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chapter twenty-five

Biomechanics during ladder and stair climbing and walking on ramps and other irregular surfaces

Andrew S. Merryweather and Donald S. Bloswick

Contents

25.1 Introduction/background

Accidents and injuries resulting from climbing on ladders and stairs and walking on ramps and irregular surfaces occur in both the occupational and nonoccupational environments. General guidelines for the design and use of these systems have been developed to reduce the chance of accident or injury, but considerable biomechanical stresses still exist. In this chapter hand and foot forces, upper and lower extremity moments, low-back stresses, physiological cost during ladder and stair use, and lower-extremity biomechanical stresses when walking on uneven surfaces are reviewed and summarized.

During ladder use, upper extremity moment and hand forces are highest during the use of vertical ladders. Lower extremity moment and foot force are highest when using ladders slanted at 20°. Foot slip potential, however, appears to be highest for vertical ladders. Peak back stresses also appear to be relatively high when climbing vertical ladders at a fast speed. Energy expended during ladder climbing is very high.

Both stair ascent and descent require joint moments considerably higher than those required for level walking and significant ranges of motion. Foot forces and body instability, however, appear to be higher during stair descent than ascent. Back stresses during stair use are not considerably greater than those during level walking. Energy expenditure requirements during stair ascent, although lower than ladder climbing, exceed that of any other routine daily physical activity.

Ambulation over ramps and other irregular surface terrain changes normal gait parameters such as cadence, stride length, differences in stance and swing phases, and some biomechanics of walking. The data available describing the differences in moments and lower extremity joint forces are limited for walking over irregular surfaces; however, data

from studies on uphill and downhill walking and running indicate deviations in ground reaction forces and resulting lower extremity joint moments. The position of the center of mass and behavior of upper extremities appears to be altered, but is not well understood. Further research is needed to describe the kinematics and biomechanics of walking over laterally sloped and other irregular surface terrains.

25.1.1 Accidents/injuries

25.1.1.1 Ladders

Climbing activities are performed as part of many occupational and nonoccupational tasks. Injuries from slips and falls or overexertion during climbing activities on ladders frequently result in significant medical expenses and workers compensation costs. Kari et al. [1] note that ladders account for 1%–2% of occupational related accidents. In Oregon, falls from ladders accounted for 457 disabling workers compensation claims or approximately 1.5% of the total claim amount for 1995 [2].

Injuries resulting from falls from ladders appear to be a serious problem in other countries as well. In both Sweden and Germany, ladder accidents account for nearly 2% of all reported occupationally related accidents [3]. In Sweden, with a population of approximately 8.5 million, ladder accidents requiring hospital care relating to recreational or leisure use are estimated at approximately 5000–6000 per year [4] and 2000 relating to professional use [5].

In a study of ladder fatalities reported by OSHA from 1984 to 1998, it was determined that 89% involved straight or extension ladders, 6% involved stepladders, 1% involved fixed ladders, and 4% did not specify [6]. In 2001 it was reported that 15,019 deaths occurred by falls, of which 439 were attributed to ladders and scaffolding, an increase from 10 years previous, representing approximately 1% of the total accidental deaths in the United States during that year [7].

Although the injuries and deaths resulting from ladders have a variety of causes, it is reasonable to assume that the ergonomic or biomechanical "match" between the task requirements and the user capabilities is an important issue.

25.1.1.2 Stairs

It has been estimated that in 1975 there were approximately 2×10^{12} stair uses, 2.6×10^{8} noticeable missteps, 3.1×10^{7} minor accidents, 2.7×10^{6} disabling accidents, 5.4×10^{5} hospital treatments, and 3.8×10^{3} deaths [8]. It has been estimated that nearly 1 million people received hospital treatment from injuries resulting from stair accidents, and nearly 50,000 were hospitalized in the United States in 1990 [9]. Templer has estimated that between 1.8 and 2.6 million people per year are disabled for at least 1 day from stair accidents [10]. In Oregon, in 1995, approximately 2400 or 7.9% of total disabling occupational claims were caused by falls down stairs or steps [2].

The National Safety Council has estimated that approximately 1462 deaths occurred in 2001 due to falls on stairs or steps [7]. According to the NSC, falls on steps or stairs accounted for 10% of all falling fatalities in 2002 [7].

25.1.1.3 Ramps and other irregular surfaces

Little attention has been paid to work related musculoskeletal disorders affecting the lower extremity, although the severity of injuries and resulting disability and costs associated with lower extremity injuries are surprising. According to the National Bureau of Labor Statistics (BLS) nearly 25% of all nonfatal occupational injuries and illnesses involving days

away from work in 2002 affected the lower extremity, and the source of 18% of all injuries was the floor or ground surface [11].

Biomechanics research in gait analysis has focused primarily on walking on horizontal surfaces with little attention paid to irregular surfaces [12–17]. In a study performed with mail-delivery workers it was found that 26% of all falls occurred on uneven ground [18].

25.1.1.4 *Ramps*

Ramp fall accidents represent only a small portion of the total injuries caused by slips and falls each year. The construction of new ramps in existing structures (to comply with the Americans with Disabilities Act [ADA]) has resulted in an increase in the number of ramps, and these numbers appear to be on the rise. Falls on ramps typically occur because of a failure to see an edge or a rapid change in surface slope causing imbalance. Many of these injuries occur in the elderly, who are more likely to use pedestrian ramps, and have slower reaction time to adjust their gait from a level to sloped condition [19]. It has also been reported that an increase in surface inclination had a significant detrimental effect on balance over flat surface standing [20,21].

25.1.1.5 *Irregular surfaces*

An irregular walking surface can be described as any surface suitable for walking that is not regulated by a standard or design guideline, but is common in some occupational environments. According to the BLS, workers in the construction and mining sectors have some of the highest injury rates in the private sector. Nearly 42% of all reportable conditions involving slips, trips, and falls in the railroad industry in 2004 were attributed to irregular surface conditions or ballast [22].

Some research has been published relating to walking on ballast, but the relationship between musculoskeletal disorders of the lower extremities and walking on different types and slants of ballast is still a matter of debate [23].

25.2 *General design guidelines*

25.2.1 *Ladders*

Ergonomic/biomechanical issues are certainly a contributing factor to ladder falls. ANSI suggests that fixed ladders be constructed so that the slant from horizontal is between 75° and 90° [24]. They suggest that there be a 30.5 cm (12 in.) distance between rungs, 40.6 cm (16 in.) between side rails, a 17.8 cm (7 in.) toe clearance behind the rung, and a minimum 1.9 cm (¾ in.) rung diameter. They also suggest that side rails be uniform and allow a power grip along the length of the ladder. ANSI suggests a 75.5° ladder slant for portable ladders, a 30.5 cm (12 in.) rung or step separation, and a minimum 30.5 cm (12 in.) distance between the side rails [25]. Since portable ladders can be constructed of metal or wood with varying strength characteristics, most other dimensions can vary depending on the type of material used; however, a minimum rung diameter of 2.9 cm (1⅛ in.) is required for wood ladders [26]. Diffrient et al. [27] recommend that for rung ladders the optimum slant is 75°–85°, with rung spacing of 17.8–30.5 cm (7–12 in.), and a rung diameter of 1.9–3.8 cm (0.75–1.5 in.).

There is considerable variation relating to the slant actually preferred by ladder users. Irvine and Vejvoda found that the average slant preferred by 20 male subjects was 71.9° [28]. Häkkinen et al. [29] found that climbers preferred a slant of 66°, and Bloswick and Crookston found that male users preferred a slant of 73.5° for both 13 and 18 ft ladders [30]. Chang et al. [31] reported that the friction requirements at the ladder base are nearly

doubled when reducing the inclination angle from 75° to 65°. According to Chang, the second most significant factor for friction requirements was the climbing speed.

25.2.2 *Stairs*

The three critical issues relating to stair design include the step depth (tread), step height (riser), and handrail size and height. The U.S. Department of Commerce recommends a tread of 27.94–35.56 cm (11–14 in.) and a riser of 10.16–17.78 cm (4–7 in.). Diffrient et al. [27] recommend a stair slant of 30°–35°, resulting in a range of 27.94 cm (11 in.) tread × 17.145 cm (6.75 in.) rise to 25.4 cm (10 in.) tread × 17.78 (7 in.) rise. Templer [10] suggests that tread depth be at 27.9–35.6 cm (11–14 in.) and riser height be 11.7–18.3 cm (4.6–7.2 in.). Pauls [9] notes that U.S. codes and standards are moving toward a requirement that tread depth be no less than 27.9 cm (10.98 in.), and riser height be no more than 17.8 cm (7 in.).

Diffrient et al. [27] recommend that railings be 76.2–86.4 cm (30–34 in.) above the leading edge of the step, with a maximum diameter of 6.7 cm (2.6 in.). Templer [10] notes that although 76.2–86.4 cm (30–34 in.) is often required in codes and guidelines, stability requirements would suggest a handrail height of 91–102 cm (36–40 in.) and a 3.8 cm (1½ in.) handrail diameter. The U.S. Department of Commerce recommends a 0.69–0.79 cm (1¼–2 in.) diameter handrail [8].

25.2.3 *Ramps and other irregular surfaces*

25.2.3.1 *Ramps*

A ramp is considered any walking surface with a running slope greater than 1:20 [32]. Various standards and recommendations have been developed to specify the need for a ramp in place of a staircase. Ramps are usually required for wheelchairs and wheeled equipment access, but can also serve the purpose of pedestrian walkways. The purpose of a ramp is to provide a smooth transition over a change in elevation. The Americans with Disabilities Act (ADA) provides guidelines for their design. The maximum slope of a ramp should be 1:12 (ANSI A117.1–1986). The maximum rise for any run should be 76 cm (30 in.). The minimum width should be 91.5 cm (36 in.). A slope of 5% or a rise of 15 cm (6 in.) is the maximum allowed before handrails are required [32,33]. No ramp should exceed about 8% slope, in addition nonskid surfaces should be provided on all ramps [33].

25.2.3.2 *Irregular surfaces*

To the authors' knowledge, no generalized design criteria have been specified for irregular surfaces. A number of irregular surface conditions exist that may be experienced during both occupational and leisure activities. Research has suggested footwear design is an important aspect to improve control while traversing irregular terrain [18,34–36]. Guidelines have been established by ASTM suggesting a standard practice for safe walking surface conditions; however, there is limited application to outdoor conditions that may be experienced by railroad, mining, and construction workers.

Andres et al. [23] concluded that in laboratory conditions with nonrailroad workers for individuals with no experience walking on irregular surface conditions, there was greater rear foot motion while walking on a laterally sloped ballast rock compared to a flat, level surface; however, no other kinematics or biomechanics information was provided about force or alterations in lower extremity posture and joint loading.

Limited research has been published on hiking biomechanics, and alterations in gait when walking uphill and downhill. Stride length and cadence are most affected, indicating an alteration to lower extremity joint load transmission [20,37–39].

25.3 Ladder biomechanics

Unless otherwise noted, all research discussed in this section deals with ladders with 28.0–30.3 cm (11–12 in.) rung separation. Ladder slant is defined as degrees from the horizontal.

25.3.1 Body movement

25.3.1.1 General description

Dewar [40] defines that one complete climbing cycle or stride begins as one foot is put on a rung and ends when that same foot is again placed on a rung. The stride for the opposite side of the body is displaced in time by 50% of the cycle. During the normal climbing activity the foot is placed on every other rung.

There is a wide variation in hand movements during ladder use. Dewar [40] defines a "lateral gait" as when the hands move in synchrony with the foot on the same side, and a "diagonal gait" as when the hands move in synchrony with the foot on the opposite side. He notes that the diagonal gait is the "natural" movement pattern. Hammer and Schmalz, however, indicate that the lateral gait is more prevalent, and McIntyre found that nearly 60% of his subjects applied the lateral gait [41,42]. Hammer and Schmalz [41] also note that people frequently change their gait between climbing activities and even within the same ladder ascent or descent.

Dewar [40] found that for males foot contact ranged from 61% to 63% of total cycle time, independent of the climbing speed, and Lee et al. [43] found contact time for males to be 55%–58% of total cycle time. Both Dewar [40] and Häkkinen et al. [29] found that climbers preferred to grip the ladder side or rail as opposed to the ladder rung.

ANSI notes that during use of portable ladders,

> When ascending or descending the ladder the user shall face the ladder and maintain a firm hold on the ladder,

and when using a fixed ladder,

> When ascending or descending a ladder, the user shall face the ladder and maintain a three point contact at all times. Three point contact consists of two feet and one hand, or two hands and one foot, which is safely supporting a users weight when ascending or descending the ladder [25,26].

McIntyre notes, however, that there are extended periods in both diagonal and lateral gait patterns when climbers have only two limbs in contact with the ladder [42]. Hammer and Schmalz note that three point contact is a percent of total time ranges from approximately 37% of total cycle time at 60° ladder slant to approximately 52% of total cycle time when the ladder is vertical [41].

25.3.1.2 Body center of mass/trunk

Dewar notes that for male subjects the body center of mass was approximately 7.5 cm (2.95 in.) further back (away from the ladder) when using the 75.2° ladder as opposed to the 70.4° ladder slant [40]. Kinoshita et al. [44] note that during vertical ladder use the body center of mass was kept further from the ladder during ladder descent than ascent. Lee et al. [43] note that for male subjects the climbing path varied less at a faster speed (106 steps per min) than at a slower (86 steps per min) climbing speed. They interpret this as indicating that the individuals displayed less control while climbing at a faster speed.

It would appear to this author that the opposite conclusion may be the case and that less variation during the faster speed would indicate more control. McIntyre notes that the movement of the body center of mass away from the point of support during use of the steeper ladders indicates a decrease in stability [42]. Although this may be true for the 70°–75° ladder slants, the extension of this logic to more extreme ladder slants should be avoided. For example, while climbing a vertical ladder the whole-body center of mass may be some distance outboard from the points of support but the body is in a "stable" position if the points of support do not slip. On the other hand, a ladder with an extremely shallow slant, say 45°, may be very difficult to use because of the difficulty of balancing on the rungs and reaching the side rails with the hands even though the whole-body center of mass would be nearly over the points of support at the feet.

25.3.1.3 *Extremities*

Dewar found that, when using the opposite leg as a reference, the maximum hip flexion angle for males was approximately 55° and the maximum knee extension angle was approximately 70° [40]. For both the 70° and 75° ladder slants the hip abduction angle was approximately ±5°. He also found that for shorter subjects both the hip and the knee had to flex more to lift the foot onto the rung. This effect was approximately the same for both ladder slants in the case of the knee but was less for the hip in the case of the 70° ladder slant.

25.3.2 *Forces and joint moments/muscle activity*

25.3.2.1 *Hand/foot force*

Lee et al. [43] found that for a 70°–75° ladder slant the legs served to move the body upward and the hand served primarily to balance the body, particularly when moving from the double to the single foot stance phase. They found that for males the total (two-hand) peak hand force was approximately 25% of body weight and that the peak hand force was somewhat less at the 70° angle than at the 75° ladder slant. McIntyre et al. [45] also found that the hands serve primarily to maintain dynamic stability for a 75° ladder slant but that as the space between the rungs increases, the hands are used more for propulsive forces to assist the legs. He notes that the one-hand forces range from 4.2% to 9.6% of body weight and that the hand forces exerted by the short subjects were higher than those of the tall subjects and that the hand forces of short subjects increased more rapidly as rung separation increased. Ayoub and Bakken found that the pull force on one hand ranged between 20% and 36% of body weight during vertical ladder ascent [46].

Bloswick and Chaffin found that for male subjects the average total force on one hand as a percent of body weight was 9.3% for 70° ladder slant, 11.5% for 75° ladder slant, 15.6% for 80°, and 24.5% for the vertical ladder [47]. They also found that the peak hand force was approximately 30% of body weight during the one-foot stance when using a vertical ladder. This approaches the estimate of 35% of body weight, which was found to be the mean grip strength on a slippery handrail of 2.2 cm (0.875 in.) diameter [48]. Bloswick and Chaffin also found that most subjects demonstrated an average preferred hand separation of 32.3 cm (12.7 in.) but that short, heavy subjects preferred a significantly wider hand separation of 39.9 cm (15.7 in.) [47]. This suggests that the generally accepted ladder width standard of 38.1 cm (15 in.) is adequate for all but short, heavy climbers. This agrees with Chaffin et al. [49] who found that a ladder width of 40.6 cm (16 in.) would provide adequate lateral stability for arm strength to resist the force of the wind.

McIntyre found that average foot forces for one foot range from 48% to 60% of body weight [50]. Chaffin and Stobbe found that peak foot forces ranged from a high of 40% in the horizontal direction to 170% of body weight in the vertical direction for

vertical ladder climbing [51]. Bloswick and Chaffin found that for male subjects the total one-foot forces, as a percent of body weight, were 63.7% for a ladder slanted at 70°, 62% for a ladder slanted at 75°, 59.3% for 80°, and 54.7% for a vertical ladder [47]. They also note that while the peak foot force is highest (approximately 85% of body weight) during the one-foot stance for a ladder slanted at 70°, the foot slip potential is highest during the use of vertical ladders where a coefficient of friction in excess of 0.4 may be required to resist a forward slip.

25.3.2.2 *Upper extremity moments*

Bloswick and Chaffin found that the average elbow and shoulder moments varied as a function of ladder slant (as shown on Figure 25.1) [47]. In addition they note that during vertical ladder use the peak elbow flexion moment and shoulder extension moments were 45% and 15% of the maximum static moment. Lee et al. [43] note that there may be a potential for localized fatigue at the elbow during long climbs since the peak hand force reached nearly 25% of body weight.

25.3.2.3 *Lower extremity moments*

Bloswick and Chaffin also found that for male subjects the average hip, knee, and ankle moment as a percentage of static maximum varied by ladder slant (as shown in Figure 25.2) [47]. They found that the peak hip extensor, knee extensor, and ankle plantar flexion moments were 30%, 15%, and 10% of maximum static moment, respectively, when climbing a ladder slanted at 70°. Ayoub and Bakken contend that the knee is a limiting articulation, as opposed to the hip [46]. They base this on the fact that hip moment capability is greater than that of the knee and that the knee must assume significant flexion and consequent reduction in moment generation capability. Chaffin et al. [49] note that based on ankle torque (plantar flexion strength) capability the minimum foot clearance behind the ladder rung should be 16.5 cm (6.5 in.). Based on ankle plantar flexion strength capability, Bloswick and Chaffin note that this distance should be a minimum of 15.5 cm (6.1 in.) [47].

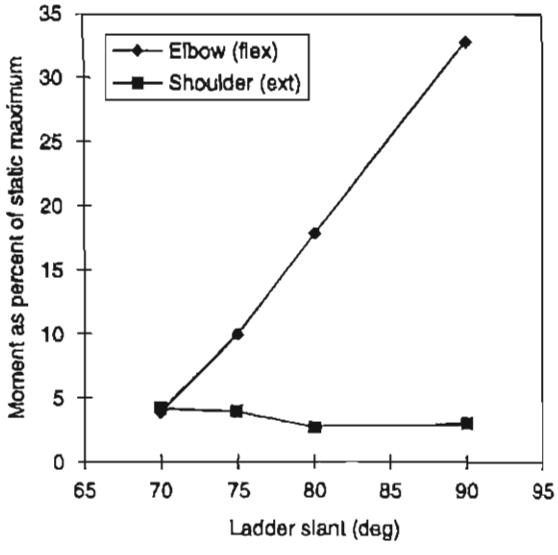

Figure 25.1 Relation of elbow and shoulder moments to ladder slant.

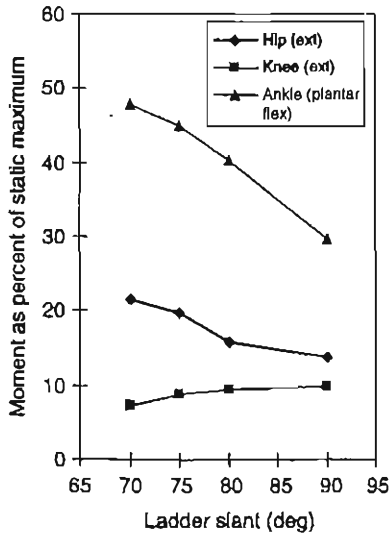

Figure 25.2 Relation of hip, knee, and ankle moments to ladder slant in male subjects.

25.3.2.4 *Back*

Bloswick and Chaffin used integrated electromyographic (IEMG) activity of the erector spinae as a measure of low-back stress during ladder climbing activities [47]. They found that for males the erector spinae activity was approximately 65% of static maximum and increased slightly as the ladder slant went from 70° to 90° (vertical). They also found that peak erector spinae IEMG activity approached 100% of static maximum as climbing speed increased when using vertical ladders.

25.3.3 *Energy consumption/fatigue*

Brahler and Blank note that the whole-body ladder-climbing exercise on a simulated climbing machine elicited significantly greater maximum oxygen consumption values for collegiate oarswomen than did either treadmill running or rowing ergometry [52]. Lehmann found that a ladder slanted at 70° required the lowest energy demand per unit of height [53]. Hammer and Schmalz also found that the time required per unit of height climbed was lowest with a ladder inclination of 70° and consider this angle as "optimal" [41]. Chaffin et al. [49] propose that rung separations of greater than 35.6 cm (14 in.) requires a "fatiguing" exertion. Kamon found that metabolic efficiency in climbing a 60° ladder was higher when using a foot-over-foot pattern than when moving both feet to the same step [54]. Hoozemans also found that there were no significant differences between 30 and 35 cm rung separation for energetic workload. The perceived exertion, discomfort, and safety indicate that 35 cm rung separation was preferred [55].

25.4 *Stair biomechanics*

25.4.1 *Body movement*

25.4.1.1 *General description*

Templer provides what may be the most comprehensive discussion of stairways [10]. It has been noted that gait on stairs must be defined differently than the gait in level walking and

can have a significant effect on the forces transmitted through the lower extremity [56–58]. Taylor et al. [59] described these forces as considerably larger during stair climbing than during walking. The anteroposterior peak shear components were 2.7 times greater for stair climbing over normal walking.

On stairs, the ball of the foot, as opposed to the heel, tends to be the first point of contact. On stairs, the gait cycle must be considered as the cycle between foot contact (toe, foot, or heel) and the subsequent foot contact of the same side of the body. This includes one stance phase and one swing phase. The stance phase begins when the leading foot contacts the step. At mid-stance the body center of mass is directly over this foot and starts to become elevated or lowered by concentric or eccentric contractions of the muscles in that leg. The stance phase continues until the weight transfer to the contra-lateral leg allows the foot to be lifted from the step.

The stance phase during stair ascent, as a percent of gait cycle, has been determined to be 65% [60], 64% (males) [61], and 50%–60% (females) [62]. The stance phase during descent, as a percent of gait cycle, was 60% [63], and 55% of the cycle for stairs slanted at 16.8°, 40% for stairs at 33.7°, and 25% for stairs steeply slanted at 45°. It has also been reported that gait cycle duration, swing and stance phase durations, cadence, and velocity are systematically related to height [62]. McFadyen and Winter note that it is conceivable that one would change climbing strategies between and within the same stair climbing activity [61].

Other points of interest relating to stair movement include that by Zachazewski et al. [60], who note that stair descent is a more dynamic process with greater inherent instability than ascent. Livingston et al. [62] note that shorter women climbed with a more rapid cadence than did taller women and that stepping rate increased as stair slant increased. Shiomi notes that a step pattern where both feet move to the same step before proceeding to the next is more stable than the "normal" foot-over-foot step pattern [64].

25.4.1.2 *Body center of mass/trunk*

Krebs et al. [65] note that the deviation of the center of mass from the center of pressure is greater during stair descent than ascent and that stair descent requires more balance than ascent. McFadyen and Winter note, however, that the body is in a more "optimal" position (center of mass closer to the point of support) while walking down stairs [61].

Krebs et al. [65] note that trunk abduction–adduction range of motion (ROM) and peak trunk flexion substantially exceeded those values during gait and that peak torso flexion during stair climbing was roughly parallel to the 33° stair slope. They also note that the trunk frontal plane ROM during stair climbing was greater than that of gait and suggest that it was to clear the swing foot over the step and minimize lower limb flexion requirements. They observed that subjects descended stairs with considerably less maximum trunk flexion than during ascent in order to maintain stability. In an observation of subjects on a stair ergometer, Asplund and Hall note that during stair climbing ergometry the average trunk flexion was approximately 18° forward from vertical [66]. Cooper et al. [67] found that subjects flexed the trunk approximately 12° with approximately 13° of anterior pelvic inclination during stair climbing. Trunk flexion and pelvic inclination were approximately 0°–3° and 0°–5°, respectively, during stair descent.

25.4.1.3 *Extremities*

Asplund and Hall note that during stair-climbing ergometry the hip range of motion was 15.2°–51.4° flexion, knee 12.7°–72.8° flexion, and the total ankle range of motion was 32.4° [66]. In a review of the literature, Livingston et al. [62] note that hip flexion is approximately 42°, knee flexion 83°–90°, and ankle plantar flexion 30°–40° during stair climbing

tasks. In their research, Livingston et al. [62] found that for female subjects the maximum hip flexion angle decreased as the slope of the stair decreased from between 38° and 45° on a 45° slanted stair down to 27°–35° on a 16.8° slanted stair. They also found that during stair climbing, hip flexion ranged from 47° to 56°. They also found that subject height was an important factor in determining knee motion during stair climbing. Short subjects had knee flexion angles ranging from 92° to 105°, whereas taller subjects had knee flexion angles ranging from 83° to 96°. They found that subjects used 14°–27° of dorsiflexion and 23°–30° of plantar flexion at the ankle during stair ascent. They observed that the subjects in their study used approximately 20°–35° of dorsiflexion and 20°–30° of plantar flexion to perform stair descent as opposed to Andriacchi et al. [68], who observed that males used 40° of dorsiflexion and 40° of plantar flexion during stair descent. Livingston et al. [62] note that subjects appear to adjust to different stair dimensions by varying the flexion extension at the knee rather than that at the ankle or hip.

25.4.2 *Foot forces and joint moments/muscle activity*

During normal stair ascent and descent the forces on the hands and moments in the upper extremities are minimal. When these forces or moments do exist they tend to result from recovery from slips and falls and are resisted by the grab rails discussed earlier.

25.4.2.1 *Lower extremity moments/foot force*

Shiomi notes that walking up stairs involves a shortening of the muscles during contraction in performing positive work against gravity and that walking down stairs results in negative, or eccentric, work in which the leg extensors (quadriceps femoris) are stretched while resisting gravity [64]. Asplund and Hall note that stair climbing ergometry also produces concentric muscle contractions throughout the lower extremity [66]. McFadyen and Winter found that, with the exception of the rectus femoris and gluteus medius muscles, all muscles had greater mean activity for stair ascent compared to descent [61]. Andriacchi et al. [68] found that for male subjects the maximum moments for stair ascent for the ankle, knee, and hip were 137.2 (101.2), 57.1 (42.1), and 123.9 (91.4) KN (ft lb) and during stair descent 107.5 (79.3), 146.6 (108.1), and 112.5 (83.0) KN (ft lb), respectively. These large hip- and knee-extensor moments peak early in the stance phase [56].

Lyons et al. [69] found that climbing stairs produced higher EMG activity in the upper and lower portions of the gluteus maximus, gluteus medius, and extensor fasciae latae muscles than did level walking. Descending stairs required lower muscles activity in these muscles as well as in the semimembranosus long head of the biceps femoris and adductor magnus muscles. They also found that the lower portion of the gluteus maximus is the primary hip extensor for ascending stairs. Shinno notes the importance of the quadriceps, particularly the vastus lateralis during stair ascent [70]. He also notes that the quadriceps is more active during stair ascent than descent. McFadyen and Winter indicate that the quadriceps are dominant and the vastus lateralis is most active during propulsion up the stairs and conclude that the knee extensors play a dominant role in stair climbing assisted by ankle plantar flexion moment [61]. They note that walking up stairs primarily involves concentric contractions of the rectus femoris, vastus lateralis, soleus, and medial gastrocnemius and that walking down the stairs is achieved primarily through eccentric contractions of these same muscles to control the force due to gravity. Shinno also indicates the importance of the quadriceps muscle in supporting the body weight during the single stance phase of the stair use [70]. He notes that the activity of the extensors is smaller in stair descending than ascending but that the biceps femoris activity is greater during stair descending than ascending. He found that the overall action of the

quadriceps muscle is higher when going up than while going down stairs and that the knee flexor activity is relatively small in both directions. He also points out that the knee joint is more unstable when going down stairs because the "screwing home" at the knee joint becomes loose, the quadriceps muscle is passively stretched, and movement speed may be increased by gravity. McFadyen and Winter note that the soleus is the primary contributor to body elevation after foot contact, although some gastrocnemius activity was observed [61].

Kowalk et al. [71] found that knee abduction moments ranged from 25 to 45 KN and were statistically smaller than the knee extension moments of 60–85 KN both for stair ascent and descent. They also found that the knee extension moments were greater during stair descent than ascent and that knee adduction moments did not exist. Costigan et al. [72] found that abduction moments were approximately 50% of the maximum found in the study by Kowalk et al. [71]. Lyons et al. [69] indicate that limb support in descending stairs depends on hip adduction but not hip extensor activity.

McFadyen and Winter note that during stair descent, energy is absorbed at both the ankle and the knee during foot contact, primarily by the plantar flexors [61]. Loy and Voloshin found that males walking up and down stairs experienced induced impulsive loading or "shock waves" in the tibia with an amplitude of 180% and 250% of level walking values, respectively [73]. Zachazewski et al. [60] also note a rapid increase in the vertical ground reaction force at foot contact.

25.4.2.2 *Back*

Cooper et al. [67] note that erector spinae muscle activity in males was approximately 25% of MVC during stair climbing and 10% MVC during stair descent. This is compared to approximately 13% MVC during level walking. Asplund and Hall note electric activity of the lumbar paraspinal muscles did not change significantly during 22 min of activity on a stair-climbing ergometer [66].

25.4.3 *Energy consumption/fatigue*

Templer notes that the energy expended during stair climbing exceeds that of any other routine daily physical activity and is comparable to heavy physical labor [10]. He notes that for a 70 kg person, the total energy cost of using stairs, while dependent on stair geometry, ranges from 0.548 to 1.12 kcal/m (vertical) for stair ascent and 0.098–0.280 kcal/m (vertical) for stair descent. He also notes that the total energy cost of vertical ascent decreases as stair slant increases up to about 45°. Steep stairs, however, are often perceived as being more fatiguing because the rate of energy expenditure is higher even though the total energy expended for a given amount of vertical ascent may not be. Ward and Beadling note that the rate of energy expenditure affects people's judgment more than the total energy expended [74]. Bruce et al. [75], however, note that when normalized for total vertical travel, shallow slanted stairs require less energy than steep stairs. It is also not surprising that they found that the addition of a load to the climber increased the energy consumption for both shallow and steep stairs. Karpovich and Shinning note that the energy expenditure during stair descent was ⅓ of that during stair ascent [76]. Using a climbing treadmill, Richardson found that energy expended during stair descent was 59% of stair ascent [77].

Shiomi proposes that, when normalized for total vertical movement per unit time, the optimum stepping rate for males is 50–62 steps per min [64]. He also notes that oxygen consumption increased as movement velocity increased during stair ascent and that oxygen consumption increased with an increase in stepping rate during both stair ascent

and stair descent. Shinno notes that stairs with a 30°–35° slope are most convenient and that optimal stair height, determined by oxygen consumption is defined as the square root of $R^2 + T^2 = 33$ cm, where R = step height and T = step depth [70]. He determined that the optimum stair has a height of 16.6 cm (6.54 in.) and a depth of 28.6 cm (11.26 in.) with a slope of approximately 30°. Seidl et al. [78] found that for female subjects the efficiency in stair use, as determined by oxygen uptake, increased approximately 5% over a 4 day training period.

In studies of special populations, Benn et al.[79] found that for older men (age 64 ± 0.6 year) stair climbing produced greater systolic blood pressure, heart rate, and rate pressure product than did treadmill walking or dynamic weight lifting and that the increases in heart rate, mean arterial pressure, and mean pressure product were extremely rapid and reached very high levels. The rate pressure product was more than twice that recorded in normal walking and 50% greater than during 4 min of uphill walking or weight lifting. In a study of simulated firefighting tasks, O'Connell et al. [80] found that stair ascent with a 20.3 cm (8 in.) stair elevation at 60 steps per min for 5 min resulted in 45% of maximum oxygen consumption and 71% of maximum heart rate. When carrying an 86.5 lb pack for 5 min, subjects averaged 80% maximum oxygen consumption and 95% maximum heart rate.

25.5 *Ramps and irregular surface walking biomechanics*

25.5.1 *Body movement*

25.5.1.1 *General description*

It is not unusual for workers to walk on inclined walkways, stairs, ladders, or other nonhorizontal surfaces. For example, miners, construction workers, farmers, and outdoor caterers constantly deal with irregular walking surfaces that can effect gait patterns and alter lower extremity joint characteristics from a horizontal walking surface. Research has been published describing the gait characteristics of up- and downslope walking and running, where the greatest effects occur with smaller cadence and walking step length [20,39,81–84]. There is very limited kinematics data describing gait dynamics on nonhorizontal surfaces including laterally sloped surfaces, and therefore further research is needed to understand the effects of traversing irregular terrain and surface types.

To understand what a gait cycle is, it is important to define what is meant by normal human gait. Whittle described normal human walking and running as "a method of locomotion involving the use of the two legs, alternately, to provide both support and propulsion [85]. Gait describes the manner or style of walking, rather than the walking process itself.

A gait cycle is typically identified by four events:

1. Initial contact (heel strike)
2. Opposite toe off
3. Opposite initial contact (heel strike)
4. Initial toe off

More detailed descriptions of human gait can be found elsewhere [85–87]. These events also subdivide the gait cycle into phases:

1. Stance phase (support or contact phase)
   a. Loading response
   b. Mid-stance
   c. Terminal stance
   d. Preswing

2. Swing phase
   a. Initial swing
   b. Mid-swing
   c. Terminal swing

These events can be analyzed and compared to what has been characterized as "normal" human gait to understand how the body reacts to sloped surfaces and other irregular surfaces.

25.5.1.2 *Body center of mass/trunk*

It is important when determining the task capabilities of workers to consider loading biomechanics of the lower extremity. Analysis of a situation of carrying loads on irregular surfaces showed altered kinematics of the lower extremity and the load transfer through the musculoskeletal system. According to McIntosh et al. some factors that distinguish walking on an incline from walking on the horizontal are the requirements to raise or lower the body's center of mass, associated work requirements, the vertical displacement during each stride, the altered friction demands, and foot clearance [88].

In an attempt to maintain balance, posture is altered, changing the location of the center of mass to improve stability while navigating fore/aft slopes. The gluteus muscles exhibit low levels of activity during level and uphill walking, but increases substantially in activity during running. The gluteus muscles during walking function to support the trunk during the support phase and decelerate the leg in the swing phase. There is no implication that fore/aft slope walking substantially increases this activity compared to level walking [89].

25.5.2 *Foot forces and joint moments/muscle activity*

With the development of technology, force platforms, muscle activity level (EMG), video capture systems, and computers have facilitated the advance of knowledge with a more complete understanding of normal human gait [85–87]. Typical ground reaction forces during level walking acquired using six-channel force platforms are displayed in Figure 25.3 where Fz is the vertical ground reaction force vector. As the walking surface changes, the ground reaction forces and resulting center of pressure used in an inverse dynamics model to describe gait joint forces is also affected. Figure 25.4 illustrates the difference that occurs in fore/aft slope (uphill/downhill) walking and medial/lateral (transverse) slope walking compared to level walking for anterior–posterior force and Figure 25.5 illustrates the changes of medial/lateral forces. These graphs were obtained through research at the University of Utah, and are comparable to those found in the literature [83,88].

The differences in ground reaction forces observed with up- and downslope walking were described by Lay et al. [83]. The anterior–posterior braking force increased dramatically while the propulsion component decreased. In upslope walking the mid-stance force decreased, and the normal force component appeared similar to level walking [84]. The peak normal force occurs earlier on inclines than on level surfaces leading to about a 5% difference between the peak shear and normal foot forces.

Some investigation has been performed to describe footwear and the effects on gait. Kersting et al. [36] indicated that footwear can change loading conditions in walking; however, what changes occur in actual workplace situations has not been investigated [36].

A highly significant difference was reported in the change of knee joint kinematics on an incline greater than 10° compared to level walking and the ankle became more dorsiflexed throughout the first 50% of the gait cycle. The angle of incline is a factor that influences all lower extremity angles to accommodate foot and pelvis kinematics as observed in previous studies of level and inclined gait [81,88,90,91].

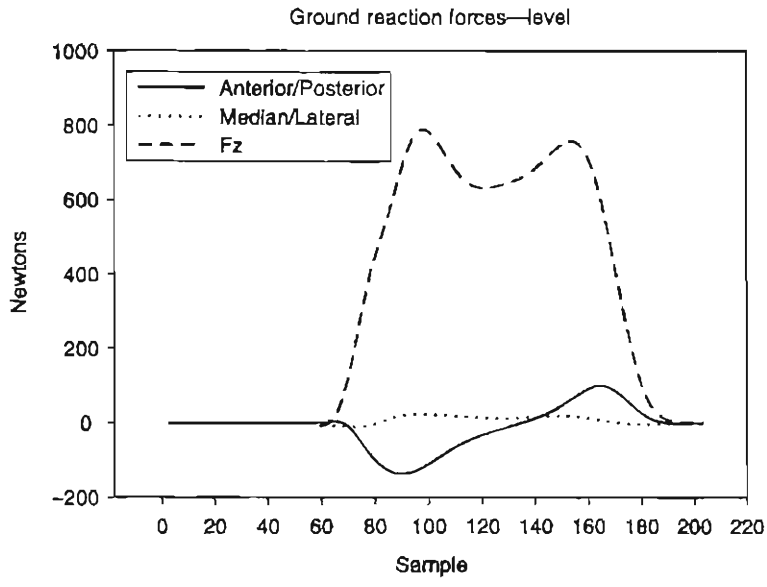

Figure 25.3 Typical ground reaction forces (GRF) for level walking.

25.5.2.1 *Back*

In looking at the moment at the L5/S1 disk interface, it was determined that a 7%–10% increase was noted while lifting on inclined surfaces. Both trunk flexion angle and angular trunk acceleration were identified as driving factors for this increase. The results of this study suggest that sloped surfaces need to be considered when evaluating risk of low-back injury where these conditions exist [92,93].

There was not a significant change in erector spinae muscle activity during sloped walking compared to level-surface walking; however, there does appear to be an increase

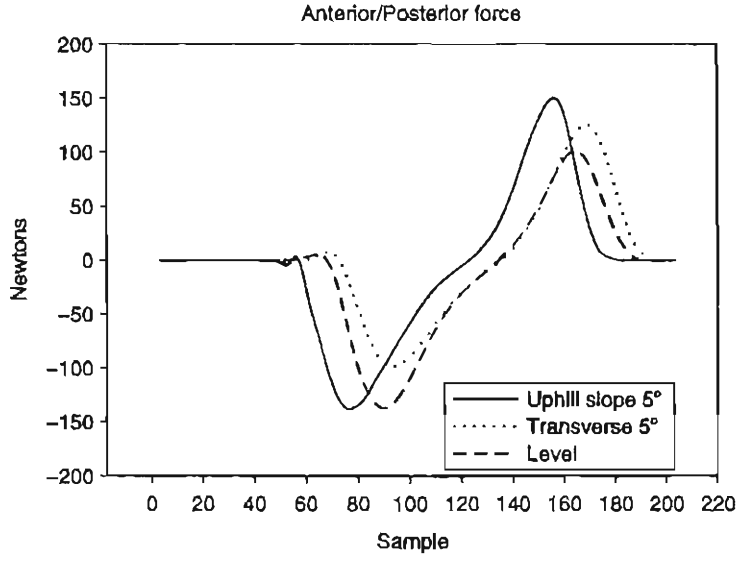

Figure 25.4 Anterior–posterior GRF for fore/aft slope and median/lateral (transverse) walking.

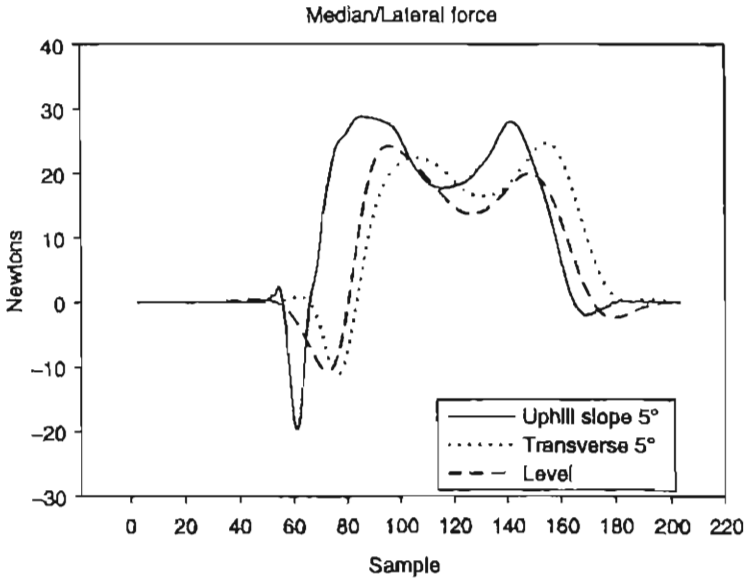

Figure 25.5 Median/lateral GRF for fore/aft slope and median/lateral (transverse) walking.

in trunk stabilizer muscle activity when traversing nonlevel surfaces [82]. It was also observed that in anticipation of walking up a sloped surface there is an increase in trunk forward flexion that influences shear stress during manual material handling tasks [82,94].

When walking down a ramp, there is a greater slip potential. If the response time to adjust gait to avoid a fall is short enough, there is still a possibility of causing overexertion and noncontact injuries due to sudden, unexpected loading, especially in the low back [95].

25.5.3 *Energy consumption/fatigue*

Steeper upslope inclines require greater power generation and are more fatiguing, whereas downslope walking appears to have greater overall energy demands and is more likely to cause pain to the lower extremity, particularly the knee [39,96]. In downslope walking there is a progressive decrease in metabolic demand until a minimum is reached, after which further increase in slope magnitude causes an increase in metabolic demand [38,97].

During upslope walking, it was determined that metabolic cost of walking upslope in men was less than for women. This may be explained by the fact that women are usually smaller in size, and have a different distribution of body mass at the peripheries. This variation may be due to greater movement of the upper limbs in women during walking, but this relationship has not been clearly established [91].

25.6 *Conclusions/recommendations*

25.6.1 *Ladders*

When climbing a ladder, the whole-body center of mass moves further back (away from the ladder) as the ladder steepness increases. In general, the legs provide power and the hands provide support; however, as the ladder steepness increases hand force increases as the hands provide more of the propulsive force. Hand force also increases as the distance between the rungs (rung separation) increases. The force on one hand is a

maximum (25%–30% of body weight) during the use of vertical ladders and this approaches the 35% maximum grip strength on a slippery handrail, which indicates that there may be some potential for hand slip in this situation. A ladder width of 38.1 cm (15 in.) appears to be adequate to accommodate preferred hand separation for most personnel and allow adequate lateral stability to resist wind force.

Foot force approaches a maximum of 85% of body weight when climbing a ladder slanted at 70°; however, foot slip potential is highest during the use of vertical ladders where a coefficient of friction in an excess of 0.4 may be required to resist a forward slip. Average shoulder moment is relatively low (approximately 5% of static maximum) during the use of ladders slanted at 70°–90° (vertical). Average elbow flexion moment increases from approximately 5% of maximum for 70° ladders up to 35% for vertical ladders. When climbing vertical ladders, peak shoulder extension and elbow flexion moments were 15% and 45% of static maximum. Peak hip extensor, knee extensor, and ankle plantar flexion moments reached 30%, 15%, and 60% of static maximum, respectively, when climbing a ladder slanted at 70°. Toe clearance behind the ladder must be approximately 16.5 cm (6.5 in.) to allow adequate plantar flexion capability during vertical ladder use.

It should be noted that the joint moments, and particularly the maximum joint moments, were cyclic and of less than 1 s duration. This reduces the potential for localized fatigue except in long periods of climbing.

Average erector spinae activity is approximately 65% of static maximum and increases slightly as the ladder slant goes from 70° to 90° (vertical). Peak erector spinae activity approaches 100% of static maximum during fast climbing of a vertical ladder. This suggests that there may be some potential for low-back stress during some ladder climbing activities.

Ladder climbing is a fatiguing physical activity and has been found to be more stressful than either treadmill running or rowing ergometry. Rung separations of 35.6 cm (14 in.) are more fatiguing than rung separations of 30.5 cm (12 in.). Ladders slanted at 70° require the lowest energy demand per unit of height and lowest climbing time per unit of height. The foot-over-foot climbing pattern is more energy efficient than when both feet are moved to the same step during the climbing activity.

25.6.2 *Stairs*

There is no clear agreement as to whether the whole-body center of mass deviates more from the foot center of pressure during stair ascent or descent. Foot forces are higher during stair descent, however, and the impulsive loading may be 250% of level walking during stair descent and 180% during stair ascent. This force is absorbed primarily by the plantar flexors. Trunk abduction/adduction range of motion exceeds those experienced during gait. Trunk flexion can approach 30° (stair slant during climbing) but is considerably less during stair descent. Hip flexion ranges from 40° to 55° during stair climbing and decreases as the stair slope decreases. Knee flexion ranges from 83° to 105° with shorter subjects demonstrating the greatest degree of flexion. Ankle dorsiflexion and plantar flexion range of motion appear to range from 15° to 30° in each direction during both stair ascent and descent. People appear to adjust to different stair dimensions by varying the flexion or extension at the knee rather than that at the ankle or hip.

Hand forces in normal use are minimal during both stair ascent and descent. Lower extremity moments and muscle forces are quite complex during stair use. With the exception of the rectus femoris and gluteus medius muscles, all muscles have greater mean activity for ascent as compared to descent and stair climbing produces higher EMG activity in the gluteus maximus, gluteus medius, and extensor fasciae latae than does level walking. Stair ascent primarily involves concentric contractions of the rectus femoris, vastus lateralis, soleus, and medial gastrocnemius with the vastus lateralis playing the most important role.

Stair descent is achieved primarily through eccentric contractions of these same muscles to control the force due to gravity. Knee extension moments are higher during stair descent than ascent. Knee abduction moments are somewhat smaller than knee extension moments and knee adduction moments are minimal for stair ascent and descent.

Erector spinae muscle activity is in the same general range as that incurred during level walking and it does not seem to be indicative of a high potential for back stresses during normal stair use.

The energy expended during stair climbing, although not equivalent to ladder climbing, exceeds that of any other routine daily physical activity. Although steeper stairs tend to be more energy efficient per vertical distance traveled, they are perceived as being more fatiguing because the rate of energy expenditure is higher. The energy expended during stair descent appears to be ⅓–½ of that expended during that of stair ascent. One study found that the "optimum" stair from an energy standpoint has a height of 16.6 cm (6.54 in.), a depth of 28.6 cm (11.26 in.), and a slope of approximately 30°.

25.6.3 *Ramps and irregular surfaces*

Up- and downslope gait has been studied with more intensity than other gait on irregular surfaces; however, there is a dearth of information available describing the effects of terrestrial locomotion on irregular surfaces with respect to lower extremity kinematics and biomechanics. Walking on inclined surfaces changes some gait parameters, but not all characteristics are affected. It appears that ankle support provided by footwear design may help reduce the pressure distribution, rear foot movement and muscle activation in the lower extremity. Metabolic costs increase slightly when walking upslope due to an elevation of body center of mass.

Ramp design contributes to an altered gait pattern and changes lower extremity joint loading, resulting in higher slip potential and a greater required coefficient of friction.

Little has been published to describe the effects of walking on irregular surfaces with respect to biomechanics and musculoskeletal disorders. The etiologies of these diseases are difficult to assess and further investigation is needed to describe the biomechanical forces at the lower extremity during irregular surface ambulation.

25.7 *Ergonomic significance*

Ladder climbing, stair use, and walking on ramps and other irregular surfaces generate considerable biomechanical and metabolic stresses on the body. An understanding of design guidelines, user preferences, and the biomechanical and physiological stresses during ladder climbing, stair use, and traversing ramps and irregular surfaces will assist in the minimization of stress and a reduction of injury potential.

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