Biomechanics for Risk Managers – Analyses of Slip, Trip & Fall Injuries

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Introduction

Falls represent a significant health problem in the United States, accounting for more than 14,000 deaths a year, and are often associated with a perturbation that occurs during normal activities such as ambulation, stair ascent, or stair descent.[1] In addition, slip or trip incidents resulting in falls are frequently linked to less severe injuries, such as those to the head, lumbar spine, shoulder and knee joints. Traditional investigations have focused on liability issues, such as code violations, thereby assuming a causal relationship between the subject event and claimed injuries. However, determination of a causal relationship between an injury and a specific fall incident requires thorough biomechanical analyses of the subject incident for evaluation of injury mechanisms (direction) and force magnitudes associated with the injuries in question.

A biomechanical engineer who is trained in the application of the concepts and methods of mechanical engineering and the physical sciences to medicine and the human body is needed to correlate mechanisms of injuries with the mode and intensity of force transfer associated with the subject incident. While such biomechanical analyses are routinely conducted in automotive accident investigations, there have been limited references to their use in slip, trip, and fall analyses.[2,3,4] In light of the limited discussions in the literature regarding biomechanical analyses in slip, trip, and fall incident investigations, the purpose of this paper is to discuss the biomechanics of falls, as well as injury mechanisms associated with common injuries from slip, trip, and fall incidents. In addition, two case studies are included to demonstrate the application of biomechanical analyses in the investigation of slip, trip and fall incidents.

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1 National Safety Council (2004). Injury Facts.

2 Nahum, A., Gomez M. (1994). Injury Reconstruction: The Biomechanical Analysis of Accidental Injury, (SAE 940568). Warrendale, PA, Society of Automotive Engineers.

3 Sacher, A. (1996). The Application of Forensic Biomechanics to the Resolution of Unwitnessed Falling Accidents. *Journal of Forensic Science*, **41(5)**: 776-781.

4 Joganich T. (2006). Biomechanical Analysis in Slip, Trip, Stumble, and Fall Incidents. Proceedings of the 2006 ASSE Professional Development Conference. Seattle, WA: ASSE.

Biomechanics of Falls

The human gait cycle is divided into two separate regions representing the period of time when the foot is in contact with the ground (stance phase) and the period of time when the foot is not in contact with the ground (swing phase), as it moves forward for the next cycle of events.[5] Falls occurring during ambulation typically occur from a perturbation during a person's gait cycle. The directionality of the fall forward or rearward is in part dependent on where in the gait cycle the perturbation occurs. The stance phase begins when the foot initially comes into contact with the floor. It is at this point, that the potential for a slip and fall due to inadequate friction between the floor/shoe interface is the greatest. During a slip and fall event, the forward motion of the slipping foot results in a rearward shift of the body's center of mass relative to its base of support, leading to a loss of dynamic equilibrium and rearward fall kinematics.[6] Such kinematics lead to the likelihood of contacting the ground with the posterior (back) and side aspects of the body. (Figure 1) Additionally, during a slip and fall event, arm movements are elicited through the body's neuromuscular system in an attempt to both assist in balance recovery, as well as to protect the body during the fall.[7]

Figure 1. Schematic representation of the kinematics of a slip and fall event indicating the potential for contact with the posterior sides of the body.

The swing phase of the normal gait cycle begins at toe-off, which is defined as the point at which the stance foot is lifted off of the walkway surface. The swing phase continues as the foot swings forward, preparing for the subsequent foot contact. During mid-swing, while the leg is perpendicular to the ground, the foot drops down close to the surface of the walkway. As the foot continues to swing forward, it elevates again during late-swing, in preparation for the subsequent foot contact. Perturbations during the swing phase of the gait cycle arise from inadequate clearance between an obstacle and the swinging foot. During a trip and fall event, the swing leg becomes impeded, thereby resulting in the body's center of mass continuing forward beyond its base of support, leading to a loss of dynamic equilibrium and forward fall kinematics.[8,9] Such

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5 Perry, J. (1992). Gait Analysis Normal and Pathological Function. SLACK Inc., Thorofare, NJ.

6 You, J. et al. (2001) Effect of Slip Movement on Movement of Body Center of Mass Relative to Base of Support. *Clinical Biomechanics* **16**: 167-173.

7 Marigold, D.S. et al. (2003). Role of the Unperturbed Limb and Arms in the Reactive Recovery Response to an Unexpected Slip During Locomotion. *Journal of Neurophysiology* **89**: 1727-1737.

8 Bren Breniere, M.C. Do. Y., and Brenguier, P. (1982). A Biomechanical Study of Balance Recovery During the Forward Fall. *Journal of Biomechanics* **15(12)**: 933-939.

kinematics lead to the likelihood of contacting the ground with the anterior (front) aspects of the body. (Figure 2) As with a slip event, during trip and fall events arm movements are elicited in an attempt to both assist in balance recovery, as well as to protect the body during the fall.

Figure 2. Schematic representation of the kinematics of a trip and fall event indicating the potential for contact with the anterior sides of the body.

Slip or trip incidents resulting in falls are frequently linked to injuries to the head, lumbar spine, shoulder, knee, and ankle joints. However, given the kinematic differences associated with slip and trip events, detailed biomechanical analyses of the subject incident are required for evaluation of injury mechanisms and force magnitudes for the injuries in question.

Injury Mechanisms

From a biomechanical perspective, causation between an alleged incident and a claimed injury is determined by addressing two questions:

1. Did the subject incident load the body in a manner known to cause damage to a body part? That is, did the subject event create a known injury mechanism?

2. If an injury mechanism was present, did the subject event load the body with sufficient magnitude to exceed the tolerance or strength of the specific body part? That is, did the event create a force sufficiently large to cause damage to the tissue?

If both the injury mechanism was present and the applied loads approached or exceeded the tolerance of the effected body part, then a causal relationship between the subject incident and the claimed injuries cannot be ruled out. If, however, the injury mechanism was not present or the applied loads were small compared to the strength of the effected tissue, then a causal relationship between the subject incident and the injuries cannot be made.

Determination of a causal relationship between claimed injuries and a specific fall event requires thorough analyses of the subject incident, an understanding of the unique tolerance level of the individual in question, and a biomechanical analysis of the associated injury mechanisms and

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[9] Pavol, M.J. et al. (2001). Mechanisms Leading to a Fall from an Induced Trip in Healthy Older Adults. *Journal of Gerontology* **56A (7)**: M428-M437.

force magnitudes. Unfortunately, this task is often incorrectly given to a treating physician who may be ill-equipped to properly analyze the subject incident. Evaluations of incident severity, as well as the associated kinematics and kinetics of the fall event are required to properly assess injury mechanisms and associated force magnitudes. Therefore, a biomechanical engineer who is trained in the application of the concepts and methods of mechanical engineering and the physical sciences to medicine and the human body is needed to correlate mechanisms of the claimed injuries with the mode and intensity of the force transfer associated with the subject incident.

Lumbar – Herniated Disc

The lumbar spine is made up of five vertebral bodies that are separated by intervertebral discs. The disc is composed of an inner gelatinous mass, the nucleus pulposus, and a tough outer covering known as the annulus fibrosis. (Figure 3) Herniated discs typically occur with the loss of structural integrity of the annulus fibrosis, often leading to compression of the nerve roots. Damage or injury to intervertebral discs occurs when a loading environment creates both a mechanism for injury and a force magnitude sufficient to exceed the strength capacity of the disc. Disc injury can result from chronic degeneration of the disc itself or from an acute event; that is, a single event wherein forces are applied to the disc at magnitudes beyond its capacity or strength. Damage (injury) to the disc in the form of herniation can result. Based upon previous research, the accepted mechanism for acute intervertebral disc herniation involves a combination of hyperflexion or hyperextension and lateral bending with an application of a sudden compressive load.[10]

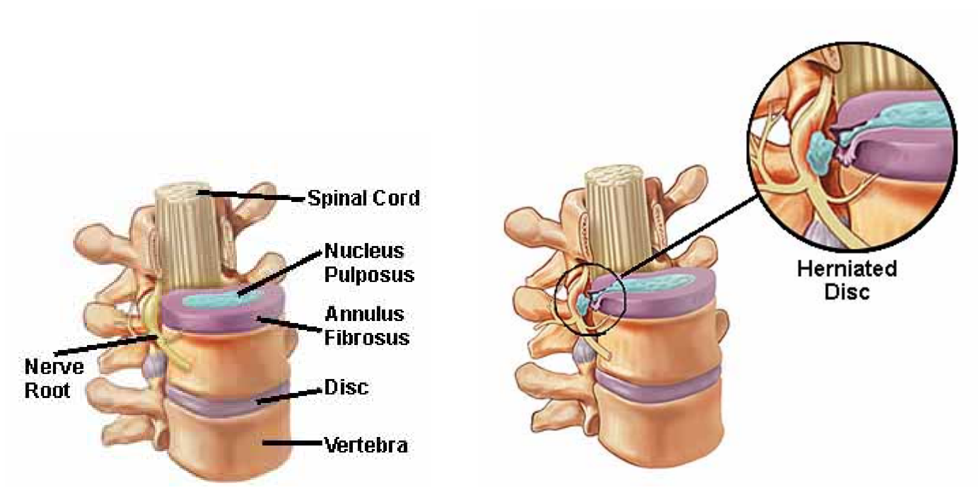

Figure 3. Schematic representation of an individual motion segment of the lumbar spine indicating the relative locations of the vertebral bodies and intervertebral discs.

As previously described, rearward fall kinematics associated with a slip event often lead to contact of the posterior (back) aspect of the body with the ground, which may induce a significant compressive load into the lumbar spine. Conversely, the forward fall kinematics associated with a trip and fall event are unlikely to induce significant compressive loads in the lumbar spine. For example, persons involved with forward fall events induced via a trip may sustain abrasions to

10 White III, A. A. and M. M. Panjabi (1990). Clinical Biomechanics of the Spine. Philadelphia, J.B. Lippincott Company.

both knees and/or hands. However, this type of forward fall event would not likely induce the compression/bending loading mechanism required to acutely herniate a lumbar intervertebral disc.

Shoulder - Rotator Cuff Tear

The shoulder consists of two primary bones: the scapula (the shoulder blade) and the humerus (the long bone of the upper arm). The end of the scapula, called the glenoid, is a socket into which the head of the humerus fits to form a flexible ball-and-socket joint. A group of four muscles (teres minor, infraspinatus, supraspinatus, and subscapularis) comprise what is known as the rotator cuff. These muscles work collectively to help stabilize the joint and to provide the muscular forces required for arm movements.

The supraspinatus muscle is one of the four muscles comprising the rotator cuff, and is responsible for initiating abduction. It runs laterally from the scapula and inserts onto the head of the humerus with the supraspinatus tendon.[11] (Figure 4) The two mechanisms for rotator cuff injury are indirect loading of the shoulder while the arm is abducted and repetitive microtrauma to the shoulder joint.[12,13] The rotator cuff is commonly injured during repetitive use of the upper limb above the horizontal plane, e.g., during throwing, racket sports, and swimming.

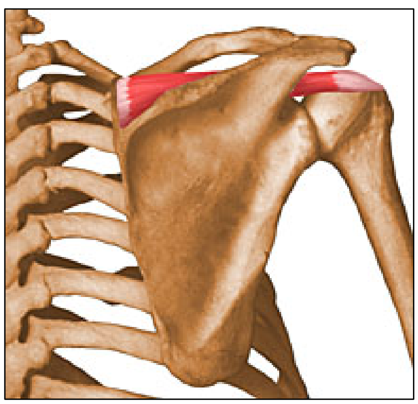

Figure 4. Posterior view of the shoulder joint indicating the location of the supraspinatus muscle relative to the humerus and the scapula.

As shown in Figure 4, the coracoacromial arch forms a roof over the rotator cuff, specifically the supraspinatus. Repetitive overhead tasks often result in impingement of the supraspinatus against the anterior, inferior aspect of the overlying acromion. In addition, differences in the shape of the

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11 Netter, F.H. (1989) Atlas of Human Anatomy, Ciba-Geigy Corporation

12 Moore, K.L. and Dalley, A.F. (1999) Clinically Oriented Anatomy, Fourth Edition, Lippencott Williams and Wilkins

13 Wolin, P.M. and Tarbet, J.A. (1997) Rotator Cuff Injury: Addressing Overhead Overuse. *The Physician and Sports Medicine* **25(6)**.

acromion have been implicated in the development of microtrauma to the rotator cuff.[14] Type I is a flat acromion, Type II is curved, and Type III is hooked. Type II and Type III have been shown to closely correlate with partial-thickness and full-thickness rotator cuff tears, respectively.

As previously described, both slip and trip induced fall kinematics may result in either direct or indirect loading of the shoulder joint. However, detailed biomechanical analyses are required to properly assess injury mechanisms and associated force magnitudes due to contact with the ground.

Knee - Meniscal Tears

The knee is a complex hinge joint that is comprised of multiple bones, ligaments, cartilaginous structures, and muscles. The medial and lateral menisci are C-shaped fibrocartilaginous structures affixed to the proximal tibial articular surface, whose primary functions are of shock absorbers between the femur (thigh) and the tibia (shin). The typical mechanism for meniscal injury is twisting of the knee when the knee is weight-bearing and flexed.[15] (Figure 5)

Knee joint loading characteristics are highly dependent upon the kinematics associated with a specific fall event. For example, biomechanical studies have shown that the slipping leg is essentially unloaded and unrestrained during a slip event. As a result, the vertical and torsional loads at the knee of the slipping leg would be relatively small and certainly much smaller than that would occur in normal walking.[16] Therefore, neither the mechanism nor the force magnitude associated with meniscal injury is created in the knee of the slipping leg during a slip and fall event.

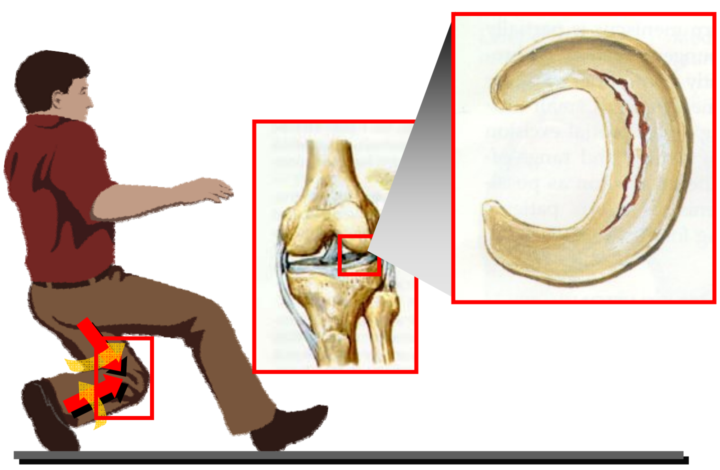

Figure 5. Schematic representation of the primary mechanism associated with medial and lateral meniscal tears.

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14 Bigliani LU, Morrison DS, April EW. (1986) The Morphology of the Acromion its Relationship to Rotator Cuff Tears. *J Orthop Trans*. **10**:228.

15 Moore K.L. (1985) Clinically Oriented Anatomy, Second Edition, Williams & Wilkins.

16 Schipplein, O.D. and Andriacchi, T.P. (1991) Interaction between active and passive knee stabilizers during level walking. *Journal of Orthopedic Research* **9**: 113-119.

However, as previously described, forward fall kinematics associated with a trip event often lead to contact of the anterior (front) aspect of the body with the ground, which may induce direct loading to the knee joints. If an interaction between a person's knee and the ground occurred during a trip and fall event, the tibia would be displaced posteriorly relative to the femur, which would be primarily resisted by tension in the posterior cruciate ligament and would load the anterior horns of the medial and lateral menisci. Conversely, this contact would not load the posterior horn of either the medial or lateral menisci abnormally. Therefore, detailed biomechanical analyses of the subject incident are required for evaluation of injury mechanisms and force magnitudes for the injuries in question.

Ankle - Lateral Malleolus Fractures

The ankle joint, as the knee joint, is a hinge joint. However, its biomechanical structure provides a much greater range of motion in a number of planes. In the sagittal plane, the foot is able to plantarflex (toes up) and dorsiflex (toes down). In the frontal plane, the foot can undergo inversion (rolling out) and eversion (rolling in). The primary articulating bones of the ankle joint are the tibia and the talus, while a number of additional bones are present within the ankle complex that allow for its complex three dimensional motions. All these bony components are joined by numerous ligaments which prevent excessive motion. (Figure 6)

Injuries to the lateral skeletal structures of the ankle are a common occurrence in fall incidents.[17] Of particular interest are lateral malleolar fractures. (Figure 6) The mechanism of these fractures typically occurs from excessive eversion of the foot and is classically associated with rolling the ankle such that the bottom of the foot faces inwards. Mild cases of ankle rolls typically result in of sprained ankles. However, in more severe cases, lateral malleolus factures may occur.

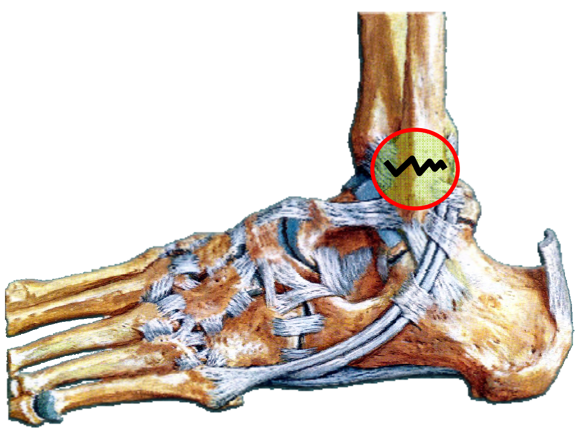

Figure 6. Lateral view of the ankle joint. Note the schematic indication of a lateral malleolar fracture.

[17] Geissler W.B. et al. (1996) Fractures and injuries of the ankle. In Rockwood, C.A. et al. (Eds) Rockwood and Green's Fractures in adults. Philadelphia: Lippincott-Ravin.

Case Study #1

A 36 year old female slipped and fell while descending a small set of stairs shortly after exiting a condominium. (Figure 7A) As a result of the subject slip and fall event, she was claiming a tear to the posterior horn of the medial meniscus in her left knee. Acute medical records indicated that she received bruises and abrasions to her back and left hand, and had complaints of left knee pain. In addition, the medical records indicated that she had degenerative arthritic disease within the left knee joint. More specifically, Grade III chondromalacia involving the patellofemoral joint and medial femoral condyle.

Investigation and engineering slip resistance testing of the subject stairs revealed that the surface provided adequate slip resistance. However, as shown in Figure 7B, the riser of the bottom step was measured to be 5 inches, while the risers of the two upper steps were measured to be 8 inches.

A.

B.

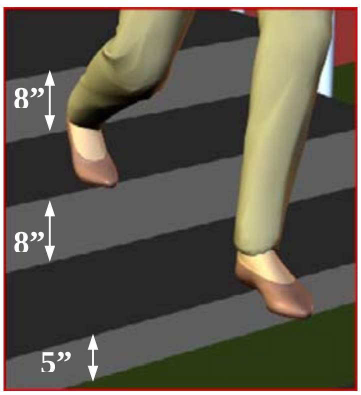

Figure 7. (A) Overall schematic representation of the scene of the subject incident. (B) Measurements of the riser dimensions of the subject stairs.

A biomechanical analysis demonstrated that the pattern of bruises and abrasions were consistent with a rearward fall initiated by a slip event. This analysis was consistent with her testimony, during which she stated that upon stepping down from the middle to the bottom step with her left leg, her left foot slipped out from under her and she contacted her left hand and lower back on top of the subject stairs. Given that during the subject event the woman’s left leg was the slipping leg the vertical and torsional loads at the knee of the slipping leg would be relatively small and certainly much smaller than that would occur in normal walking or stair descent.[18] Therefore, neither the mechanism nor the force magnitude associated with meniscal injury were created in the knee of the slipping leg during the subject slip and fall event.

It is important to note that although the investigation of the subject stairs revealed a code violation due to the 3 inch differential in riser height between the bottom step and the upper two

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[18] Mow, V. C. and W. C. Hayes (1991). Basic Orthopaedic Biomechanics. New York, Raven Press.

steps, this violation was not proximate to the subject slip and fall event because the woman fell prior to stepping down to the ground from the bottom step.[19]

Case Study #2

A 49-year-old female alleges to have slipped and fallen on a wet landing surface while descending a stairway at a marina. (Figure 8A) The landing surface was constructed of textured fiberglass with imbedded abrasive non-skid particles. (Figure 8B) The female testified that during the subject incident she fell to her left, hitting the wall and eventually landing on her left side. In addition, she testified that at the time of the subject incident she was wearing thick flip-flop sandals. Acute medical records indicated that the plaintiff sustained a left lateral malleolus ankle fracture. (Figure 9)

Engineering slip resistance testing showed that the surface provided adequate slip resistance even under wet conditions. Given the lack of a slippery landing surface, it was reasonable to conclude that causative factor(s) other than a slippery landing surface accounted for the woman's fall incident. A biomechanical analysis revealed that the woman fell to her left and that the mechanism associated with the injury sustained to her left ankle was of an ankle roll to the outside. Based on these findings, in conjunction with the lack of a slippery landing surface, it was concluded that the woman's left heel slipped off the outside edge of her flip-flop sandal, thereby rolling her ankle, as opposed to her footwear slipping on the landing surface. Consequently, the woman's fall incident was causally related to a misstep, rather than a slippery surface.

A.

B.

Figure 8. (A) Picture of the subject stairway. (B) Picture of the textured fiberglass landing surface containing imbedded abrasive non-skid particles.

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19 International Building Code (2000). Stairways. Section 1003.3.3

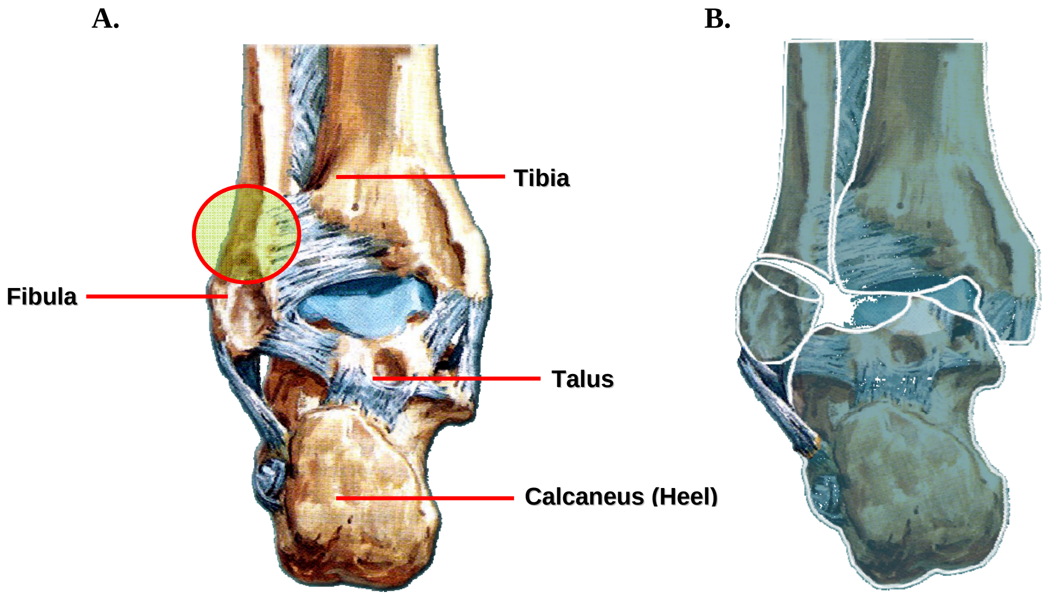

Figure 9. (A) Posterior view of the left ankle joint indicating the location of the left malleolar fracture. (B) Schematic representation of the mechanism associated with subject lateral malleolar fracture.

Conclusions

In summary, this paper provides a valuable discussion related to the biomechanics of falls, as well as injury mechanisms associated with common injuries associated with slip, trip, and fall incidents. As demonstrated in the case studies, traditional investigations focusing on liability issues, such as code violations, may fail to establish a causal relationship between the subject event and the claimed injuries. In contrast, biomechanical analyses in the first case study demonstrated that the claimed injuries were inconsistent with the described fall kinematics, injury mechanisms and force magnitudes. Furthermore, this analysis illustrated that the code violation was not proximate to the claimed injuries during the subject slip and fall event. In the second case study the biomechanical analysis revealed the underlying mechanism of injury was not related to the purported slip hazard associated with the presence of water on the landing. This paper emphasizes the importance of utilizing a biomechanical engineer who is trained in the application of the concepts and methods of mechanical engineering and the physical sciences to medicine and the human body to correlate mechanisms of the claimed injuries with the mode and intensity of the force transfer associated with the subject incident.