Session No. 636

Footwear Characteristics and Potential Implications on Worker Safety

Michelle F. Heller, PhD, PE
Senior Engineer
Exponent Failure Analysis Associates
Philadelphia, PA

Michael J. Kuzel, PE, CHFP
Principal Engineer
Exponent Failure Analysis Associates
Phoenix, AZ

Introduction

Footwear has been a part of human civilization for about the last 10,000 years (Cavanagh, 1980, 9). One of the earliest pairs of shoes discovered by archeologists was made of sagebrush bark that was knotted together, and the shoe was comprised of an outsole with ridges, a covering for the forefoot, and straps for around the heel. Since then, footwear has evolved to "protect your feet and prevent injury" (AAOS, 2010), as well as enhancing an individual's fashion. Specialized footwear has been developed to enhance safety and performance while an individual engages in workplace and sporting activities. Understanding the types and characteristics of different available shoes can assist the safety professional in evaluating the footwear of the workforce. This paper is meant to serve as a brief introduction to some of the aspects of footwear that may have implications for worker safety.

Human Gait

The average adult in the United States takes between 6,000 and 7,000 steps each day as part of their daily activities (Tudor-Lock and Bassett, 2004, 5). Requirements of an individual's occupation as well as their preferred recreational activities may either increase or decrease this estimate for that individual. Walking is an activity common to people across all cultures and demographics and is defined by the characteristic pattern of placing one foot before lifting the other to progress in a given direction (Merriam-Webster). The human gait cycle is comprised of the stance phase (Figure 1) and the swing phase (Figure 2). The stance phase begins with heel contact and ends with toe off, while the swing phase begins with toe off and ends with the following heel contact. An individual's footwear defines the interface between his/her foot and the ground during each step.

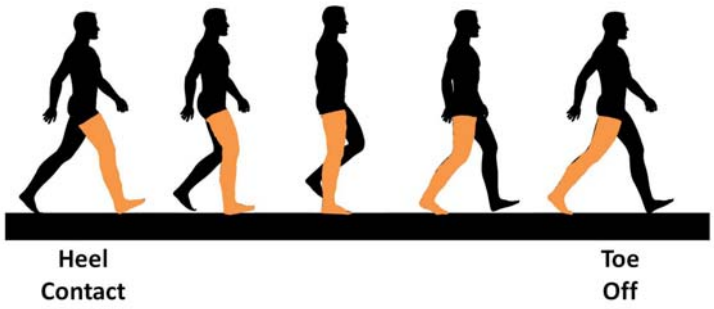

Figure 1. Stance phase of the human gait cycle.

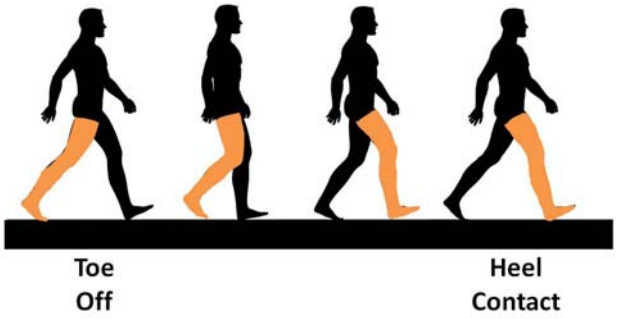

Figure 2. Swing phase of the human gait cycle.

Anatomy of a Shoe

While footwear is a familiar part of people's everyday lives, the common components of various shoe types may not be as well-known. The American Academy of Orthopedic Surgeons has provided descriptions of some of these components (AAOS, 2010):

- Toe box: "Tip of the shoe that provides space for the toes. The toe box may be rounded or pointed and will determine the amount of space provided for the toes."
- Sole: "The insole is inside the shoe; the outsole contacts the ground. The softer the sole, the greater the shoe's ability to absorb shock."
- Heel: "Bottom part of the rear of the shoe that provides elevation. The higher the heel, the greater the pressure on the front of the foot."

One of the most ubiquitous types of footwear is the athletic shoe, or sneaker. Figure 3 demonstrates the terminology used to describe the parts of a typical athletic shoe.

Figure 3. Components of a typical athletic shoe.

Another type of footwear that is commonly worn in industrial and construction settings is the boot. While many types of boots are available for specialized functions (*e.g.*, steel-toed boots, waterproof boots, etc.), and each of these types of boots may have different features. The parts of a typical boot are similar to those of an athletic shoe, as illustrated in Figure 4.

Figure 4. Components of a typical boot.

Finally, workers in non-industrial environments are more likely to wear casual or fashion dress shoes. Figure 5 depicts men's and women's dress shoes.

Figure 5. Men's dress shoe and women's heeled shoe.

Selected Footwear Characteristics

The shoe serves as the interface between an individual's foot and the ground, and there are biomechanical considerations regarding a person's footwear choice that may affect both his/her gait and balance.

Shoe Fit

Shoe fit is an important factor that may affect movement within the environment; shoes that are either too large or too small have the potential to cause problems for the person wearing them. Poor-fitting footwear has been implicated as a cause of falls among the elderly population (Barbieri, 1983). Goonetilleke *et al.* (2000, 515) discussed the challenges associated with shoe fit, stating, "When the foot-shoe 'tightness' exceeds a certain threshold, discomfort or pain results….If the shoe is 'loose on the foot, it is generally not as uncomfortable (even though function may be impaired) as when it is tight. In either case, the acceptable looseness/tightness is subjective and rarely quantified. Worst of all, the customer cannot predict the 'fit-drift' and the bearability or even acceptability of the shoe-foot fit in the long term." Footwear fit remains largely subjective, although methods have been proposed to quantify parameters of shoe fit (Goonetilleke and Luximon, 2001; Kos and Duhovnik, 2002; Barton *et al*., 2009). Another safety issue related to shoe fit and comfort is worker fatigue, as described in the Canadian Centre for Occupational Health and Safety (CCOHS) document *Foot Comfort and Safety at Work*, "a worker who is tired and suffering pain is less alert and more likely to act unsafely."

Heel Height

While most people would associate the footwear property of heel height with women's footwear, it is a parameter that is worthy of consideration for both men's and women's shoes. High-heeled shoes such as stilettos are associated with women, but certain types of men's shoes may also have an elevated heel height (*e.g.*, dress shoes, cowboy boots). As such, the potential biomechanical ramifications of heel height should be considered for both men's and women's footwear.

Shoes with a higher heel increase the forces at the forefoot and change the distribution of forces across the forefoot (Schwartz *et al*., 1964). Additionally, high-heeled shoes raise the location of an individual's center of gravity relative to the ground and decrease the person's stability, resulting in a more conservative gait pattern involving shorter step and stride lengths as shown in Figure 6 (Merrifield, 1971).

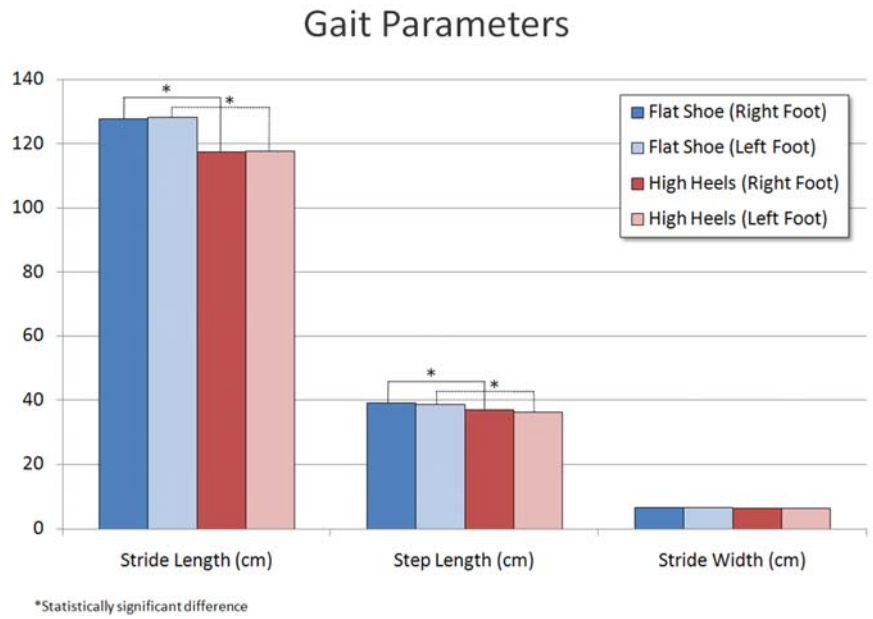

Figure 6. Gait parameters affected by high-heeled shoes (data from Merrifield, 1971).

Real-world accident data has indicated that lower heel height may decrease a worker's risk of falling. A representative of Continental Airlines indicated that when they lowered their required heel height to ¼ inch for their employees, including flight attendants, the company's fall incidents decreased by 80% (Sixel, 1998).

Collar Height

Shoes with a higher collar height (such as boots or "high top" athletic shoes) have been shown to reduce the rate and the extent of ankle inversion, which may help to prevent ankle sprains (Ricard *et al.*, 2000). Such shoes may also aid in a person's proprioception of ankle position, which is supported by the work of Robbins *et al.* (1995) involving how individuals' perceptions of their ankle position were more accurate when their ankles were taped. Lord *et al.* (1999) conducted assessments of static and dynamic balance in older women wearing high- and low-collar shoes and found that the women exhibited better balance when wearing the high-collar shoes. The authors discussed how both the physical ankle support and the tactile cues may play a role in the enhanced balance experienced when wearing high-collar shoes.

Midsole

The midsole is the layer of the shoe found between the insole and the outer sole of the shoe. The biomechanical effects of the midsole thickness and hardness have been investigated by researchers. When men were asked to walk along a balance beam, falls were less likely to occur when the men were wearing shoes with harder and thinner soles, indicating that these factors affect stability (Robbins *et al.*, 1994). These results were confirmed in a subsequent study performed by the same research group (Robbins *et al.*, 1997).

Perry *et al.* (2007) found that the midsole hardness affects an individual's ability to control their balance during gait termination, with the soft midsole causing the greatest constraint to the range of his/her center of mass over his/her base of support when compared to the barefoot condition. Furthermore, it has been suggested that a softer midsole may insulate the foot from sensory signals regarding balance disturbances. While the composition of a shoe's midsole is not often a factor in footwear selection, biomechanical research has shown that it can affect an individual's performance.

Outer Sole

Shoe wear can affect the friction generated between the outer sole and the ground during locomotion by changing the character of the sole surface as well as the shape of the contact area between the shoe and the ground. Research has demonstrated that the ratio between the anterior-posterior ground reaction force (GRF) and the vertical GRF decreased with decreased shoe traction when individuals were stepping over obstacles of varying heights (Houser *et al.*, 2008). Changes in this ratio can affect an individual's risk of slipping.

Biomechanical research has shown that young adults are more likely to experience a slip event when wearing a show with a harder outer sole (Tsai and Powers, 2008). Outer sole hardness has been shown to affect gait kinematics, with harder soled soles eliciting changes such as slower walking speed, shorter stride length, and less ankle dorsiflexion at initial contact (Tsai and Powers, 2009). The peak utilized coefficient of friction was also less when individuals wore shoes with a harder outsole. Tsai and Powers (2009) suggested that the subjects had perceived the harder-soled shoes to be "more slippery" and thereby adjusted their gait in such a way that the peak utilized coefficient of friction was lessened.

Protective Footwear and Footwear Standards

Certain industries and work environments require specialized shoes that protect the workers feet. OSHA Standard 1910.136(a) states that employers shall ensure that employees wear "protective footwear when working in areas where there is a danger of foot injuries due to falling or rolling objects, or objects piercing the sole, and where such employee's feet are exposed to electrical hazards." Consensus standards, which OSHA 1910.136 references, have been developed that specify the safety characteristics of shoes worn in these types of environments. A review of these specifications is beyond the scope of this discussion. The reader is directed to ASTM F2412 and ASTM F2413 for detailed information about the test methods and performance specifications.

In environments where foot protection is required, the standards do not address characteristics of the shoe that may be biomechanically relevant, *i.e.*, the proper fit, midsole characteristics,

collar height, heel size or height, or slip resistance properties of the outer sole.[1] Outside of the environments addressed by OSHA, there are no universal standards for footwear in the workplace. This has been revealed in more recent inquiries for interpretations of 1910.136 regarding safety of wearing open toed shoes and open heeled shoes in office environments and in a pharmacy (OSHA Standard Interpretations, 1910.136, August 28, 2003 and July 17, 2006). Consistent with other interpretations of 1910.136 provided over the last 25 years, the response has been clear that employees who are not exposed to possible foot injuries due to falling/rolling objects, objects piercing the sole, or electrical hazards are not required to wear protective footwear. As such, there are no limitations on the various types of comfort, casual or fashion footwear that is often seen in the workplace.

As discussed above, shoe characteristics have been found to affect balance, stability, and ultimately the risk of falling. Although no standards or guidelines exists for environments that do not present specific hazards to the feet, individuals should be thoughtful about their selection of footwear, including what shoes they choose to wear in their work environment. Consistent with the biomechanical research, the Canadian Centre for Occupational Health and Safety's recommendations for appropriate footwear for work include a straight inner edge from the heel to the end of the big toe, a firm fitting heel counter, a wide enough to box to allow free movement of the toes, a mechanism for fastening across the instep to prevent the foot from slipping in the shoe, and a flat shoe or one with a wide, low heel (CCOHS, 2011).

Conclusion

Many factors need to be taken into account when considering what footwear is most appropriate for a given task. Issues such as electrical exposure and the potential for falling objects need to be considered when selecting footwear for certain segments of the workforce. When such measures are unnecessary, more choices are available for a given worker's footwear selection. However, even in these environments, the variety of footwear characteristics that may affect balance, stability, and the likelihood of experiencing a fall event should be taken into account when footwear is selected.

Bibliography

American Academy of Orthopaedic Surgeons (AAOS) (2010). "Shoes." http://orthoinfo.aaos.org/topic.cfm?topic=A00143 Accessed April 2010.

ANSI. (1999). Personal Protection – Protective Footwear (ANSI Z41-1999). Itasca, Illinois: ANSI.

ASTM International. (2005). Standard Test Methods for Foot Protection (ASTM F2412-05). West Conshohocken, Pennsylvania: ASTM International.

ASTM International. (2005). Standard Specification for Performance Requirements for Foot Protection (ASTM F2413-05). West Conshohocken, Pennsylvania: ASTM International.

[1] Although ASTM F2413-05 describes in the Scope that the "The objective of this specification is to prescribe ***fit***, function, and performance criteria for footwear…" (emphasis added); no further discussion of shoe fit occurs in the standard.

Barbieri EB. (1983). Patient falls are not patient accidents. J Gerontol Nurs 9(3), 165-73.

Barton CJ, Bonanno D, Menz HB. (2009). Development and evaluation of a tool for the assessment of footwear characteristics. J Foot Ankle Res, 2-10.

Canadian Center for Occupational Health and Safety (CCOHS). *Foot Comfort and Safety at Work.* http://www.ccohs.ca/oshanswers/prevention/ppe/foot_com.html. Accessed March 2011.

Cavanagh PR. The Running Shoe Book. Mountain View, CA: Anderson World, Inc., 1980.

Goonetilleke RS, Luximon A, Tsui KL. (2000). The quality of footwear fit: What we know, don't know and should know. Proceedings of the IEA 2000/HFES 2000 Congress, 515-518.

Goonetilleke RS, Luximon A. (2001). Designing for comfort: A footwear application. Computer-Aided Ergonomics and Safety Conference 2001.

Houser JJ, Decker L, Stergiou N. (2008). Stepping over obstacles of different heights and varied shoe traction alter the kinetic strategies of the leading limb. Ergonomics 51(12), 1847-59.

Kos L, Duhovnik J. (2002). A system for footwear fitting analysis. International Design Conference – Design 2002, 1187-1192.

Lord SR, Bashford GM, Howland A. (1999). Effects of shoe collar height and sole hardness on balance in older women. J Am Geriatr Soc 47(6), 681-4.

OSHA. (2009). 29CFR1910.136. Foot Protection. Washington, DC.: OSHA.

OSHA. (2003, August 28). Standard interpretation, 29CFR1910.136. Foot Protection. Washington, DC.: OSHA.

OSHA. (2006, July 17). Standard interpretation. 29CFR1910.136. Foot Protection. Washington, DC.: OSHA.

Merriam-Webster Dictionary. New York, NY: Macmillan, 1994.

Merrifield HH. (1971). Female gait patterns in shoes with different heel heights. Ergonomics 14, 411-7.

Perry SD, Radtke A, Goodwin CR. (2007). Influence of footwear midsole material hardness on dynamic balance control during unexpected gait termination. Gait Posture 25, 94-98.

Ricard MD, Schulties SS, Saret JJ. (2000). Effects of high-top and low-top shoes on ankle inversion. J Athl Train 35(1), 38-43.

Robbins S, Waked E, Gouw GJ, McClaran J. (1994). Athletic footwear affects balance in men. Br J Sports Med **28**, 117-22.

Robbins S, Waked E, Rappel R. (1995). Ankle taping improves proprioception before and after exercise in young men. Br J Sports Med 29, 242-247.

Robbins S, Waked E, Allard P, McClaren J, Kroughlicof N. (1997). Foot position awareness in younger and older men: The influence of footwear sole properties. J Am Geriatr Soc 45(1), 61-6.

Schwartz RP, Heath AL, Morgan DW, Towns RC. (1964). A quantitative analysis of recorded variables in the walking pattern of "normal" adults. The Journal of Bone and Joint Surgery. American Vol 46, 324-34.

Sixel LM. (1998). Some urge firms to boot high heels. Houston Chronicle, Business Section, 11/27/1998, Page 1, 3 STAR Edition.

Tsai Y, Powers CM. (2008). The influence of footwear sole hardness on slip initiation in young adults. J Forensic Sci 53(4), 884-888.

Tsai Y, Powers CM. (2009). Increased shoe sole hardness results in compensatory changes in the utilized coefficient of friction during walking. Gait Posture 30, 303-306.

Tudor-Locke C, Bassett, DR, Jr. (2004). How many steps/day are enough? Preliminary pedometer indices for public health. Sports Med, 34(1), 1-8.