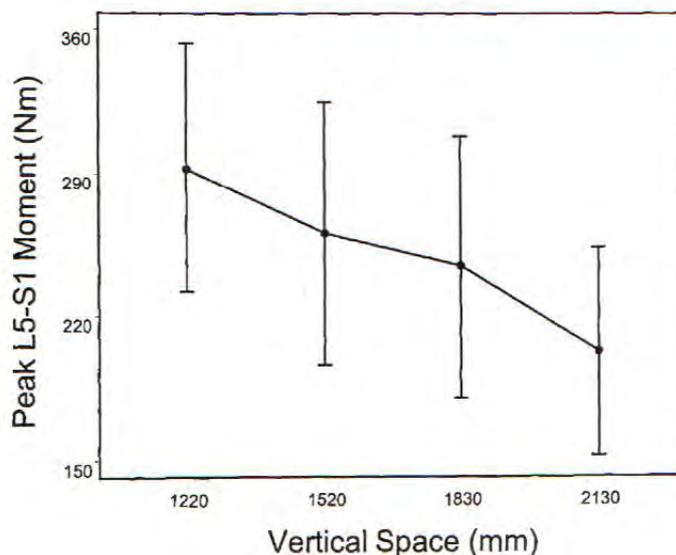
FIGURE 106.5 Relationship between vertical space restrictions and peak moment experienced during a cable hanging task. (From Gallagher, S., Hamrick, C.A., Cornelius, K., and Redfern, M. 1995. "Peak L5-S1 Moments Associated with a Cable Hanging Task," Poster Presentation at the 39th Annual Meeting of the Human Factors and Ergonomics Society Conference, San Diego, CA, October 9-13 1995.)

limitations associated with a particular working position. Examining a variety of measures, on the other hand, appears to help develop a better understanding of the multivariate stressors that workers experience, and may also point out the strengths and limitations of our own analysis techniques.

106.6 Heat Stress

Mining has long figured prominently among occupations routinely exposed to high heat stress (Martinson, 1977). This is particularly true for *deep mines* (for example, South African gold mines), mines sunk in hot countries, or in mines situated along zones where high heat flow from the earth occurs (Misaqi, 1991). Medical experts recognize that exposure to hot, humid conditions is both unhealthy and unproductive. Figure 106.6 illustrates the decreasing productivity of mineworkers loading mine cars and drilling rock as the ambient temperature is increased. Of course, many serious health problems are associated with heat exposure, including heat cramps, heat exhaustion, and heat stroke. The latter condition can often lead to death. However, heat stress can also have a significant impact on safety even below levels that may cause actual physical harm (Hancock and Vercruyssen, 1988). With even moderate heat exposure, workers may ignore unsafe working conditions, have decreased dexterity, coordination and cognitive ability, and are more apt to act emotionally. This may lead to rash acts by people performing hazardous jobs.

A great deal of our knowledge of the effects of heat stress, and on methods to control these effects, may be credited to the Human Sciences Laboratory of the Chamber of Mines of South Africa (Wyndham et al., 1973). In the 1920s, as the gold mines in the Witwatersrand were sunk to depths greater that 1800 meters, virgin rock temperatures continued to climb, and the ambient wet bulb temperatures in the mine began to exceed 30 degrees C. Heat stroke became an alarming problem; in 1930 alone, 27 deaths from heat stroke occurred. This rash of deaths prompted an intensive period of research, resulting in several control measures to protect mineworkers against the adverse effects of physical work in high heat and humidity conditions. These included better acclimatization to heat, recognition of heat intolerant individuals, definition of safe heat stress limits, and adaptation of microclimate cooling systems for use in the gold mining industry. Of these, the most important advances were in the field of heat acclimatization (Strydom, 1966). Initially, the acclimatization regimen was accomplished over a 12 to 14 day period by exposing miners to cooler production areas of the mine and progressing them to the hotter production
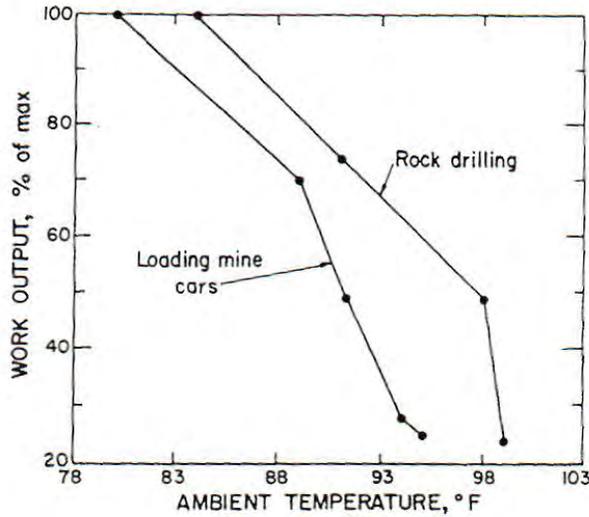
FIGURE 106.6   Effects of ambient temperature on miners' capacity to load mine cars and drill rock. (From Misaqi, F. L. 1984. *Heat Stress in Mining.* Safety Pamphlet No. 6, Mine Safety and Health Administration, Beckley, WV.)

areas. However, the laboratory continued to refine the procedure and ultimately initiated an 8-day regimen where workers were acclimatized by bench-stepping at a workload of 1 liter O$_2$/min in environmental chambers set at a wet bulb temperature of 32 degrees C. This procedure has been very successful in controlling the incidence of heat-related illnesses.

106.7   Equipment and Tool Design

Environmental conditions in underground mines not only affect the physical capabilities of underground workers, they also have a profound impact on the design of underground equipment and tools. For example, the restricted spaces in coal mines present a huge challenge for developing appropriately designed operator compartments and/or workstations. Underground mobile equipment may be so low profile that operators must lie completely down on their sides or back to operate the machine. This presents extreme problems for visibility and operator fatigue. Furthermore, mobile underground equipment may not have sufficient vertical space to provide systems for shock absorption, leading to serious whole-body vibration exposure. Add to this the problems of seating in mobile underground equipment. Often, seating consists of a steel seat welded to the frame of the vehicle. Illumination is also a critical design issue in underground mines, which are wholly dependent on artificial lighting systems. Other issues of concern include the design of hand tools and personal protective equipment used by miners.

Mobile Underground Equipment Design

Development of ergonomically designed operator compartments and workstations for underground mining equipment is an imposing task. The interaction of the confined space of the mine and the massive equipment required to mine the coal often results in operator compartments cramped and poorly designed. It is common to find operator compartments less than 76 cm in height and less than 61 cm wide. Visibility is almost inevitably influenced by the cramped conditions, often requiring the operator to lean out of the cab, which may expose him to hazards. Illumination systems in these confined spaces often cause the operator to be exposed to disability glare, further restricting visibility. In many cases, controls are designed and/or placed awkwardly. This increases the chance that controls may be improperly activated (or not activated at all) in emergencies. This is clearly a recipe for disaster (Conway and Unger, 1988). Fortunately, a great deal of international attention has been focused on the ergonomics of operator compartment and workstation design during the last 25 years. Major findings of this research are reported below.

Visibility

In the early 1980s, the U.S. Bureau of Mines sponsored research to learn critical visibility requirements for three common varieties of mobile underground equipment: shuttle cars, continuous miners, and scoops (Sanders and Kelley, 1981). Structured interviews and task analytic procedures were employed to evaluate the required visual information to perform tasks such as loading, hauling, or dumping. From this analysis, specific points were identified that must be visible to satisfy visibility requirements. These points, called visual attention locations (or VALs), were defined with reference to generic machine locations. For example, machine operators must be able to view a point on the ground sufficiently far away to stop their vehicle to avoid collision. The results of this VAL research have recently been incorporated into a computerized analysis package. Visibility analysis is automated to determine, for example, the relative visibility rating for a 5th percentile female or a 95th percentile male operator. This allows the designer easily to manipulate and optimize the visibility design of the operator's compartment, without the need to build expensive and time-consuming mockups.

Whole-Body Vibration

A study of mobile underground equipment operators in the early 1980s indicated that between 33 and 39% of operators are exposed to levels of whole-body vibration exceeding the ISO fatigue-decreased proficiency level (Remington et al., 1984). Between 7 and 14% were exposed to levels exceeding the ISO exposure limit. Other tests have been reported that miners may experience nearly 35% of the ISO 8-hour exposure limit simply riding for the 30 minutes it takes to get to the working face of the mine (Love et al., 1992). The effects of whole-body vibration have been studied in several Bureau of Mines experiments. A study by Bobick et al. (1988) examined the effects of 30 minutes of random whole-body vibration typical of a mine haulage vehicle on several measures, including back strength, dexterity, stature, heart rate, blood pressure, and subjective discomfort. Vibration was found to increase HR and BP, and discomfort ratings, but had no influence on back strength, stature, or dexterity. A subsequent study (Bobick et al., 1989) showed no compromise of back muscle strength nor endurance related to short-term vibration exposure. These authors suggest that the lack of effect on back strength suggests that the low back pain associated with whole-body vibration may depend on postural and mechanical effects rather than any change in the function of the back musculature. The effects of WBV exposure on postural stability have also been investigated (Cornelius et al., 1994). Balance seemed unaffected by short-term exposure to whole-body vibration.

Seating Design

There is an increasing awareness in the mining industry of the importance of providing appropriate seating for operators of underground mobile equipment. This is no doubt due to the sequelae of exposure to whole-body vibration. While this awareness is slowly infiltrating the industry, many seating designs for underground equipment currently remain relatively primitive. In fact, even some latest mining equipment provides only a bent steel plate bolted to the machine frame as the only means of operator support (Love et al., 1992). When this situation is combined with the inability to provide shock absorption systems (again, due to lack of sufficient clearance to dissipate the energy), the effects should become apparent. The restricted headroom in many underground mines provides additional challenges for the equipment designer. In very low mines, equipment operators may have to lie down to run mobile equipment. When conditions are not quite as severe, the operator may have to assume a reclining position that affects visibility. Given the problems enumerated above, it is not surprising that past attempts at improving seating by equipment manufacturers have not met with a great deal of success.

The goals for seating design in underground mobile equipment are similar to those in other applications: provide a stable position from which to control the machine, provide some isolation from vibration and jolting, and reduce the risk of postural fatigue (McPhee, 1993; Collier et al., 1986). There have been guidelines put forth for the design of seating in underground equipment for various seam heights (Collier
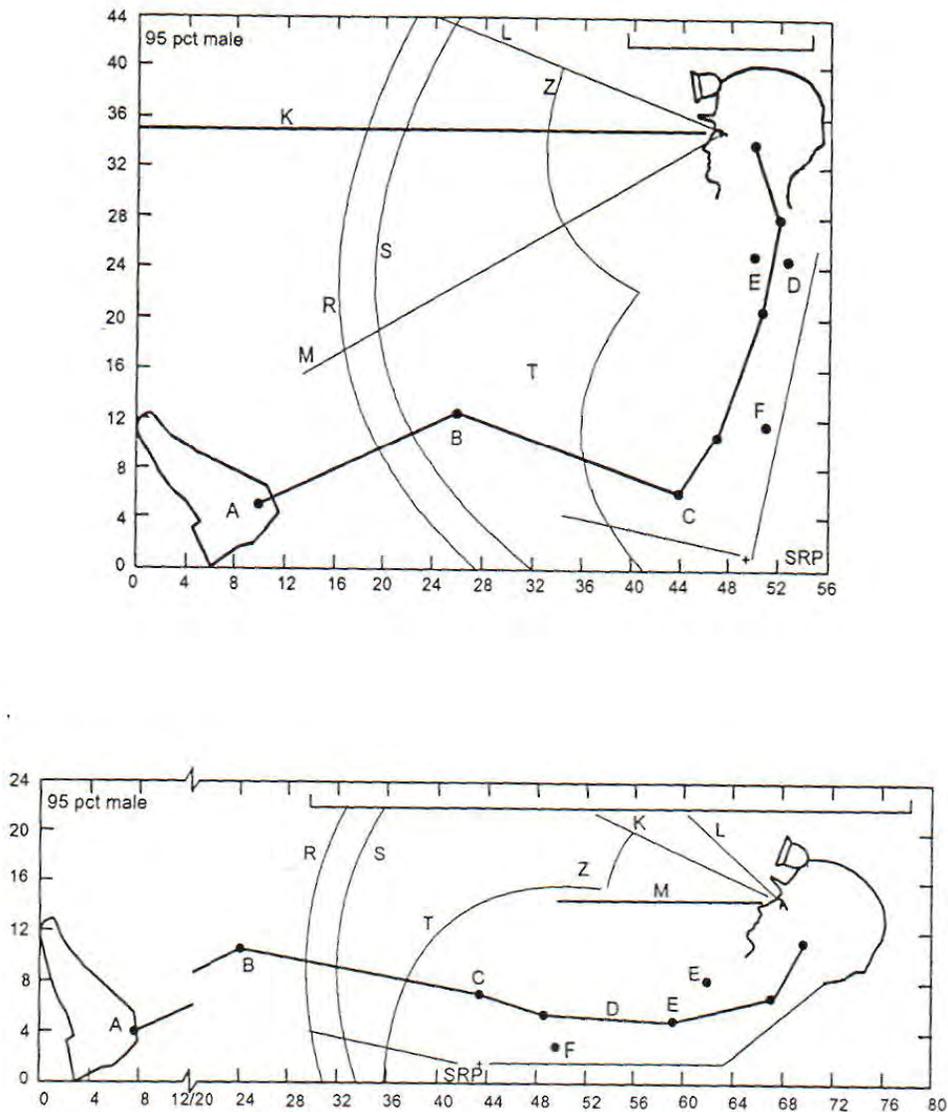
FIGURE 106.7 Seating space envelopes for 95th percentile miners in 107 cm (top) and 56 cm (bottom) cab heights. (From Canyon Research Group Inc. 1982. *Human Factors Design Guidelines for Personnel Carriers*, 37 pp., Canyon Research Group, Westlake Village, CA.)

et al., 1986; Mason, 1992; Canyon Research Group, Inc., 1982). Figure 106.7 illustrates the effects of vertical space restrictions on seating envelopes for the 95th percentile miner for two cabs: 107 and 56 cm in height (Canyon Research Group, Inc., 1982). Comparison of the two cabs clearly illustrates the increased cab length, reduced reach envelopes, and restricted field of vision associated with a reclined seating posture. Collier et al. (1986) present three design options for underground equipment seating. These included "normal" seating (for canopies > 1460 mm, of roof clearances > 1610 mm), a version with an increased backrest angle for canopies between 1440 and 1460 mm, and a "constant eye-height" option for canopies between 1135 and 1285 mm. A special consideration for mining equipment seating is the provision of sufficient space so that the operator's *caplamp battery* and *self-contained self-rescuer* (*SCSR*) can be worn on the belt. An example of such a design is provided in Figure 106.8 (McPhee, 1993).

Illumination

Proper design of illumination systems is a critical issue in the mining environment. In fact, underground mines (and surface nighttime operations) are often completely dependent upon artificial lighting systems.
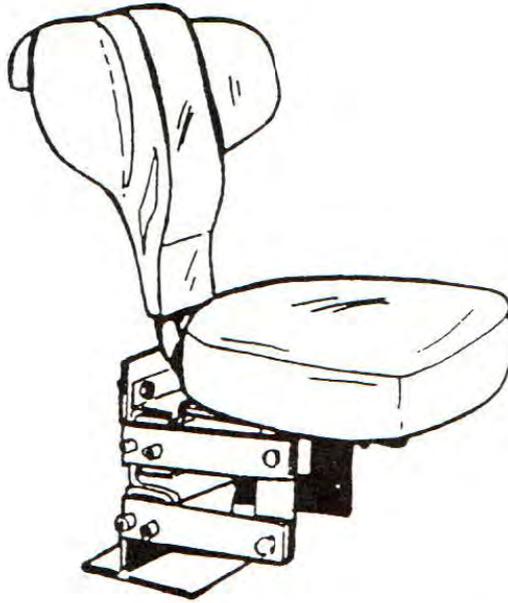
FIGURE 106.8 A prototype mining operator's seat developed using ergonomics principles and operator feedback. Note cutouts in the seatback, accommodating belt-worn personal protective equipment. (From McPhee, B. 1993. Ergonomics for the Control of Sprains and Strains in Mining. 36 pp., Handbook published by the National Occupational Health and Safety Commission (Worksafe Australia), Sydney. With permission.)

As humans receive the bulk of their information visually, the quantity and quality of illumination provided by lighting systems are extremely important for safety, productivity, and morale of the mining workforce (Sanders and Peay, 1988). Part 75.1719 of the Code of Federal Regulations discusses illumination requirements for different areas of underground mines, along with electrical standards, and other requirements to increase visibility in the mine environment (Lewis, 1986). The primary illumination standard states that underground equipment at the working face must provide *luminance* of at least 0.06 foot-Lamberts on the coal face. The illumination required to provide 0.06 foot-Lamberts (two footcandles) is adequate for most mining tasks, but is not so bright that severe adaptation problems will occur when the miner must go into darker areas of the mine (Lewis, 1986).

Presently, laboratory mockups are a major part of the process lighting equipment manufacturers (LEMs) must go through to design an approved underground machine-mounted illumination system. Moreover, when a lighting system is modified by using different *luminaires* within an existing configuration or by changing a luminaire's location or orientation, additional laboratory measurements may be necessary to approve the system. The U.S. Bureau of Mines, aware of the difficulties described above, has developed a PC-based computer model that will enable users to easily design, alter, and evaluate underground machine-mounted illumination systems without having to build a mockup or prototypes. A new method of modeling illumination provided by underground mobile equipment luminaires has been developed as part of this model (Gallagher et al., 1996). The Mine Safety and Health Administration has recently authorized the use of this computer model in the certification of mobile underground equipment illumination systems.

Control Design

An analysis of underground mining fatalities for the years 1972 and 1979 indicated that more than 7% of mining fatalities in underground coal mining during that period were associated with improper design of controls. The number of nonfatal injuries caused by poor control design remains unknown; however, it is safe to assume that this number is also substantial (Sanders and Peay, 1988). More recently, a spate of injuries among roof bolter operators also implicated control design as a contributing factor. A typical problem observed in mining equipment is lack of control standardization (Helander et al., 1980). An
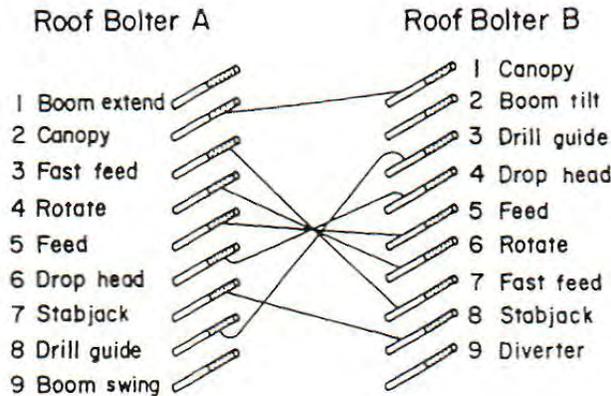
FIGURE 106.9   Different arrangements of roof bolter controls from the same manufacturer. (From Helander, M., Conway, E.J., Elliott, W., and Curtin, R. 1980. *Standardization of Controls for Roof Bolter Machines. Phase I. Human Factors Engineering Analysis* (contract HO292007, Canyon Research Group Inc.). Bureau of Mines PFR 170-82, NTIS PB 83-119149, 192 pp.)

example is provided in Figure 106.9. This figure depicts two varying arrangements of roof bolter controls, both coming from the same manufacturer. It is not an uncommon occurrence to have machines with different control arrangements working in the same mine, but perhaps in different *working sections*. If a worker who usually works on roof bolter A is suddenly called upon to fill in on roof bolter B, the risk of improper control activation is greatly increased. Many similar situations may be cited. Unfortunately, this is not an area where a great deal of progress has been made in mining. It is important that human factors design principles be considered in the design of new equipment, and, what is more important, that mines insist on good human factors design in their procurement process.

Maintainability Design

In the early days of mining automation, equipment consisted of relatively simple machines that could be easily maintained using simple hand tools. These have since been replaced by increasingly powerful and complex mining systems (Conway and Unger, 1991). The demands on the maintenance function have increased concomitantly. Unfortunately, little regard is given in the design of this equipment for ease of maintenance and serviceability. The following problems are most frequently observed in mining equipment (Long, 1983): (1) poor access to machine parts or areas for routine maintenance tasks, (2) inadequate access openings to reach parts needing repair or replacement, (3) need to remove or dismantle ancillary components to gain access to the failed unit, (4) inadequate provisions for safe handling of heavy or large parts, and (5) inadequate tools to perform required maintenance tasks. As a result of such design deficiencies, relatively simple maintenance tasks are turned into complex, time-consuming procedures. Recently, some recommendations for improving the maintainability design of mining equipment have been published (Conway and Unger, 1991). These recommendations contain both maintainability engineering information for equipment manufacturers and a buyer's guide for the evaluation of the maintainability design of mining equipment.

Ergonomics Design Guidelines

Some mining operations now require ergonomics evaluations to be performed on major items of underground equipment prior to their purchase (Mason, 1992). This is a positive development in terms of implementing ergonomics in mining, but also demands that appropriate design information be provided to engineers, designers, and purchasers of this equipment. In the late 1980s and early 1990s, a number of ergonomics design handbooks were developed for specific pieces of underground machinery (Canyon

Research Group, 1982; Collier et al., 1986; Mason, 1992). An effort to develop a generalized ergonomics measurement tool resulted in the Bretby Operability Index (Mason, 1992). This index provides a means through which an initial ergonomics screening of new equipment can be performed. Areas requiring a more detailed assessment can be quickly identified, so that ergonomists can focus developing recommendations in these areas.

106.8 Hand Tool Design

Most analyses indicate that hand tools are involved with between 7 and 10% of all nonfatal lost-days accidents in the mining industry (Marras et al., 1988a, 1988b; Sanders and Peay, 1988). Most of these injuries (approximately 75% or more) are associated with nonpowered hand tools. Many traditional hand tools are used in the mining industry. Of these, hammers, wrenches, and knives are most commonly implicated in accidents (Sanders and Peay, 1988). However, there are many specialty tools used for specific mining tasks, for example, the *scaling bar* or the *jack leg drill*. Many of these specialty tools also appear to have very high frequency and severity rates associated with them (Marras et al., 1988a, 1988b). The types of injuries associated with mining hand tools are most often struck-by and overexertion. There is some indication that the awkward postures observed in low-seam coal mines may contribute to both types of injuries. Research in this area has resulted in recommended design changes that may be useful in improving handtool design (Marras and Lavender, 1988). As an example, a counterbalanced scaling bar was developed which was found to significantly reduce compressive forces on the spine compared with the conventional scaling bar (Marras and Lavender, 1991).

106.9 Personal Protective Equipment

In response to the multiplicity of mining hazards, miners are equipped with an extensive array of personal protective equipment (PPE) (Sanders et al., 1981). This equipment includes (at a minimum) ear protection, safety glasses, respirator, hard hat, cap lamp and battery, mining belt, overalls, gloves, safety boots, self-rescue device, and in low-seam mines, knee pads. Unfortunately, much of this equipment has not received proper consideration with regard to ergonomics nor the unique environmental conditions present underground. However, in the past 15 years, a number of studies have been performed to address issues pertaining to miners' PPE. This research has resulted in the development of an improved slip-resistant tread design for mining boots, improved overall designs with retro reflective materials for increased detectability, and improved knee pad designs (Sanders et al., 1981).

Another item of PPE that is currently generating some controversy is the introduction of belt-worn self-contained self rescuers (SCSRs). These devices are heavier than the *filter self rescuers* (*FSRs*) they replaced, but have the benefit of immediately providing the miner with an hour's worth of oxygen to escape a mine fire. The FSRs worn previously were lighter; however, they were not protective from all noxious gases produced by a mine fire and still required the user to don another device before escape was possible. Some miners feel the new devices are too heavy and cumbersome, and are resisting the change. Research is currently under way to examine methods of improving the ergonomics design of these devices.

106.10 Status of Knowledge and Unresolved Issues

Our knowledge of ergonomics issues in mining has increased a tremendous amount over the last two decades. However, we would be sadly mistaken if we were to imply that all (or even a sizable portion) of the relevant issues were resolved. There remains much to be learned and surely some to be discarded from what we believe we know presently. The following list discusses some of the most important unresolved issues, in the author's mind, that need to be addressed:

1. Ergonomics research in mining has far outstripped its implementation by the industry. While there have been significant ergonomics success stories in mining, by and large effective mining ergonomics committees are relatively rare. How can we improve the dissemination of ergonomics information and facilitate the development of committees in this industry, particularly among smaller mines with limited resources?

2. The unique stresses of working in restricted postures do not appear to be well-addressed by many of our current ergonomics models. As we continue to develop our knowledge of the ergonomics and biomechanics of traditional industrial tasks, it is important not to limit our research too narrowly. We should continue to broaden the applicability of our models to atypical postures and unusual situations. This process would undoubtedly provide us with better insight into the adaptive mechanisms used by the body, and may well spawn new ergonomics and biomechanics paradigms.

3. Recent years have seen a rapid growth in the development of new mining technologies. However, human-centered design principles have often been neglected in the design and implementation of new equipment and new technologies (Randolph and Love, 1991). Increased technology transfer efforts must be focused on the manufacturing sector of the mining industry, so that equipment can be designed to facilitate increased productivity, decreased risk of accidents, and improved worker satisfaction and comfort.

Defining Terms

Caplamp: The lamp worn by a miner on his safety hat or cap for illumination purposes. The caplamp is powered by a rechargeable battery worn on the miner's belt.

Deep mine: A mine where the coal or mineral deposit is at a depth exceeding 915 m (3000 ft). Some gold mines have been sunk to depths exceeding 3050 m (10,000 ft).

Filter self-rescuer (FSR): A protective device, worn on the miner's belt, to be worn in the event of a mine fire or explosion. This unit protects the miner from the potentially lethal effects of carbon monoxide inhalation.

Jack leg drill: A percussive type of automatically rotated rock drill that is worked by compressed air. This drill has a supporting bar (leg) that allows the drill to be used to drill into vertical mineral faces.

Low-seam mine: In general, a mine where the mineral seam is less than 1.2 m (4 feet) in thickness.

Luminaire: A complete lighting unit. These are mounted on underground mobile equipment to ensure compliance with mine lighting regulations.

Luminance: The luminous intensity of a surface in a given direction per unit of surface area.

Roof bolter: In bituminous coal mining, a machine used to drill holes and install bolts into the roof of the mine to prevent rock and slate falls. The term may also refer to the operator of this machine.

Scaling bar: A barlike implement used to remove loose rock from the roof of the mine in order to prevent this rock from falling unexpectedly and injuring a worker.

Self-contained self-rescuer (SCSR): A self-sufficient breathing apparatus which provides respiratory protection in oxygen-deficient or highly toxic atmospheres. In contrast to the filter self-rescuer (which only provides protection from carbon monoxide), this unit isolates the wearer's lungs completely from the toxic atmosphere.

Stoop: A working posture involving bending the trunk forward and down, sometimes simultaneously bending the knees, commonly used in the cramped spaces in underground coal mines.

Stoopwalking: Walking in a stoop posture.

Working section: The area of the mine where the coal, ore, or mineral is being mined.

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For Further Information

An excellent source of information pertaining to ergonomics in mining is the text *Human Factors in Mining* by Sanders and Peay. This text is becoming a bit dated (it was published in 1988); however, it remains among the most comprehensive treatments available.