CHAPTER **7e**

Workplace-Related Lower Extremity Disorders: Workplace Adaptations with Case Studies

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MAGNITUDE OF THE PROBLEM

Work-related lower extremity musculoskeletal disorders

A significant amount of research has been performed in the area of cumulative trauma disorders of the upper extremity and low back pain of occupational origin.[127] Although studies on this topic are important enough to warrant further investigation, it is becoming more important to address the need to evaluate the lower extremity cumulative trauma syndrome. According to the Bureau of Labor Statistics, there were 1.4 million injuries and illnesses in private industry that required days away from work in 2002. Of these, 488,000 (34%) were musculoskeletal disorders, defined as injuries or disorders of the muscles, nerves, tendons, joints, cartilage, and spinal disks. Twenty-one percent of these musculoskeletal disorders occurred in manufacturing and about 9% occurred in construction. The back accounts for the greatest number of occupational injuries and illnesses, but reports for the upper extremity (hand, finger, wrist) and lower extremity (knee, foot, toe) are comparable with each other for both total injuries and illnesses (Fig. 7e.1A) and for musculoskeletal disorders only (Fig. 7e.1B). Moreover, the severity of injuries and illnesses to the lower extremity exceeds that for both the upper extremity and back, trailing only that of the shoulder (Fig. 7e.1C). For the years 2000-2002 the median number of days away from work for back, upper extremity, lower extremity, and shoulder injuries and illnesses has averaged 6, 6, 8, and 12 days, respectively.

According to 2002 Bureau of Labor Statistics data, the services industry, which includes health care and social assistance, accounted for more lower extremity musculoskeletal disorders with days away from work than any other broad industry category (11,092). Manufacturing (5759) and transportation and public utilities (5668) were next, with about half the number of lower extremity musculoskeletal disorders with days away from work as services but higher severity rates with median days away from work of 11 and 15 days, respectively. Construction, which was fifth on the list of industries having lost work-day lower extremity musculoskeletal disorders (4748), also experienced more severe cases than services, having a median number of days

lost of 15. Furthermore, in the construction industry, musculoskeletal disorders involving the knee resulted in a median of 29 lost work days, a severity higher for the knee than any of the industry groups having more total lower extremity musculoskeletal disorders.

Despite these facts from the Bureau of Labor Statistics, scientific studies and journal articles found in the literature predominantly address the upper extremity. Entering the key words "upper extremity musculoskeletal disorders" and "lower extremity musculoskeletal disorders" into a popular search engine yields 877 and 20 hits, respectively.

There is additional justification for this new emphasis area based on the following facts: The working population is aging, and because age-induced muscle strength impairment affects the lower extremity and the upper extremity, it stands to reason that tasks requiring repetitive and sustained use of lower limbs detrimentally affect this part of the body. In contrast to the upper extremity, the lower limbs are under sustained static and dynamic loading due to weight bearing. When a person is simply standing upright, the lower extremity joints (such as ankle, knee, and hip joints) experience sustained biomechanical loading. These loadings become significantly high and repetitive (2 to 20 times the body weight) during simple walking and running.[16,43] With an aging musculoskeletal system, such high repetitive loading may detrimentally affect the health of the joints.

Furthermore, with the aging process, it is well established that in the general population the incidence of musculoskeletal disorders such as osteoarthritic knee is very high. It is estimated that over 80% of people over the age of 55 have a clinically diagnosed osteoarthritic condition.[64,138] In the aged population the joint complaints of the lower extremities are more frequent than that of the upper extremities.[11] There is sufficient evidence in the literature[4] that osteoarthritis causes more absenteeism than any other joint trauma. Therefore, a worker population chosen from such a sample is at a high risk of developing significant musculoskeletal disorders of the lower extremity.

Keeping in mind the changing demographics of the aging work force and the fact that lower extremity injuries account for about 20% of all compensable injuries, it is rather important that we further study this particular cumulative trauma. In particular, because most of the industrial tasks require some amount of sustained standing, it places excessive loading on the already traumatized lower extremity joints due to aging. Furthermore, jobs requiring excessive kneeling and walking further traumatize the aging lower extremity joints.

A review of the literature indicates that a variety of occupations that require excessive use of the lower extremities shows a high incidence of musculoskeletal disorders. For example, osteoarthritic/arthritic and other types of musculoskeletal conditions of the knee, ankle, and hip have been documented in carpet layers, ballet dancers, housemaids, miners, and construction workers.[13,24,26,38,63,66,69,105,107,108,122] Similar findings of lower extremity trauma have been documented in people involved in professional athletics such as soccer, football, bicycling, and running.[8,24,60,101]

Coggon et al[33] concluded that there is strong evidence for occupational osteoarthritis from prolonged kneeling and squatting but reported that obesity may be a factor in such workers. A study by Lindberg and Montgomery[67] reported that
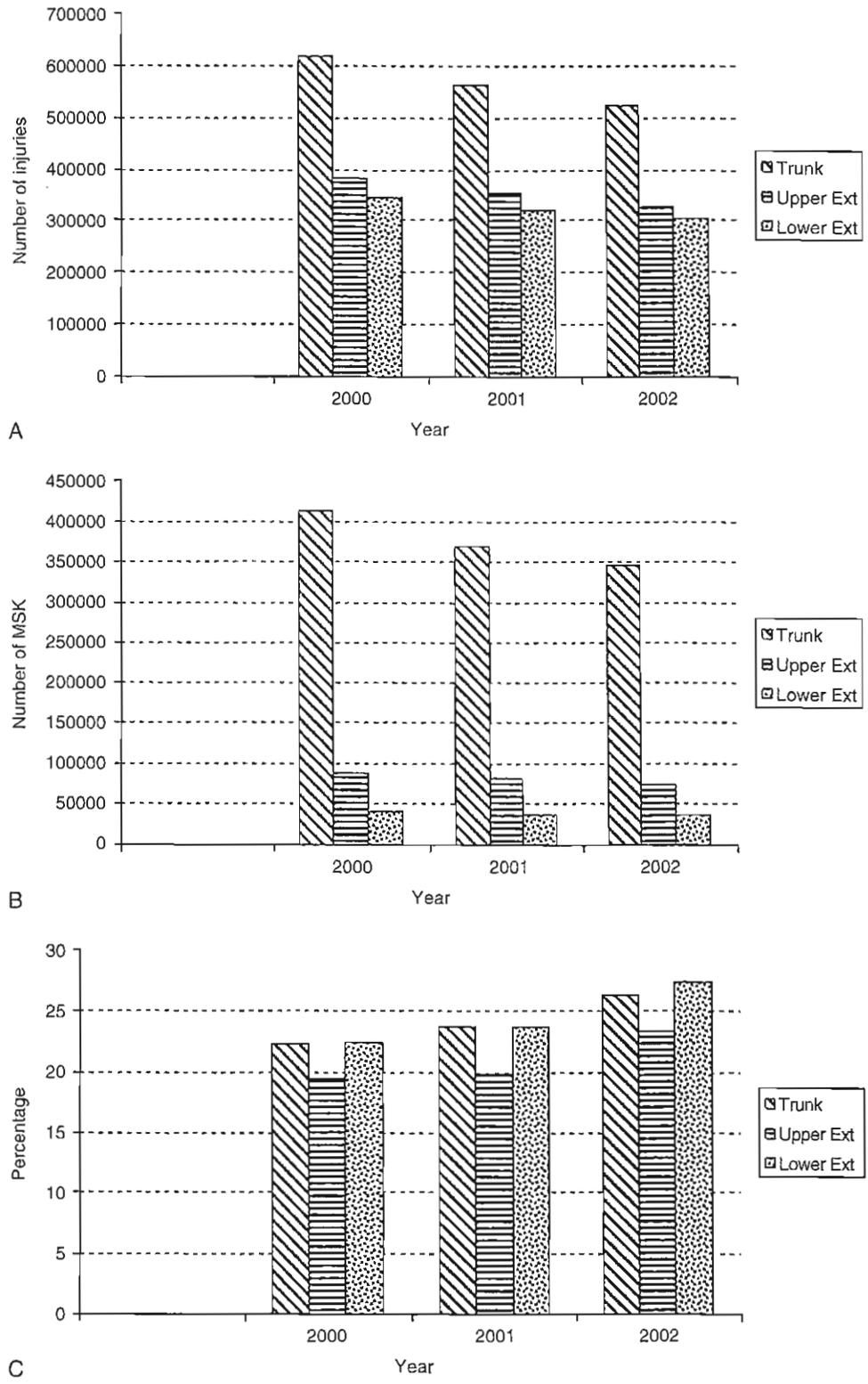
Figure 7e.1 **(A)** Number of nonfatal occupational injuries and illnesses with days away from work for select parts of the body, years 2000-2002. **(B)** Number of musculoskeletal disorders (MSK) involving days away from work for selected body parts, years 2000-2002. **(C)** Percentage of nonfatal injuries and illnesses with days away from work exceeding 30 days for selected body parts, years 2000-2002.

osteoarthritic knee conditions in 322 shipyard workers (average age, 66 years) were significantly related to long-term (30 years) exposure to heavy labor rather than age. An epidemiologic study[106] of 342 chain saw operators and 277 rock drill operators indicated that these workers showed not only classic cases of vibration white finger disorders but symptoms of numbness and coldness in the legs as well. The workers with the most frequent symptom were older and had longer exposures to vibration. The results imply vibration-induced disturbance of circulation of the lower limbs. Earlier studies[14,139] showed that whole body vibration can cause modification of the cardiovascular system relevant for the lower extremities. Such disorders do not occur suddenly; rather, it is the long-term insult by the externally applied forces that gives rise to microtrauma of the biologic tissues in question.

The human body undergoes microtrauma on a daily basis from performing routine tasks such as walking, running, and climbing stairs. For normal tissue, exposure to such a low level of force causes gradual replacement of microscopically injured tissues with new ones. However, when the activities become more stressful and repetitive and the loading envelope reaches a certain limit, the biologic system no longer is able to respond by regeneration, and the result is pathologic conditions. Furthermore, the onset of such pathologic response is highly dependent on the existing health status of the tissue. For example, with the aging process, the susceptibility of injury to tissues under loading to externally applied forces is high. Middle-aged or elderly workers who are exposed to repetitive loading of certain parts of their bodies may be highly susceptible to injury due to declining health status in their tissue properties and not being able to sustain the insult caused by the external loading.

Case study of carpet layers

Lower extremity trauma in carpet installers The concept of microtrauma induced by repetitive loading as described above is used for analyzing the job of carpet layers in our laboratory. This section presents the approach involving ergonomic/biomechanical principles to better understand, characterize, and monitor lower extremity trauma experienced by these workers and to provide some solutions to help minimize this trauma.

There are occupations (such as carpet laying) where knee injury claims have been significantly higher than knee injury claims from all occupations. Morbidity data indicate that carpet installers experience more than 10 times the number of lower extremity disorders than expected, given the percentage of these workers in the United States.[117] Although others such as tile setters, floor layers, drywall installers, cement and concrete finishers, and carpenters also use their lower extremities in the performance of their jobs by kneeling, the carpet layers' exposure to mechanical loading to the knee is not limited to the task of kneeling. A comparison of knee disorders among essentially equal numbers of carpet and floor layers to painters indicated that the former group reported more knee pain, knee accidents, and treatment regimens for the knees than the latter group. Osteophytes of the patella were more common among the carpet and floor layers as measured by radiographic changes.[55] Ultrasonography performed by these same authors found thickening of the prepatellar or superficial infrapatellar bursa in 49% of carpet installers versus 7% of house painters.[54]

The carpet layers further heighten the trauma to their knees by impacting on a carpet stretching device called a "knee-kicker" at a rate of about 140 kicks per hour with impact peak forces averaging around 3000 N[15] (Fig. 7e.2A). Similar research found that seven male carpet layers using a knee-kicker over 39 trials demonstrated peak forces of 2933 N.[128] In general, the carpet installation task requires use of awkward body posture, high impact forces to the knees, high acceleration of lower legs, and repetition that is biomechanically demanding and, therefore, provides reasons for high risk of knee disorders (Fig. 7e.2, B to D). The epidemiologic data of high morbidity (107.8) among carpet layers compared with tile setters and general floor layers substantiate the fact that these workers are at a relatively high risk of developing lower extremity musculoskeletal disorders.[117] According to the Industrial Commission of Ohio's report,[3] the percentage of carpet layers' knee injury claims was about four times higher than knee injury claims filed by all other Ohio workers. In an epidemiologic/medical study of 112 carpet layers, 42 tilers and terrazzo setters, and 243 millwrights and bricklayers, Thun et al[122] reported that carpet and floor layers have a high frequency of bursitis, needle aspiration of knee fluid, and skin infections compared with the other workers in the study. Their study also showed that the frequency of impacting on the knee-kicker was the only statistically significant predictor of bursitis. The act of kneeling was one of several descriptors of knee aspiration and skin infection of the knee.

The above summary[12,17-19,54,55,68,117,122,128] of existing research studies on carpet installers clearly indicates a serious knee morbidity problem exists among these workers. The data so far supports the fact that the knees of these workers are actually traumatized by their occupation, and the resulting cost of medical expenses, earning loss, and physical and psychologic suffering compels us to investigate further monitoring and prevention of such a disability of the lower extremity.

Biomechanical basis for clinical responses to the carpet installation task Most of the postures used during the carpet installation phase of the job of installing carpet pose unusual biomechanical demands on the musculoskeletal system. In our previous study with carpet layers,[17] we were able to identify typical postures that produce either static or dynamic sustained loading on the lower extremities (in particular, the knee joint). In Figures 7e.2A and 7e.3, we present examples of typical body postures that produce sustained static biomechanical loading of the knee joint. Such kneeling postures are maintained about 75% of the work period. The arrows in Figure 7e.3 indicate the potential areas of pressure points due to distributed ground reaction forces acting at the interface of the ground and the body. Because of excessive knee flexion angles and direct ground pressure at the infrapatellar region associated with these postures, the infrapatellar bursa is susceptible to injuries. This conclusion agrees with the finding of investigators at the National Institute for Occupational Safety and Health (NIOSH) who reported more frequent infrapatellar bursitis than prepatellar bursitis in this work force.[122]

In Figure 7e.3D, a typical posture is shown which describes the dynamic act of knee-kicking with the suprapatellar region of the knee. In our previous study[17] we found that most of the
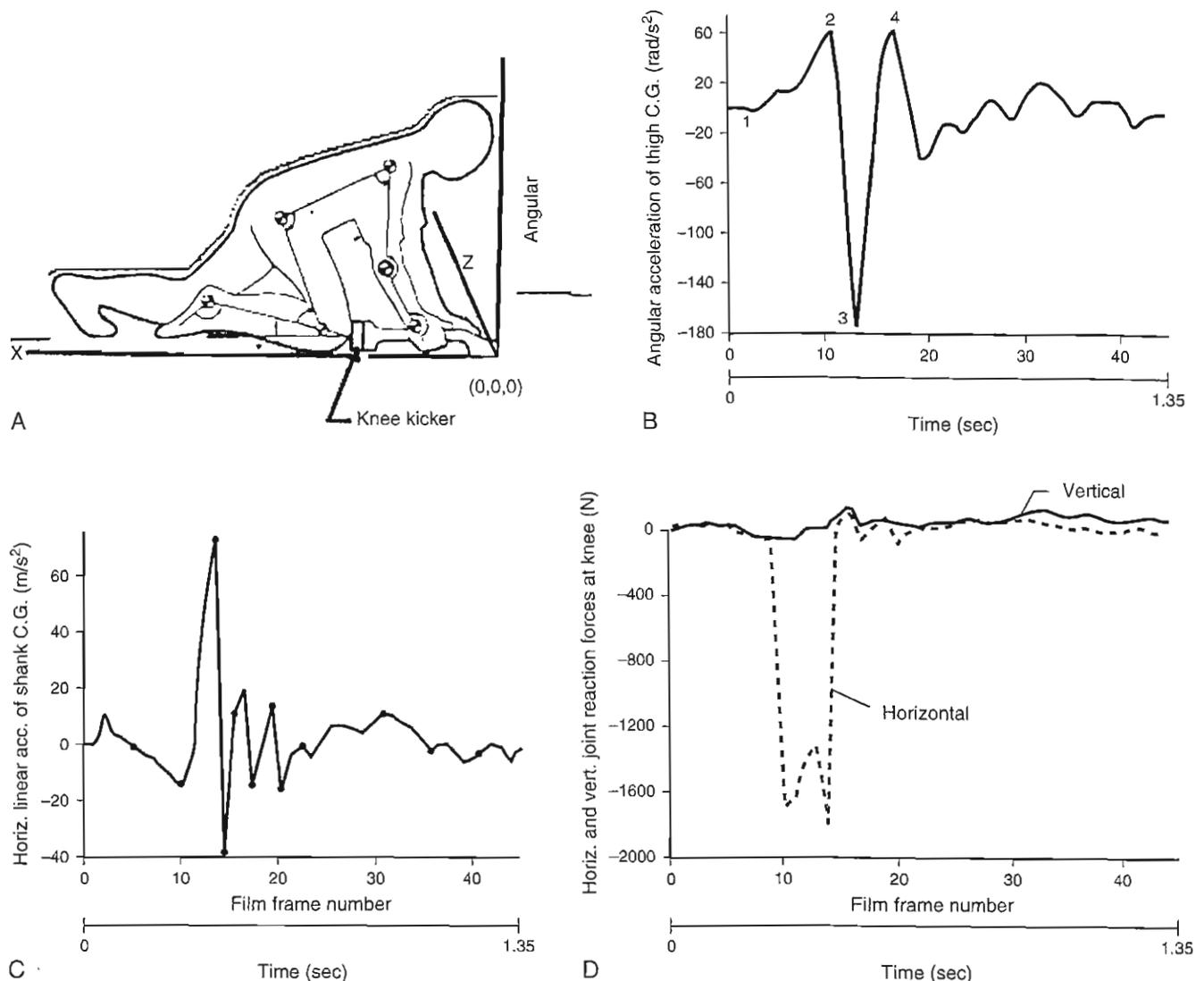
Figure 7e.2 **(A)** Schematic of coordinate system for carpet stretching task. **(B)** Angular acceleration of thigh center of gravity (C.G.). **(C)** Horizontal linear acceleration of shank C.G. **(D)** Joint reaction forces at knee.

time (70%) workers were involved in carpet stretching tasks, using the knee-kicker to stretch the carpet. The knee-kicking motion required vigorous and quick extension and subsequent flexion of the knee joint as the carpet stretching tool was struck. Therefore, this movement of the leg and the direct impact on the knee-kicker with the knee potentially exposes the bursae (fluid-filled sacs whose function is to reduce friction and distribute stress) located anterior and posterior to the patella to trauma (Fig. 7e.4). The epidemiologic/medical evaluation study on carpet layers by Thun et al[122] concluded that only the use of the knee-kicker predicted the occurrence of bursitis and to some extent knee tapping (using a needle to withdraw fluid from the knee). Our biomechanical explanation presented above and shown in Figure 7e.4 supports the findings of Thun et al.[122]

In the case of carpet layers performing the carpet-stretching task (using a knee-kicker), it appears that the bursae located

posterior and anterior to the patella and the infrapatellar bursa are in direct contact with the quadriceps muscle and the patellar tendon, respectively. Under such a repetitive movement condition, the tendon moves repeatedly over the bursae, causing mechanical irritation that gives rise to inflammation, causing fluid to be released into the bursae. Fluid in the bursae produces swelling and tenderness. If the inflammation is intense, the overlying skin becomes red and feels hot when touched. Symptoms typical of inflammation include[95] swelling caused by accumulation of fluid that may require knee tapping, redness and local rise of skin temperature caused by increased blood flow around the injured area, tenderness on touching the affected area, and impaired function. Early signs of superficial tissue damage due to sustained kneeling or impacting a knee-kicker may be indicated by skin redness caused by increased blood flow and therefore local rise of skin temperature. Therefore, one of the medical/physiologic
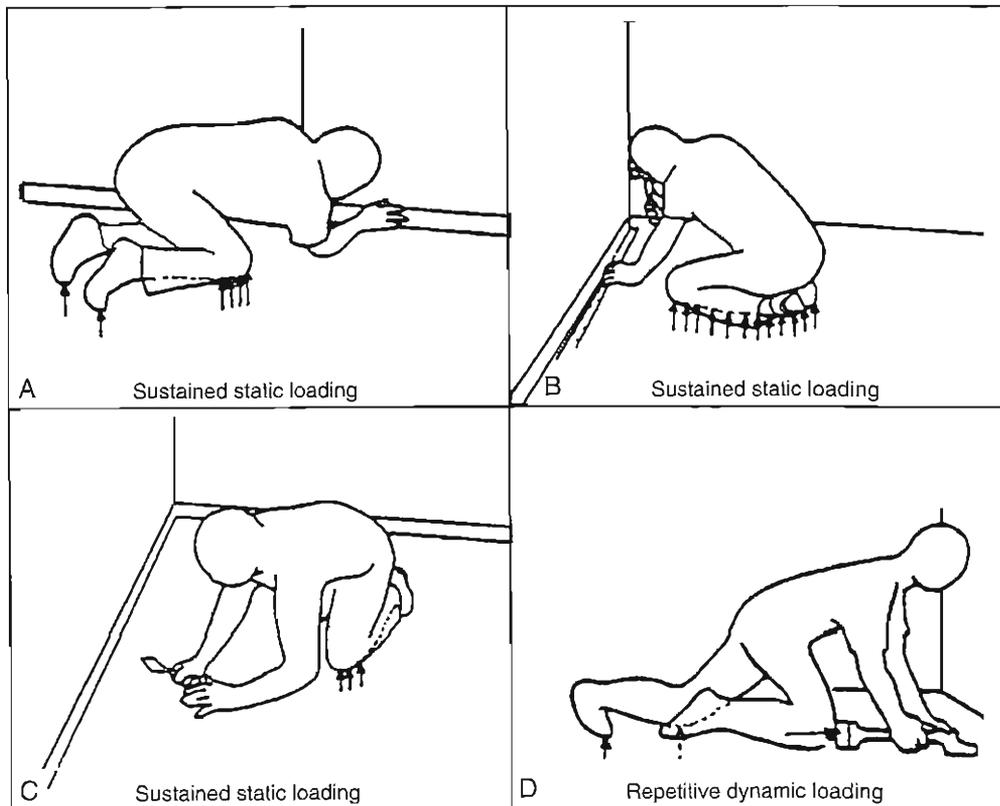
Figure 7e.3 (A-D) Lower extremity locations of potential pressure points and/or vigorous impact force on body postures of the carpet installation process.
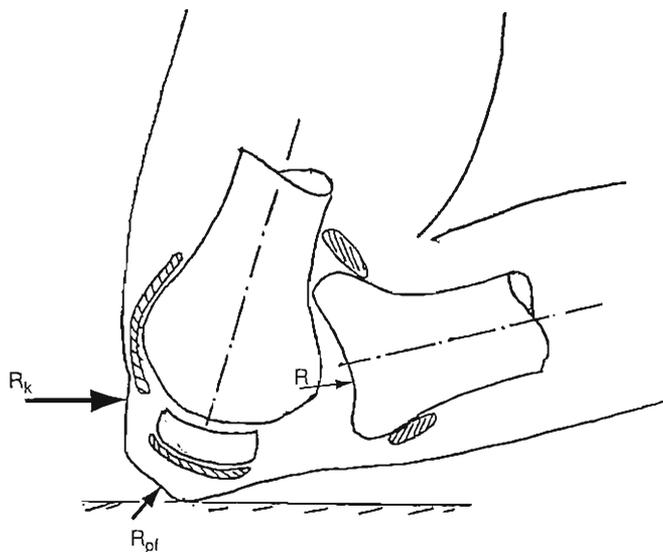

Figure 7e.4 Force configuration in the sagittal plane during impact phase of the knee kicking cycle. Ground reaction forces are assumed to be negligible. R_K, Impact knee force on the knee-kicker; R_{pf}, patellofemoral force; R, resultant force.

parameters of measurement should be skin temperature distribution and the degree of skin redness that could be used as preclinical indicators of inflammation/bursitis.

In comparison with frictional bursitis, the condition of hemobursa (bleeding into a bursa) may be produced in people whose activities require them to make repeated contact with a hard surface or object, such as those experienced by carpet layers. In the case of carpet layers, sheer impact force on the knee-kicker may be sufficient to injure the bursae located posterior and anterior (pre) to the patella. Blood within the bursae causes chemical irritation, and in severe cases it may clot, causing adhesion of connective tissue and loose bodies. At this stage, chronic inflammation is likely to set in. The presence of loose bodies causes a specific cracking and grating sound when the knee is flexed and extended. Chu et al[32] showed that the presence of loose bodies can be quantified by noninvasively measuring and characterizing the "acoustic signature" using a special purpose (20 to 20,000 Hz) microphone (attached to a waveform analyzer) in an auscultation examination of the knee joint. Development of this kind of methodology is highly recommended for a future project because this technique may be sensitive enough to identify the preclinical signs of the existence of loose bodies as well as some degenerative knee joint disorders.

In addition to the trauma to the bursae, Thun et al[122] also reported the existence of arthritic conditions in the carpet layers. They did not specifically distinguish between osteoarthritis and

rheumatoid arthritis. In the carpet layers' case, biomechanics can be used to explain the existence of potential osteoarthritis. Previous investigators[77,100] implied and showed that with increase of articular stresses and asymmetric loads beyond the capacity of resistance of bone and cartilage tissues, osteoarthritic lesions appear and develop. From our field study and biomechanical analysis of the impact data and the position of the knee during the impact phase of the kicking cycle, we see that the result of R_k (impact knee force on knee-kicker) and R_{pf} (patellofemoral force) (Fig. 7e.4) either (1) acts eccentrically at the articulating surface, creating uneven pressure distribution on the cartilage and therefore present conditions for developing osteoarthritis, or (2) acts laterally, resulting in eccentric squeezing of the patella against the femur that increases localized stress with bone osteophytes, destruction of cartilage, and narrowing of joint space. Either of the above two conditions in conjunction with the impacting nature of the load experienced by the carpet layers give sufficient biomechanical reasons to promote osteoarthritis of the knee. Whatever the nature of the underlying cause, it appears that there is a need to quantify the existence of knee osteoarthritis in carpet layers at a preclinical stage. To date, this type of degenerative disease (generally irreversible) can be identified only when the actual sclerotic lesions have appeared on the tibiofemoral joint surface. These lesions are visible on an x-ray film.

In our laboratory we have further developed, refined, and validated a previously reported[133] noninvasive method for quantifying preclinical biomechanical parameters of knee osteoarthritis.[2,50,111] Briefly, this technique allows noninvasive quantification of stiffening (or damping) properties of subchondral bone in the osteoarthritic patients compared with normal subjects. Previous study[101] has shown that stiffening of subchondral bone may be used as a preclinical indicator of knee osteoarthritis. The experimental protocol involves attaching single-axis accelerometers at the tibial tuberosity and femoral condyles of each subject for collecting heel-strike–induced acceleration waveforms. The rationale is that the stiffer subchondral bone of osteoarthritic patients produces high-frequency bone vibration compared with those produced by normal subjects. Because of decreased damping capacity of the subchondral bone, harmful forces due to external loads (either produced by the occupational task and/or natural heel strike events) damage the knee cartilage and eventually traumatize the tibiofemoral bony surfaces. Ultimately, the incoming forces continue to progress toward the hip, causing it to become the next target of trauma.

The results from our previous and ongoing studies with clinically diagnosed osteoarthritic patients[2,52,113] (Bhattacharya, Watts, and Waters, 2004, unpublished data) indicate that this technique can differentiate osteoarthritic acceleration patterns from those obtained from normal subjects. The purpose of this study[52] was to describe the accelerometric technique used to estimate tibial damping properties among osteoarthritic subjects. Tibial tuberosity bone vibration was captured in 8 osteoarthritic patients and 10 normal subjects with a skin-mounted low-mass accelerometer described in the literature.[7,25,130-132] The subject was asked to walk on a force plate.

Trabecular damping was estimated assuming a single degree of freedom model in which the tibia and foot were considered together as a lumped mass and the trabecular behaves as a linear
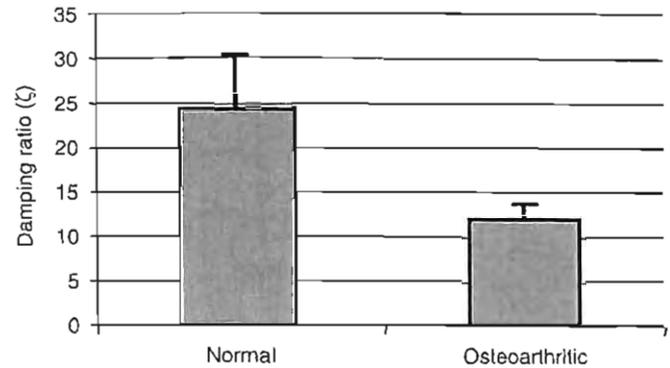

Figure 7e.5 Tibial damping calculated by accelerometric technique. (From Huang S, Bhattacharya A: *Chin J Med Biol Eng* 13:255-264, 1993.)

spring and viscous damper.[10,34] During a force plate event (patient steps across force plate), the single degree of freedom system responds to the transient force in accordance with the solution to the second-order differential equation. Using a frequency response function (transfer function between the force plate and the acceleration at the tibia), the solution to a differential equation, a trabecular-damping fraction (ratio, ζ), was obtained directly from a measured frequency response function using a technique adapted from Coleman[34] and Bendat and Piersol.[10] The results showed that the osteoarthritic subjects have higher resonant frequency and decreased damping (Fig. 7e.5) than the normal subjects. It implies that the subjects with osteoarthritis have a decreased shock-absorbing capacity in the tibia and stiffer bone compared with normal subjects. Therefore it is a worthwhile effort to investigate this technique for identifying preclinical signs of osteoarthritis in the carpet layers.

Based on the above discussion and our previous studies, the following parameters should be measured as descriptors of mechanical loading of the knee joint in carpet layers: kneeling time, knee-kicking frequency, kneeling pressure/force, and knee-kicking impact force. The above parameters can be used to define new indices of biomechanical loading of the knee joint for carpet layers. One such index, called the Cumulative Impact Loading Index, is described in our earlier publication.[18] The corresponding clinical/physiologic response variables should include (1) location and size of inflammation region, (2) skin temperature distribution of the inflamed region, (3) degree of skin redness, (4) range of motion of knee joint, (5) acoustic identification of the existence of loose bodies, and (6) noninvasive preclinical quantification of an osteoarthritic condition.

Work-related lower extremity vascular problems

Many occupations require long periods of standing, including workers in the manufacturing, service, and retail sectors. Epidemiologic studies have shown certain health outcomes to be associated with occupational prolonged standing, including

chronic venous insufficiency,[41,57,58,125] varicose veins,[1,56,114,126] low back pain,[73,85,105] symptom-free venous reflux,[61] hip osteoarthritis,[37] leg and foot pain,[105] varicose symptoms without varicose veins (hypotonic phlebopathy),[5] venous disease,[42] arthrosclerotic progression (as measured by ultrasound of carotid intima media thickness),[56] and trunk varices.[116] Abramson et al[1] estimated the prevalence of varicose veins in the general population to be 10% in men and 29% in women. Krijnen et al[57,58] found the prevalence of venous insufficiency in a population exposed to occupational standing to be 29%. Chronic venous insufficiency is often unrecognized in the occupational population because it is sometimes asymptomatic.[58] Much more research is needed to investigate causes of venous insufficiency.[41]

Biomechanical studies have shown prolonged standing to be associated with increased plantar pressures[61] and pain and increased leg internal fluid volume.[57,58] Prolonged standing can cause lower leg and back discomfort.[102] Magora[75] reported a high incidence of lower back pain for workers standing more than 4 hours a day. In addition to lower back pain, supermarket workers such as checkout personnel have a high incidence of lower limb discomfort and pain.[105] Leg discomfort and fatigue is also found in assembly and quality control inspection workers.[103] Eighty-four percent of French female health care workers stand more than 4 hours a day, compared with 43% in the general population.[39] German laundry workers stand 70-80% of their work time per day.[39]

Physiology/biomechanics of prolonged standing

The upright posture poses a challenge for the human cardiovascular system. In the upright position about 70% of the total blood volume is below the heart level and three fourths of the blood volume is located in the compliant veins.[104] With upright posture, the increased hydrostatic pressure causes marked distension of the veins, causing pooling of the blood as increased filtration of fluid from the capillaries remain in the interstitial space (extracellular fluid) of the legs instead of returning to the heart. In the upright position, the mean capillary pressure of a person of average height may increase by 80 mm Hg to a value of about 125 mm Hg.

During sudden upright position, the hydrostatic column of the blood in the vein between foot level and the heart level is broken up by a series of one-way venous valves. However, as the standing time progresses, the blood continues to flow from the arteries into the lower extremity veins, causing the blood to pool and thereby forcing the valves to open, causing an uninterrupted hydrostatic column of blood to form between the foot vein and the right atrium. Under these conditions, about 600 ml of blood usually shifts from the central circulation to the veins in the lower legs.[72] Up to 30 minutes of standing causes the following responses to take place. When humans stand upright, both central venous and arterial pulse pressures fall, causing an increase in venous muscle tone via innervation of the sympathetic vasoconstrictor nerves supplying the smooth muscles of the venous walls. The increase in venous muscle tone increases the stiffness of the vein walls, causing the pressure of the blood within the veins to rise; this increased venous pressure then drives the blood out of the vein toward the right heart.[114] Once the standing task continues beyond 30 minutes, both the neural and humoral responses play significant roles. With prolonged standing, the

stimuli to initiate neural/humoral responses are a decrease in central venous pressure, arterial pulse pressure, and arterial mean pressure. The neural/humoral responses are an increase in sympathetic activity, plasma norepinephrine, heart rate, vasoconstriction, and vasopressin or antidiuretic hormones.[104] The release of antidiuretic hormones is modulated by the atrial mechanoreceptors that sense the shift in fluid volume to the lower leg as a decrease in fullness of the vascular system. This hormone has water and salt retention properties that may constitute an effective long-term adjustment to the upright posture.

The mechanism behind muscle pain/discomfort due to prolonged standing is not well understood.[52,113-115] Some human studies[113-115] using thermodilution techniques (along with hematocrit, hemoglobin, lactic acid, and muscle biopsy) have shown that submaximal static muscle contraction (such as prolonged standing) causes an increase in muscle water content due to an increase in extracellular water (possibly affecting muscle membrane potential due to changes in potassium and sodium contents of the muscle as per Sjogaard et al[113]), and with maximal static contraction intracellular water increases. One reason for an increase in water in the muscle is because lactate formed during fatigue is transported into the t-tubules where it attracts water and causes t-tubule swelling and vacuolation.[62] Bakke et al[9] in a study on humans showed significant correlation between muscle edema (as measured by an increase in extracellular fluid retention by the muscle) and subjective pain/discomfort. Therefore, previous studies,[28] in which external leg volume was measured before and after prolonged standing, showed no statistically significant correlations between leg discomfort and leg volume change. This insignificant relationship could be due to the fact that an increase in leg discomfort may not be linearly related to venous pooling, because with sustained standing, compensatory mechanisms may actually reduce the venous pooling temporarily.[9,104]

WORKPLACE ADAPTATION/ RECOMMENDATIONS

Injury/disease prevention plan for jobs requiring use of knee: carpet layers' tasks

The development of an effective injury prevention program involves three phases: (1) identification and estimation of the level of the health hazard/injury for a specific job, (2) development of a hazard/injury monitoring program, and (3) control of the hazard. As far as the carpet layers study is concerned, the hazard has been identified and its potential risk determined. We, in our laboratory, and others developed techniques to estimate the level of biomechanical loading and estimation/ measurement of medical/physiologic variables of lower extremity trauma. For example, to monitor and quantify the level of external loading exposure to the knee joints during daily carpet installation activities, we designed and developed an "electronic kneeling meter" that can measure and record the number of kneelings, length of kneeling time, and number of kicks applied by a worker during a working day[15,20,46] (Fig. 7e.6). These parameters are then used for calculating a cumulative loading parameter for the knee joint. This unit is a self-sustaining microcomputer
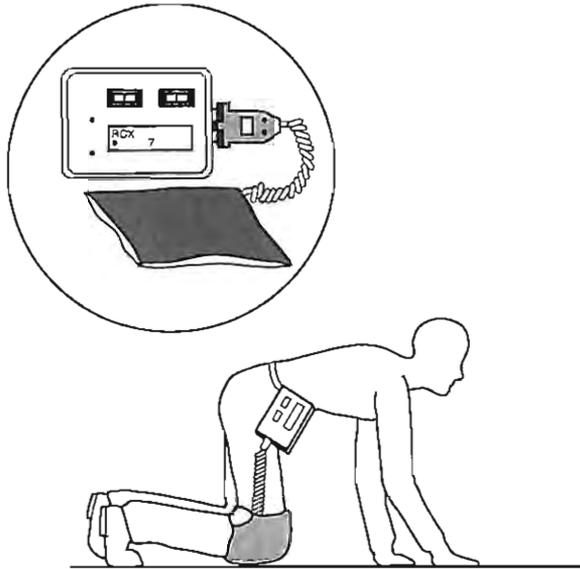
Figure 7e.6 Kneeling/knee-impact meter.

system controlled by a microprocessor through a software program stored in a nonvolatile microprocessor chip. This device is worn as a knee pad on the infrapatellar and suprapatellar regions. The entire system is designed for portability, and the display and storage of kneeling parameters remains intact for at least 4 hours before the data need to be downloaded (on a laptop computer) and stored for future analysis. The use of this device allows quantification and characterization of the dose of external loading on knee joints associated with tasks requiring the use of the lower extremities.

For the quantification and characterization of early medical/physiologic effects of exposure to chronic low-level biomechanical loading of the knee, a microprocessor-based liquid crystal thermography technique was developed in our laboratory.[46] The developed system, which is inexpensive and portable for field use, uses flexible sheets embedded with liquid crystals that have both thermal and fluid properties. These sheets are factory calibrated to produce different colors for known temperature ranges. The flexible liquid crystal sheets are cut to fit the surface of the suprapatellar and prepatellar regions of the knee joints. For the evaluation of the temperature profile of the knee regions exposed to knee-kicker impact and kneeling tasks, the subject is first seated in an air-conditioned room with his or her leg inside a glare-free box. Once the liquid crystal patch is placed on the knee joint (either suprapatellar region or the prepatellar region), the colors are allowed to change and finally stabilize. An individual thermographic sheet displays its full range of colors from brown (coldest) to blue (hottest) within a range of 3 or 4°C. These color changes are continuously recorded on tape with a video camera. The video data are analyzed off-line with the help of a TARGA-16 based video-digitization system with custom-developed software that allows calculation of liquid crystal areas of equal temperature zones. The output of this software allows us to identify the "hot spot" regions of the knee joint of the subject. This technique has been evaluated on arthritic and rheumatic patients, and the results suggest that the technique is

accurate in detecting joint inflammation in the absence of visible impairment.

This thermography system was tested at the site of a local hotel undergoing renovation.[46] Two carpet-installer tradesmen volunteered to undergo a day of testing with the thermography sheets. Both were experienced workers with 10 and 11 years experience as carpet installers, respectively. Measurements were taken before work began, at mid-morning and mid-afternoon breaks, just before lunch, and at the end of the work day. Because the thermography sheets we used had a narrow temperature range and we did not know what temperatures to expect from the workers' knees, we assembled a collection of thermography sheets that could detect temperatures from 22 to 42°C. The two tradesmen went about their typical work activities that included a mix of unloading rolls of carpet from the delivery truck, cutting carpet and pads to size, laying tack strip and molding, and stretching carpet. We assumed that the workers were spending about 75% of the work time on their knees as indicated by our previous study.[18] The individual and combined results for the upper knee (suprapatellar) of the two workers over the course of the work day are presented in Figure 7e.7.

Measurements were taken on both the prepatellar and suprapatellar regions of the knee, but only the suprapatellar are presented because this part of the knee, which makes contact with the knee-kicker, produced the most dramatic results. The highest knee temperature detected was 30.1°C. The percentage of total patch area for each temperature color was calculated by outlining each color with the computer mouse and using the customized computer program to calculate the total area for each color outlined.

The results of this case study indicate that the use of contact thermography, in conjunction with the analytical methods described above, may be an effective and expedient means of obtaining quantitative measures of knee temperature patterns in response to work involving the knee. Although the increase in the size of the "hot spots" on the knees of the two volunteer carpet installers was steady and consistent over the course of the day, the exact cause of the inflammatory response cannot be ascertained from an analysis of thermographic records alone. Questions to be answered are whether or not the observed inflammatory response was due to the work that was performed that day or to an existing knee inflammation that the workers may have developed over the course of their careers. Other questions that are raised include whether or not recovery to the knees would occur overnight, and whether these workers would demonstrate similar patterns of knee temperature increases while performing other knee-intensive activities such as walking, stair climbing, or crouching with a bended knee. A larger more in-depth study is needed to address these issues. Nonetheless, we conclude the following from this study:

1. Knee temperatures appear to increase consistently as cumulative biomechanical loading increases.
2. Contact thermography is able to detect these changes.
3. The thermographic system we developed provides a feasible means of measuring knee temperature at the work site.

Some of the techniques such as those described above are tested and validated, and others may require some refinement. What remains to be done is the development and validation of a
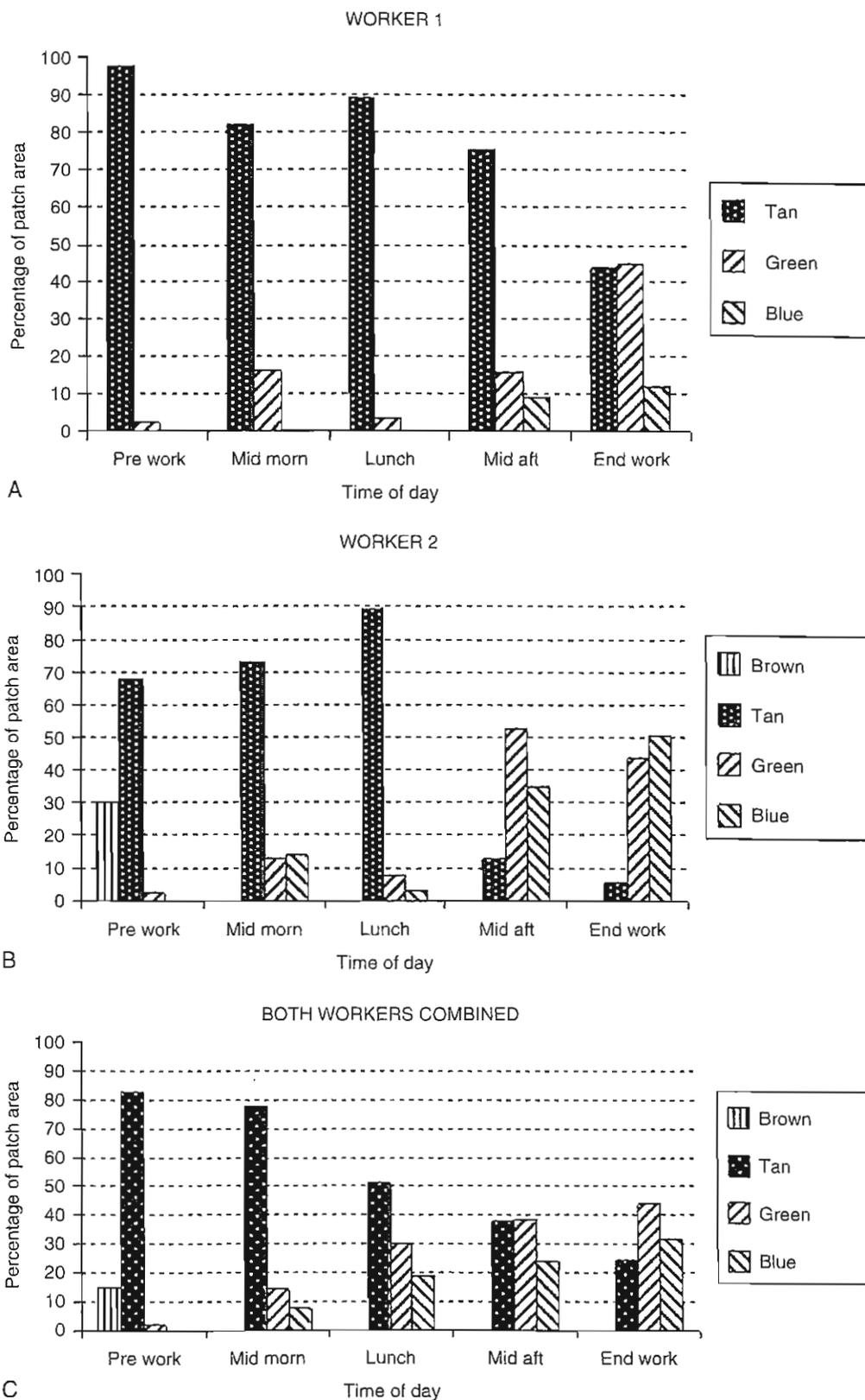
WORKER 1

A

WORKER 2

B

BOTH WORKERS COMBINED

C

Figure 7e.7   Histograms showing the distribution of thermography patch colors for each worker separately and combined results for both workers. (From Habes D, Bhattacharya A, Millliron M: *Appl Ergonom* 24:111-115, 1994.)

dose-response curve in a long-term prospective study that would be appropriate for development of a trauma/injury monitoring program. The methods and device(s) described here set the framework within which a long-term prospective study can be developed in the future. It is through such prospective study that one can determine the dose-response characteristics of job-related lower extremity cumulative trauma caused by external loading.

The biologic system is capable of tolerating short-term low levels of external loading with complete recovery. However, it is possible, after a certain amount of biomechanical insult to the knee region, that the biologic system will show early (preclinical) signs of tissue damage/trauma as manifested by the inflammatory process. Even before the inflammatory process sets in permanently, the workers may show an increasing level of discomfort of the knee joint region as the biomechanical loading increases due to daily exposure to kneeling and knee-kicking. In summary, it appears that the dose-response curve may have several dimensions, including cross-correlation among variables of biomechanical loading, knee joint discomfort rating, medical/physiologic response, and incidence of permanent knee injury. Such a dose-response curve (once established with a large population) could be made available to the worker or trade groups, such as unions, to show its application regarding identifying their members' state of risk by measuring certain cumulative biomechanical parameter(s) on a regular basis along with proper and periodic medical evaluation. The primary objective would be to avoid getting close to the "irreversible trauma zone" of the proposed dose-response curve shown in Figure 7e.8. This could

be possible by suggesting proper work practice procedures and work rotation (rotating workers from knee-kicking activity, which is more traumatic, to other tasks of the carpet installation job).

We drafted a preliminary guideline for the development of a work practice guide.[16] It is envisioned that with the availability of such a monitoring program, one can make significant improvement in arresting and minimizing the high morbidity ratio found among carpet layers. Some of the information that will be generated for carpet layers can be modified for use by other professions (tile setters, floor layers, etc.), and in other occupations where the kneeling posture is also common.

In addition to the above-mentioned significance to worker health associated with the proposed development of a dose-response curve, tool redesign is certainly another approach that needs to be explored to investigate methods to further reduce injury among carpet layers. A study conducted by Liu et al[68] in which the knee-kicker pad was modeled as a viscoelastic solid, concluded that the typical pad does little to attenuate the impulse of the kick stroke. That is, the pad is effective in transmitting the force produced by the worker's knee to the carpet being stretched but does little or nothing to cushion the blow to the worker's knee. The authors concluded that different pad materials need to be developed that better absorb harmful force transmissions and distribute the forces more evenly to the knee and for a longer time. They believed that with future research such a material could be found that reduces the trauma to the worker's knee while maintaining the sharp impulse applied to the carpet.

In response to the research described above, NIOSH published an Alert entitled "Preventing Knee Injuries and Disorders in Carpet Layers."[83] The purpose of a NIOSH Alert is to inform workers and employers of a health hazard, solicit the public for assistance in preventing the described health hazard, and provide recommendations for injury prevention and control based on what is known at the time. In the Alert, NIOSH recommended the following:

1. Employers educate workers about the hazards of kneeling and using a knee-kicker.
2. Workers wear protective knee pads while working on hard floor surfaces.
3. Power stretchers should be used wherever possible.
4. Conduct research to develop carpet installation methods that further reduce the physical stress and trauma incurred by carpet layers.

A power stretcher is a tool that looks like a typical knee-kicker but is anchored to the opposite wall by attaching a series of telescoping tubes to its end. Once the power stretcher is spanned across the width of the room, force is produced by pushing downward on a handle that uses the leverage obtained from the stationary wall. Power stretchers are effective and relieve the worker from impact forces to the knee but are not used as often as possible because they are expensive, require more setup time, often lack portability, and cannot be used in small spaces such as hallways and stairs.

A new type of carpet stretcher mechanism has emerged that promises to remedy some of the inconveniences of the power stretcher while maintaining its ability to stretch carpet. Called the "stretcher adapter," it is a short piece of tube attached to
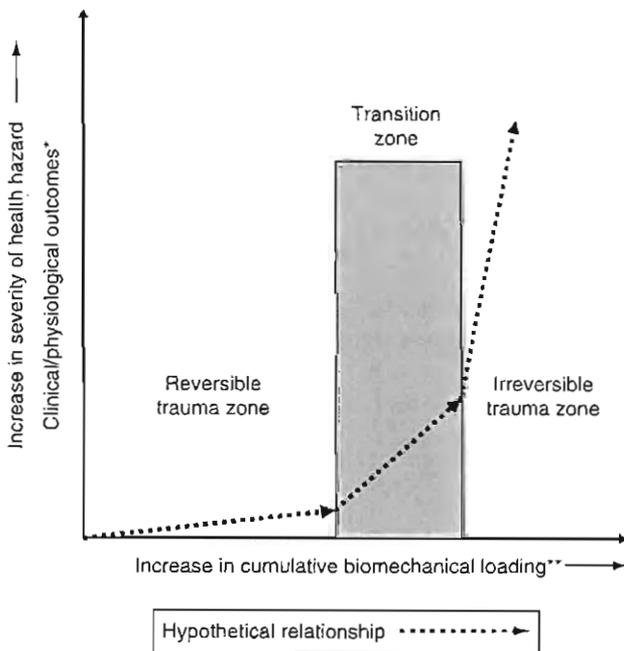
Figure 7e.8   Schematic of hypothetical association between cumulative biomechanical loading of the knee and the early symptoms of clinical/physiologic outcomes.

the end of the power stretcher head that receives its leverage by insertion of a sharp pin directly into the floor. The stretcher adapter puts a hole in the carpet, underlying pad, and floor and cannot be used when installing carpet over concrete, but it reduces the setup time for the power stretcher, is lightweight and inexpensive, and can be used in small spaces such as hallways and closets (http://mctltd.com/StretchAdapter.htm).

The stretcher adapter also causes no structural damage as can occur when a power stretcher is anchored against a wall in the room being carpeted. Innovations like these are what is needed (provided such devices are properly evaluated and found satisfactory) to relieve the carpet installer from the hazardous insults to the knee that have long been associated with this industry.

Communication with trainers and safety specialists at carpentry and floor laying unions indicate that there is more emphasis on safety and safe work practices now than ever before. Workers also have better personal protective equipment such as knee pads that protect the knee and lower leg (www.proknee.com), cushioned insoles for work shoes, and even cushioned antifatigue material that can be wrapped around any type of shoe (http://www.safetyseven.com/ergoflash.html). For carpet and floor installers there are improved tools that reduce fatigue and physical trauma to the lower extremity such as automatic scrapers for ripping up existing flooring, carpet stretchers that can be activated with a lever instead of the knee (www.kneeless.com), and double-headed mini–carpet stretchers that more easily and quickly align seams for carpet that is glued to the floor. Nail guns used by carpenters eliminate the fatigue of hammering and allow framing and trim work to be accomplished quickly and efficiently, which means less time spent in hazardous postures such as kneeling and squatting. The experts say that a worker who is not fatigued will more likely take the time to work smartly and safely.

According to one source, the traditional carpet stretcher is still used, but sparingly. One of the main recommendations of the NIOSH carpet layer Alert[83] was to more extensively use the power stretcher. At first this device was not commonly used by carpet installers because it was cumbersome to use, expensive, and time consuming to set up. Modern designs are lightweight and easy to set up, and attachments exist that eliminate the need to span the stretcher between opposite walls to stretch carpet (http://mctltd.com/StretchAdapter.htm). These improvements have made the power stretcher the tool of choice in most carpet installation jobs.

It is widely believed that comparatively few injuries to the lower extremity for carpenters and floor layers may be due to under-reporting. Despite improvements in tools and installation methods, workers still place a priority on finishing jobs on time. Sometimes cutting corners and overworking their bodies is needed to achieve these goals. The bottom line is that more emphasis on safety and the availability of more safety and health information, such as the NIOSH carpet layer Alert, may have made a difference in the musculoskeletal health of building trade workers, but working smart and safe is a constant struggle that must continually be reinforced. Ultimately, surveys of workers in controlled studies must be conducted to determine the true extent of any changes in the hazards of this type of work and the manner in which workers cope with it.

Antifatigue mats for jobs requiring prolonged standing

To reduce body discomfort and fatigue, antifatigue mats have been used in many industries. Many researchers have investigated the relationships between subjective measures, such as self-reported body discomfort, while working on different surfaces (such as an antifatigue mat) and objective measures, such as electromyography recording on the lower legs and back,[35,40,47,48,74,79,140] leg volume,[28] movements of the ankle and center of pressure, and other biomechanical parameters.[28,40,47,48,74] Because of the pull of gravity, prolonged standing may cause poor venous pump activity, which may cause leg edema and body discomfort.[137] In addition, poor venous pump activity has been documented as a result of prolonged standing on poor resilient surfaces.[23] The effects of various standing surfaces on venous pump activity were evaluated in some studies.[21-23,102,103] The results have shown that antifatigue mats with increased elasticity/stiffness can increase venous pump activity of the legs and reduce body discomfort.[28] However, the range of values of elasticity/stiffness and energy absorption of the floor mats, which are shown to be beneficial, have not been reported in the literature.

Impact of contaminants on antifatigue properties of floor mats

In many working environments, such as automobile parts manufacturing plants or food processing facilities, antislip and/or antifatigue mats are often contaminated with water, oil, or other fluids. The effectiveness of the antislip properties of antislip and/or antifatigue mats with different contaminations and the reduction of body discomfort while performing a job task are not well documented in the literature. The effectiveness of the antislip property of mats is "qualified" by manufacturers as "good" slip resistance. This measure is not adequate for working environments because the slip resistance of the mat is related to the shoe worn by the worker and the task being performed.[29-31] Furthermore, the presence of contaminants such as water and oil can modify an antifatigue mat's mechanical properties, which have been reported to relieve postural fatigue due to prolonged standing.[28] Cham and Redfern[28] reported that floor mats with increased elasticity, decreased energy absorption, and increased stiffness are associated with lower levels of fatigue of the lower leg and the back area. However, repeated exposure to oil and/or water decreases the mat's stiffness and elasticity, thereby compromising its antifatigue properties. Contaminants also reduce the antislip properties. Previous studies from our laboratory showed that postural stability is significantly compromised during dynamic and semidynamic task performance on slippery surfaces.[27,28,30,31,71,135]

Limited studies[109] from our laboratory also showed that leg muscle workload associated with bicycling significantly ($p < 0.007$) impairs postural stability. Previous electromyographic studies[51,80] have shown that pedaling activity uses predominately the same muscle groups (hamstrings, triceps surae, gluteus maximus, tibialis anterior, and quadriceps) that are needed to perform standing and walking activities. Seliga et al[109] showed that postural sway length significantly increased with increasing workload from 40 to 125 watts, implying postural instability. Therefore, when postural muscles are overworked for maintaining

upright balance on a slippery surface, it is reasonable to assume that with prolonged standing/walking on slippery surfaces, the postural muscles experience further fatigue and discomfort, causing potential postural instability and fall/near fall-related injuries.

In a pilot study at an auto manufacturing plant, the effect of task performance on slippery surfaces (concrete and floor mats) on body part pain/discomfort and slips and their association with surface coefficient of friction was carried out by our research group.[70] The results suggest that workers' body pain or discomfort may be caused by the task characteristics or the combination of working on the slippery surface and the task characteristics. Under these circumstances, there is a need to modify the mat's properties in such a way that it has a reduced rate of absorption of a contaminant such as cutting fluid/oil/coolant and an increased coefficient of friction value, while preserving the desired material properties associated with its antifatigue features. One such technique is to deposit plasma polymerized films onto the mats to vary the coefficient of friction and to control the uptake of cutting fluid/coolant/oil.[118-121]

The above literature review raises several questions regarding the floor mats used in industries where workers have to perform tasks during prolonged standing on mats contaminated with oil/coolant/cutting fluid: How do contaminants modify the mechanical properties of the floor mats? Do contaminants detrimentally modify the antifatigue properties of the mats? Do antislip mats provide proper frictional properties as well as antifatigue properties?

Shoe inserts/insoles for jobs requiring prolonged walking

Because walking and running give rise to heel strike–induced forces in the musculoskeletal system, the transmission, absorption, and attenuation of energy that intakes to the skeleton due to heel strike are an important component of bone physiology and pathology.[44,84,98,134] The human locomotion system, which consists of natural shock absorbers (joints with viscoelastic components, articular cartilage, meniscus, intervertebral disks, trabecular bone, etc.), is subjected to constant insult not only during weight-lifting activities but also during normal daily activities such as walking and running.[6,16,130,131] During heel strike, the vertical force component acting on the foot is on the order of 1.5 times the body weight depending on walking velocity.[16,129] These force waves are gradually attenuated by the body's natural shock absorbers on their way toward the head. The process of force wave attenuation is the body's natural way of protecting the vital organ, the brain. In healthy subjects, 70% of the incoming shock waves are absorbed by the body's natural shock absorbers before it reaches the forehead.[7,16,44,130,133,134] Among all natural shock absorbers in the human body, the trabecular bone has the highest capacity (170 times higher than that provided by the cartilage) to attenuate incoming shock wave associated with heel strike during walking and running.[96] Previous researchers have shown that such cumulative loading may give rise to gradual fracture of subchondral bone trabeculae, which through healing of the fracture actually renders the subchondral bone stiffer, thereby decreasing its shock-absorbing capacity.[94,97,99,124]

Such stiffening of subchondral bone has been found to be associated with osteoarthritis, one type of degenerative musculoskeletal disease.[45,94,97]

Based on the above discussion of the potential detrimental impact of heel strike–induced trauma of the knee joint, it is reasonable to use a shock-absorbing type of material in the lower extremities to dampen the incoming shock waves. The use of shoe inserts and insoles have been reported in the literature to help minimize pain and discomfort associated with degenerative disorders of the knee such as osteoarthritis. In our laboratory, a study[110] with 24 subjects (normal and osteoarthritic patients) was carried out to determine the impact of shoe insert (pad) in reducing heel strike–induced acceleration measured at the tibial tuberosity. The results showed that a shoe insert or pad reduced the high-frequency heel strike force-induced shock waves over a larger frequency range as compared with that provided by the physiologic shock absorbers available in the human body when a shoe insert was not used.

Specialized shoe orthotics have been evaluated to determine their effectiveness in minimizing osteoarthritis associated pain/discomfort.[84] Kerrigan et al[53] tested lateral-wedged (5 degrees) insoles and found them to be biomechanically effective in potentially reducing loading of the medial compartment in patients with knee osteoarthritis. In a study by Toda et al,[123] two types of shoe inserts were evaluated. The effectiveness of a novel lateral wedge insole with elastic strapping was compared with that of a traditional shoe insert/insole in 90 female subjects with osteoarthritis of the knee in an 8-week study. The subjects wearing the novel lateral wedge insole with elastic strapping showed a significant improvement in their pain and decreased femorotibial angle and talar tilt (i.e., leading to valgus angulation of the talus). For the traditional patients wearing shoe inserts such improvements were not found. Although Kerrigan et al,[53] Toda et al,[123] and others[36] reported some beneficial effects of the use of laterally wedged insoles, Maillefert et al[76] did not show any pain relief from short-term (6 months) use of the shoe insert in medial femorotibial osteoarthritic patients. In addition to the use of shoe inserts, there is some evidence in the literature regarding the role of exercise programs for minimizing insult to the knee joint. Oddis[84] recommended use of isometric muscle strengthening of the quadriceps, which may act as the shock absorber for the injured knee.

Although studies of shoe inserts in osteoarthritic patients have been well documented in the literature, there are a lack of data regarding the use of this form of intervention in occupational populations. Finally, there is a need for research studies where shoe inserts and specialized exercise programs can be tested as preventive tools in workers exposed to activities requiring prolonged walking and standing.

A two-part case study from an industry in workplace accommodations for an acute knee injury and subsequent chronic pain, discomfort, and work restrictions

Case study part 1: Prevention of recurrence of a knee injury that resulted from a fall while

descending a staircase and carrying a 24-pound power tool

The worker and task

A right-handed 52-year-old man approximately five feet ten inches tall and weighing about 210 pounds worked as a maintenance and service technician for over 18 years for the same company. At the time of this writing, he was one of seven technicians performing roughly the same tasks. His job required frequent walking throughout the facility and occasionally ascending and descending staircases while carrying various tools and equipment that weighed from just a few pounds to nearly 40 pounds. He estimated that he typically climbed and descended staircases three to five times during each regular 8- to 10-hour shift. The nature of the business and potential safety hazards required him to wear steel-toed boots with metatarsal arch protection, a flame-resistant long-sleeved jacket, a hardhat, eye protection, and hearing protection.

The facility where he worked was built in the early 1970s, and it had not changed significantly over the next 30 years, except for occasional cleaning, repairs, and minor alterations to the walking and working surfaces. Until the spring of 2001, this worker had no history of knee or lower extremity injuries or discomfort and could not recall experiencing any significant slips, trips, or falls during his 18 years of service. He reported to be "very familiar" with the facility and until the experience described below had not missed a day of work as a result of a work-related mishap. However, according to the company's Occupational Safety and Health Administration (OSHA) 200 logs, there had been three other lost-time injuries to three separate workers resulting from slips, trips, and falls during the previous 3 years.

The accident and injury

One afternoon in April 2001, the worker was returning to the tool crib after completing a job that required the use of a powered chipping hammer to break concrete. He reported carrying the tool, which weighed about 24 pounds, in his right hand and walking at a moderate pace. He decided to cross over a bridge that recently had been closed for repairs but had been reopened. He stated that he typically had crossed the bridge many times in the past but that his regular path over the bridge had been altered for about 3 days while repairs to the bridge were in progress. The bridge was constructed with seven metal steps up one side, a platform over and across some mechanical equipment below, and seven metal steps down the other side. The worker climbed up the first set of steps, crossed the platform, and while descending the other side, misjudged a step, lost his balance at about the third step from the bottom and fell to the floor, dropping the power tool and feeling a sharp burning pain in his right knee. After the fall, he stood up carefully and took a few steps toward the chipping hammer that had slid several feet across the floor, but he could not bear the pain so he sat down on one of the steps and then called and waited for assistance. An emergency medical examination that evening discovered a torn medial collateral ligament in his right knee that would require surgical repair and 3 to 4 weeks of lost work.

Safety and ergonomic assessment

Recall that the worker had no history of knee or lower extremity disorders and did not recall experiencing any significant slips, trips, or falls during his 18 years with the company. Also, he had become very familiar with the facility and until this accident had not missed work as a result of an on-the-job mishap. Therefore, the assessment of the safety hazards and ergonomic risk factors began with the design and construction of the staircase at the specific location of the accident according to the following criteria:

1. Standard conventional angle of stairway rise (slope), height of each step (riser), depth of each step (tread run), slip resistance of each tread and leading edge (nosing), and uniformity throughout the entire flight of stairs per:
   a. OSHA 29 CFR 1910.24 (e): *Angle of stairway rise*[88]
   b. OSHA 29 CFR 1910.24 (f): *Stair treads*[89]
   c. Lehmann[65]: Stairs of the following dimensions require the least energy consumption and "seem to cause the fewest accidents."[59]
      i. Slope of 25-30 degrees
      ii. Recommended formula: $2h + d = 630$ mm (24.8 in); where h = height of riser and d = depth of tread
   d. Rapid Entire Body Assessment, REBA[49]

Assessment results

OSHA 29 CFR 1910.24 (e)[88] states that fixed stairs shall be installed at angles to the horizontal (slope) of between 30 and 50 degrees. The 43-degree slope of the staircase at the location of the accident was in compliance with the standard.

Table 7e.1 from the OSHA standard[88] shows "riser" and "tread run" combinations that when uniform throughout the entire flight of stairs, produce a stairway within the permissible range. The table also shows the slope (*angle to horizontal*) produced by each combination and that each step of a stairway having a 43-degree slope should have a "riser" of approximately 8-1/2 inches and a "tread run" of roughly 9 inches. OSHA 29 CFR 1910.24 (f) reemphasizes that the "risers" and "tread runs" shall be *uniform* throughout any flight of stairs.[89]

Each of the seven steps that were being descended by the worker at the time of the accident were measured as shown in Table 7e.1 (accuracy ± 1/8 inch) and numbered from the top step to the bottom. The measurements show that the bottom three steps had rise dimensions that did not comply with Table 7e.1 of the OSHA standard,[88] and that the riser dimensions were not

Table 7e.1   Stairway riser and tread run in case study part 1

Step no.	Riser (in inches)	Tread run (in inches)
7	8-5/8	9-0
6	8-1/2	9-0
5	8-1/2	8-7/8
4	8-3/8	9-0
3	8-0	9-0
2	7-7/8	8-7/8
1	9-5/8	9-1/8

uniform throughout the flight of stairs. Further investigation revealed that steps 2 and 3 had been repaired because they had become rusted and had partially broken loose from the metal frame. Steps 2 and 3 had been raised slightly and rewelded to the frame, which shortened their riser dimensions by 5/8 and 1/2 inch, respectively, consequently increasing the riser of step 1 by 1-1/8 inches.

OSHA 29 CFR 1910.24 (f) states,[89] "all treads shall be reasonably slip-resistant and the nosings shall be of non-slip finish. Welded bar grating treads without nosings are acceptable providing the leading edge can be readily identified by personnel descending the stairway and provided the tread is serrated or is of definite non-slip design." The treads of the stairway at the accident location were welded bar grating without nosings, and their leading edges were not clearly identifiable. The tread was serrated and of nonslip design.

According to Lehmann,[65] a staircase slope of 25-30 degrees with uniform risers of 170 mm (roughly 6-5/8 inches) and tread runs of 290 mm (roughly 11-3/8 inches) requires the least energy consumption and seems "to cause the fewest accidents." Lehmann's recommendation for the most "efficient" riser and tread run dimensions can be expressed by the formula

$$2h + d = 630 \text{ mm } (24.8 \text{ in})$$

where h = height of riser and d = depth of tread.

Steps 4 through 7 of the 43-degree-slope staircase where the accident occurred had relatively uniform risers (h) of an average 8-1/2 inches and tread runs (d) of roughly 9-0 inches. Although the 43-degree slope fell within range of the 30-50 degrees specified by OSHA, it exceeded the most efficient slope recommended by Lehmann[65] by 13 to 18 degrees. Also, substituting the 8.5 inches for "h" and 9.0 inches for "d" in the formula gives the result 2(8.5) + 9.0 = 26.0 inches, which is 1.2 inches greater than the ideal.

Other assessment tools

Other ergonomics assessment tools that have been used previously in the facility to identify risk factors related to the various types of injuries and discomforts reported by the workers are the Rapid Upper Limb Assessment (RULA),[78] the Rapid Entire Body Assessment (REBA),[49] the Job Strain Index (JSI),[82] and the Washington State Caution/Hazard Zones (WAC 296-62-051).[136] Each of these tools focuses almost exclusively on the upper extremities, with the possible exception of REBA. Although REBA does not address stresses to the lower extremities specifically, it does include the effect of the legs in its postural analysis of the entire body.

REBA is a postural analysis tool developed especially for the type of unpredictable working postures found in health care and other service industries.[49] Because the working postures of a maintenance and service technician are often unpredictable, REBA was applied after the accident, in this particular case to determine the "action level" (i.e., risk level and action required) of the task of "descending the staircase while carrying a 24-pound tool." The results of REBA are summarized below:

- Score A (trunk, neck, and legs) = 7 (on a scale of 1 to 12)
  - = 4 + 2 (load/force: > 10 kg for the 24-lb tool) + 1 (load/force: shock or rapid buildup of force from "misjudgment" of step)
- Score B (upper arms, lower arms, and wrist) = 1 (on a scale of 1 to 12)
- Score C (combination of scores A and B from Table C) = 7 (on a scale of 1 to 12)
- REBA score = 9 (on a scale of 1 to 15)
  - = 7 (score C) + 1 (activity score: static load of carrying tool) + 1 (activity score: action caused rapid large range in postures or an unstable base)
- REBA action level = 3 (on a scale of 0 to 4)
  - "High" risk level requiring action "necessary soon."

In retrospect, if REBA had been applied beforehand, it would have identified the task as "high" risk in need of corrective action soon, but a question remains: What would have, or should have, triggered the necessity for an assessment, since simply returning a tool to the tool crib typically would not be considered a particularly hazardous task? Answer: The repairs to the bridge should have prompted a safety inspection and an ergonomics assessment of the "changes" made to the walking and working surfaces over the bridge.

Conclusions and corrective actions

As a result of the accident and injury and following the assessments according to OSHA 29 CFR 1910.24 (e) and (f), Lehmann's[65] empirical data, and REBA, the following conclusions were made and corrective actions implemented:

1. The first three steps on the descending staircase of the bridge were replaced. The new risers were each 8-1/2 inches high and the tread runs 9 inches deep (accuracy ±1/8 inch). A complete inspection of the entire bridge and staircase was performed, and an inspection schedule of all bridges and staircases throughout the facility was developed.

2. The leading edges of all the steps at the bridge were made clearly identifiable using yellow and black diagonally striped tape. A plan and schedule to identify unmarked steps and to apply tape as needed was implemented.

3. The following long-term plans were made (Case Study Part 2 covers the long-term accommodations in greater detail):
   a. Reduce the slopes and change the risers and tread runs of the staircases at the location of the accident and throughout the facility to match Lehmann's[65] recommendations as closely as possible.
   b. Relocate the tool crib and strategically locate tool storage cabinets to minimize transit hazards (i.e., climbing and descending stairs), distances and times.

Case study part 2: Accommodations for chronic knee pain and work restrictions while walking, while climbing stairs, and during static standing subsequent to the knee injury described in case study part 1

The worker and task

The 52-year-old maintenance and service technician described in the first part of this case study returned to his regular job in early June 2001, about 7 weeks after his knee injury. Although modifications had been made to the staircase that contributed to his injury and to many of the other staircases to bring them into

compliance with OSHA 29 CFR 1910.24 (*fixed industrial stairs*),[91] the job still required the following physical activities:

- Frequent walking on various surfaces;
- Ascending and descending staircases three to five times a day while carrying tools;
- Climbing portable and fixed ladders four to five times per week;
- Occasionally climbing on various machines and structures to perform maintenance and service tasks;
- Static standing on a concrete floor for up to an hour at a time;
- Occasionally crouching, once or twice a day, to work on low level equipment.

Also, the safety hazards in the plant had not changed; therefore it was a requirement to wear full foot protection and all the personal protective equipment described in Case Study Part 1.

Modifications made and planned during the worker's absence

During the injured worker's 7-week absence, the first three steps on the descending staircase of the bridge at the location of the accident were replaced with steps of the correct design and dimensions. Inspections and repairs of the most frequently used bridges and staircases throughout the facility were completed, and the leading edges of most of the steps were made clearly identifiable using yellow and black diagonally striped tape.

In addition to the above modifications, the following long-term plans were made:

1. To reduce the slopes and change the risers and tread runs of the staircases at the location of the accident and throughout the facility to match Lehmann's[65] formula as closely as possible.
2. To relocate the tool crib and strategically locate tool storage cabinets to minimize transit hazards, such as climbing and descending stairs while carrying tools and excessive walking distances and times.

Physical discomforts, limitation, and work restrictions

Upon returning to his job, the worker felt confident in his ability to perform the essential functions of the job and was relatively satisfied with the progress of his recovery. However, he reported mild to moderate pain and occasional swelling and joint stiffness, especially after walking for more than about 2 hours, standing for more than an hour, and especially after climbing stairs of slopes greater than about 40 degrees, climbing ladders more than twice daily, or crouching for more than a minute or two.

Postoperative medical reports from the physician of record stated that the surgery to repair the medial collateral ligament in the right knee, as well as the subsequent recovery, had progressed with no complications; however, some preexisting degenerative joint disease (osteoarthritis) was discovered. The physician's report placed restrictions on duration and frequency of walking, static standing, climbing stairs and ladders, and crouching and stressed the importance of avoiding reinjury from a slip, trip, or fall.

A written opinion and functional capacity evaluation from a physical therapist stated that the worker had participated cooperatively in his rehabilitation program thus far and was progressing reasonably well; however, it would take approximately 1 year for

him to reach maximum improvement in strength and range of motion.

In summary, the opinions from the worker himself, the physician of record, and the physical therapist provided the following work restrictions for which reasonable accommodations were to be made during the first 6 to 8 weeks of his return to work (work restrictions to be reassessed after each 6- to 8-week period):

1. Walking is to be limited to 2 hours per day.
2. Static standing must not exceed 1 hour per day.
3. Staircases with slopes greater than 40 degrees are to be avoided.
4. Climbing portable and fixed ladders is to be restricted to twice daily.
5. To prevent unexpected or unnatural loading of the knee (i.e., twisting, lateral stress, hyperextension, extreme flexion, etc.), the most obvious slip, trip, and fall hazards should be identified and removed wherever practicable.
6. All crouching, squatting, kneeling, or any activity that requires the right knee to be flexed more than 90 degrees is to be avoided.
7. Climbing on structures without regulation steps, grab bars, walking platforms, and handrails must be avoided.
8. Jumping down from platforms or other structures is to be prohibited.

Assessment methods and tools

In addition to ensuring compliance to the above restrictions for the injured worker, the following safety standards and ergonomics guidelines were to be enforced for the purpose of minimizing risk of injury (or reinjury) to any of the workers:

1. All staircases were to be equipped with railings and guards in compliance with OSHA 29 CFR 1910.23 (d)(1)(i) through (v).[87]
2. The most frequently used staircases were to be modified so that the tread heights and depths fit as closely as possible the following formula recommended by Lehmann.[65] According to Kroemer and Grandjean,[59] "stairs of these dimensions are not only the most efficient but also seem to cause the fewest accidents."

$$2h + d = 630 \text{ mm } (24.8 \text{ in}), \text{ where } h = \text{riser height and } d = \text{tread depth}$$

3. All portable ladders were to comply with OSHA 29 CFR 1910.25 (*Portable wood ladders*),[91] and 1910.26 (*Portable metal ladders*),[92] and with 1910.27 (*Fixed ladders*).[93]
4. All walking surfaces were to be inspected and brought into compliance with OSHA 29 CFR 1910.22 (*General requirements*)[86] regarding housekeeping and aisles and passageways.

Controls and interventions

Table 7e.2 shows the controls and interventions that were implemented over a period of approximately 90 days to facilitate compliance to the prescribed work restrictions, safety standards, and ergonomic recommendations.

Three-year follow-up

In June 2004, a brief telephone interview of the injured worker was done to determine his condition and to check the current status and effectiveness of the workplace modifications. In summary,

Table 7e.2   List of controls and interventions to facilitate compliance to work instructions, safety standards and ergonomic recommendations

Restriction, standard, or guideline	Control or intervention
Walking < 2 hours per day	An electric-powered cart was purchased for transportation across flat surfaces.
	The main tool crib was moved to a central location and three tool cabinets were placed near the three most frequently visited work areas.
Static standing < 1 hour per day	Antifatigue matting was placed on the concrete floors in eight locations.
	Five adjustable-height standing support stools were placed where "standing work" was common.
Avoid staircase slopes > 40 degrees	Five bridges with staircases were modified to comply with the formula 2h + d = 630 mm (24.8 in) which reduced their slopes from approximately 43 to about 35 degrees. All frequently used staircases with slopes > 40 degrees that couldn't be modified were marked accordingly.
Climbing ladders < twice daily	A mobile "cherry picker" was purchased for the maintenance and service department.
Eliminate slip, trip, and fall hazards, and all walking surfaces must comply with 29 CFR 1910.22[86]	A videotape of all walking surfaces throughout the facility was developed and presented to management and all maintenance and surfaces technicians. A 1-year corrective action plan with monthly status checks was developed.
	A 2-hour training program in "preventing slips, trips, and falls" was given to all maintenance and service technicians.
No crouching, squatting, or kneeling	Two large electric motors and one pump were raised from floor level to elbow height. Two standing support stools were placed at these locations, and four adjustable "low stools" were placed near four machines where low-level work is performed regularly.
No climbing on structures without steps, grab bars, etc.; and no jumping down from platforms	Steps with slip-resistant treads, grab bars, and walking platforms were installed (welded) to two machines that are climbed on regularly.
All staircases must have railings and guards per 29 CFR 1910.23 (d)(1)(i) through (v)[87]	*Stairways < 44 inches wide* were inspected to comply with:
	Both sides enclosed–hand rail on right side descending
	One side open–stair railing on open side
	Both sides open–stair railing on each side
	Stairways > 44 inches but < 88 inches wide were checked for compliance with:
	Hand rail on each enclosed side
	Stair railing on each open side
	Stairways ≥ 88 inches wide were checked for:
	Hand rail on each enclosed side
	Stair railing on each open side
	Intermediate stair railing midway
Frequently used staircases should comply with the formula, 2h + d = 630 mm	Although the bridge and staircase at the accident location plus four other bridges in the main walkway of the facility had been made OSHA compliant since the accident, they were further modified to comply also with the Lehmann formula.
	For example, the average riser and tread depth of the 43-degree steps at the accident location were changed from 8-1/2 and 9 inches, respectively, to 7-1/4 and 10-1/4 inches, which reduced the slope to about 35 degrees and required the bridge to be lowered and the staircases to be lengthened.
All ladders must comply with 29 CFR 1910.25, 26, and 27[91-93]	All ladders were inspected and required to be in good condition or otherwise removed from service and tagged.
	A 2-hour training program in ladder safety, including maintenance and utilization of ladders, was given to all maintenance and service technicians.

the injured worker was still actively employed as a maintenance and service technician but in a more supervisory role. He estimated that his workload had been reduced approximately 20% to 30% since the time of his accident and shortly thereafter. His work restrictions have been lifted, but he still experiences occasional stiffness and discomfort in his right knee; however, he sincerely believes that the modifications to the bridges, stairways, and the other walking-working surfaces have made his job, and the work of all the maintenance and service technicians, safer and less physically demanding. Since his accident in April 2001 and following the implementation of the workplace modifications described above, there have been no lost-time injuries reported from slips, trips, and falls according to the OSHA 300 logs. Comparatively, during the 3 years before the accident described in this case study there had been three other lost time accidents from slips, trips, and falls.

Summary and conclusions

This two-part case study describes workplace modifications that were applied, in part 1, for the prevention of the recurrence of an acute injury resulting from a fall while descending a staircase and, in part 2, to accommodate the subsequent long-term pain, discomfort, and work restrictions of the injured worker. The task that was being performed when the injury occurred was assessed using the OSHA standard for walking-working surfaces, namely related to staircase design and construction and an ergonomic formula that suggests an efficient and safe relationship between staircase riser, tread depth, and slope. An ergonomic assessment of the task also was performed using the REBA tool. Each assessment method discovered noncompliances and risk factors that were determined to be likely contributors to the accident. The workplace modifications were directed toward correcting the noncompliances and eliminating or significantly reducing the ergonomic risk factors that were identified. A brief follow-up approximately 3 years after the accident indicated that the modifications were instrumental in allowing the injured worker to return to his regular job and to prevent recurrence of a similar accident and injury.

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Musculoskeletal Disorders in the Workplace

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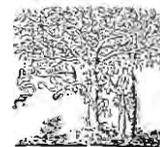
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