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Bio-Engineering Analysis of Design Disparities and Female Injury Rates

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Introduction

The characteristics of the U.S. workforce are changing rapidly, especially with respect to gender and age. In 1970, women represented just slightly more than one-third of the labor force. In 2009, women represented 46.7% of the labor force (approximately 43 million women) with an increasing number entering traditionally male-dominated jobs in construction, mining, heavy manufacturing, and agriculture.(US Bureau of Labor Statistics, 2010) The aging workforce is another major change in the character of the workforce. In 1988, 22.3% of the 55+ year old female labor force was actively employed and by 2018, the Bureau of Labor Statistics (BLS) estimates 39.5% of older women will be actively employed. (Toossi 2009)

Historically, the BLS annual Surveys of Occupational Injuries and Illnesses have reported that women sustain fewer and less severe injuries at work than do men; however, scientifically controlled research studies, which rely upon more accurate exposure data and better control of potential confounders, suggest otherwise. Taiwo et al. (2009) analyzed a ten-year occupational cohort (1/1/96 – 12/21/05), which documented injuries sustained by the hourly labor population at six US aluminum smelters. Female workers in this heavy manufacturing industry were found to have a significantly greater risk for sustaining all forms of injury after adjustment for age, tenure, and standardized job category (odds ratio = 1.365, 95% confidence interval: 1.290, 1.445). Studies among electric utility (Kelsh 1996, 2004; Sahl 1997), postal (Zwerling 1993) and semiconductor industry workers (McCurdy 1989) and U.S. Army trainees (Jones 1993) have also suggested that females are at higher risk for occupational injuries.

Gender differences in injury rate also persist in particular types of injury. In 2008, three main areas of non-fatal, bodily injury which required time away from work for all employees in private industry were the trunk (~34%), the extremities (~22%) and the head (~7%). (USBLS 2008) Lower extremities, in particular, have been shown to account for up to 27% of full-time equivalent (FTE) days lost (Kelsh 2004). In a twelve-year cohort study of electrical utility workers, women sustained a significantly higher lower extremity injury rate (1.97 – 2.25 rate ratio, 95% confidence intervals) compared to men, after the raw rate data was adjusted for occupation, job experience, and age. (Kelsh 1996) In this same study, the injury rate ratio (females/males) for falls was 2.0 (1.9 – 2.2, 95% confidence interval). Taiwo and coauthors (2009) reported that sex differences in injury patterns among workers in heavy manufacturing were not fully explained by such factors as ergonomics, age, tenure, job category, temporality, organizational culture, health services usage and symptom reporting.

One factor likely contributing to the reported gender differences in injury rate is the inherent biomechanical design disparities between the female versus male human body regarding injury tolerance, kinematics and kinetics. The field of biomechanical engineering is separate and distinct from the disciplines of ergonomics and human factors, yet the field has not been broadly applied to better understand the etiology of occupational injury. Thus, the purpose of this paper is to provide an abridged review of the scientific literature within the field of biomechanical engineering related to gender differences in injury tolerance, in general, and lower extremity injuries and falls, in particular. Implications for industrial design and public policy are discussed.

Women Are Not Scaled Down Men

Physiological and anatomical differences exist between female and male human bodies, which may predispose the female body to higher incidence of injury and/or different types of injury when both genders are exposed to the same risk environment. Such gender-based, design disparities include, but are not limited to, bone fracture tolerance, thermophysiologic and pain response, and lower extremity tolerance.

Bone Fracture Tolerance

The effects of age and gender on the structural strength of bone are well documented. (Yamada 1970) Fracture tolerance is a function of the inherent mechanical strength of the biological tissue as well as the cross sectional area over which a potentially injurious force may be applied. The female skeleton, in general, and the long bones of the extremities, in particular, are characterized by smaller (approximately 20-25%) cross-sectional areas when compared to males. (Table 1) These geometrical differences between genders result in higher magnitude stress applied to female long bones when subjected to the same mechanical loads as males. Compressive breaking loads for the long bones of the extremities are lower for females compared to males and diminish with increasing age. (Table 1) Tolerance values for other bones of the male and female skeleton can be found in Yamada (1970).

Thermophysiologic and Pain Response

The differences in thermophysiology (thermal regulation) of the female versus male human bodies are discussed in an excellent review article by Cheung (2000). These authors report a significant influence of individual physiologic characteristics, such as surface area to mass ratios, on the impact of protective clothing on temperature regulation in uncompensable heat stress (UHS) occupational environments.

Extremity Long Bone	**Cross-Sectional Area (mm^2)**		**Compressive Breaking Load (kg)**	
	Female	**Male**	**Female**	**Male**
Femur	260	330	20-39 yrs: 4,190 40-59 yrs: 3,980 60-89 yrs: 3,540	20-39 yrs: 5,050 40-59 yrs: 4,780 60-89 yrs: 4,290
Tibia	180	240	2,820	3,660
Fibula	50	70	590	860
Humerus	160	200	2,100	2,580
Radius	70	80	780	950
Ulna	70	90	850	1,140

Table 1. Table showing cross sectional area and compressive breaking loads of the long bones of the extremities, as presented by Yamada, 1970.

Females, in general, have higher surface area to mass ratios; however, this potential advantage for evaporative heat loss becomes less evident under increasingly severe conditions of uncompensable heat stress (e.g. using fire or hazardous material protective clothing). McClellan (1998) compared the thermoregulatory responses of men and women wearing protective clothing while engaged in aerobic exercise. Male subjects, on average, had a higher aerobic fitness (49 versus 43 ml/kg/min) and lower body fatness (15 versus 20%) compared with female subjects. Males exhibited a lower rise in rectal temperature (T_{re}), the T_{re} tolerated at exhaustion was higher, and tolerance times were extended 25% (from 114 to 143 minutes) compared to females. According to Cheung (2000), these gender differences in thermal regulation under UHS environments may be exacerbated during certain phases of the female menstrual cycle.

A sex difference also exists in the time course of pain (Hashmi 2009). In a controlled laboratory environment, females reported more pain than males at the outset of the first exposure to pain; however, only females demonstrated adaptation and habituation that allowed them to experience less pain over time. The authors conclude, “A consequence of these considerations is that the generalization of females as more pain sensitive than males depends strongly on the time of pain measurement.

Lower Extremity Injuries

A combination of three unique, biomechanical factors among females, not present in the male body, creates an unfavorable loading environment within the lower extremity. These factors may contribute to falls in the workplace, knee ligament injury and the development of chronic joint pain: (1) higher magnitude, mechanical loads to the joints, due to gender differences in gait and resultant muscle moments, (2) smaller bone structure compared to men, with resultant higher contact stresses on female joints’ articular surfaces and (3) different joint alignments (i.e. a larger medial angulation of the distal femur, the Q angle, within female bodies.) (Figure 1)

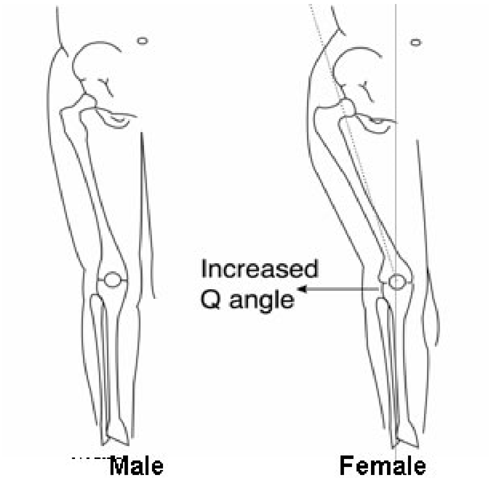

Figure 1. Graphic depiction of gender differences in lower extremity "Q Angle."

Inherent differences exist in the walking kinematics (gait) between males and females, which result in differing, three-dimensional, muscle loads crossing the hip, knee and ankle joints. The direction, as well as magnitude, of these muscle loads may predispose women to particular types of acute, lower extremity injury and chronic, degenerative disease processes. Reports of higher incidence of hip osteoarthritis among older women (Oliveria 1995; Bolen 2002) and higher rates of hip arthroplasty (replacement) and hip arthroplasty revisions (Kurtz 2005; Hawker 2000) among women when compared to men are consistent with gender-based differences in gait.

In a study of 42 healthy, older subjects (21 male, 21 female; aged 50-79 years), the female subjects demonstrated significantly different kinematics and hip joint kinetics during walking (Boyer 2008). When compared to male subjects, the females exhibited increased external hip adduction, increased internal rotation and increased hip extension, after normalizing for body size for all self-selected walking speeds. Ground reaction force exhibited no gender differences; therefore, the muscle moment loads acting on female joints were necessarily higher than the male subjects. The greater joint moments found at the hip per unit weight and height for females suggests the contact stresses on the hip joint during walking are greater for females than for males. These gender differences in joint kinematics were also found to extend across a range of gait speeds and surface inclinations. (Chumanov 2008) Another study, which focused on a static single leg standing task, also found that the peak contact stress normalized to the subject's body weight was significantly higher in magnitude in female versus male subjects. (Iglic 2001)

The knee joint, in addition to the hip joint, exhibits kinematic and kinetic gender differences, which may predispose certain female workers to higher injury rates. Numerous studies have reported a higher incidence rate of injury to the anterior cruciate ligament (ACL) among female athletes compared to male athletes (DeHaven 1986; Boden 1996; Traina 1997, Ireland 1999; Gwinn 2000). Chappell and co-workers (2006) investigated ACL injury in a cohort of seventeen men and nineteen women during a "vertical stop-jump-land" task using telemetric electromyography and video photogrammetry. While this kinematic pattern is most typical of certain track and gymnastics female athletes, it is also likely representative of certain tasks among female workers in heavy industrial settings. Any task, which requires workers to jump over short distances and/or jump down to a lower surface from relatively low elevations (i.e. 12-18 inches), would result in similar “landing” profile. Chappell found that female subjects exhibited greater internal rotation of the knee, greater quadriceps activation and decreased hamstring activation upon landing compared to male subjects. Kernozek (2008) further demonstrated that females have increased anterior shear loads in the knee when fatigued.

Implications for industrial design and public policy

According to the US Bureau of Labor Statistics (2010), the proportion of days-away-from-work cases occurring to women increased from 37 percent to 39 percent in 2009, even though the proportion of women in the workforce remained the same (48%). Additionally, the 2009 incidence rates of females suffering falls on the same level were significantly higher compared to males (23.0 versus 13.5). The Department of Labor Occupational Safety and health Administration (OSHA) recently issued a Notice of Proposed Rule Making (DOL, 2010) “Walking-Working Surfaces and Personal Protective Equipment (Fall Protection Systems).” Notwithstanding the most current BLS data, the NPRM does not contemplate any intervention strategies to address the disparate fall injury incidence rates among female compared to male workers.

The anthropometric literature from the fields of human factors and industrial engineering document the anatomical differences between male and female workers, which should inform organizations of the critical need to purchase fall protection systems that fit the full anthropometric range of workers exposed to fall hazards, including women. Moreover, the mechanical design of fall protection systems should include careful consideration of the lower fracture tolerance thresholds for the female vs. male skeleton, including the pelvis, ribs and extremities. Fall protection system design must include safety factors, which incorporate the full breadth of human tolerance to mechanical trauma, particularly the lower threshold limit for female workers.

The collective biomechanical engineering studies of hip and knee joint mechanics have significant implications for female workers engaged in tasks requiring long periods of standing. Energy absorbing foot mats reduce ground reaction forces and adjustable foot rests reduce joint moments induced by muscle loading. These engineering controls should be introduced routinely into the workplace for workers, particularly female workers, engaged in prolonged standing tasks. These studies also demonstrated gender-biased kinetics that likely creates an unfavorable loading situation in the female knee and predisposes it to ACL rupture during landing maneuvers. In an industrial setting, the preferred intervention strategy is to eliminate any error provocative environments, which necessitate jumping and landing maneuvers. If the hazard cannot be eliminated or controlled by engineering design, female workers, in particular, should receive training to step down and/or over any seemingly innocuous distance rather than jump over it.

This abridged review of the scientific literature within the field of biomechanical engineering was necessarily limited in scope to only a few examples of gender disparities in injury tolerance, in general, and lower extremity injuries and falls, in particular. Similarly, only a few implications for industrial design and public policy were presented. Today’s workforce in the United States, however, is 46.7% female, approximately 43 million women. Some personal protective equipment available in the marketplace has been designed specifically to *fit* women; however, have these designs also specifically considered female injury tolerance (e.g. to thermal and mechanical loads)? All occupational safety and injury control strategies, including the most effective – elimination through engineering design - should necessarily consider the full spectrum of injury tolerances among intended users, including the female worker.

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