Simulation on Human Body Injury Locations during a Fall due to Slip

Ha Van Vo[1] and R, Radharamanan[2]

Abstract – Most of the engineering projects at Mercer University School of Engineering require some level of simulations before the construction of prototypes. This paper presents one such study where students carried out simulations on human body injury locations during a fall due to slip. The objective of this study is to analyze the varying forces in the fall injuries that depend on the location of the center of gravity of the body of angle of slip. Force versus time dependent simulations were carried out using Lifemod software for thoracic and lumbar vertebrae. An example of a fall injury was carried out and the simulation results showed that the highest and the lowest compressive stresses occur at the lumbar vertebrae (2,250 psi) and thoracic vertebrae (1,750 psi) respectively. The stresses calculated were significantly lower than the ultimate stress value of cortical bone. It can be concluded that there will be no bone fracture occurring at the vertebrae but there will be possibly ligaments and muscles tearing.

Keywords: Injury biomechanics, falling accident, slip and fall, vertebral simulation, and ligament sprain.

INTRODUCTION

In the area of injury biomechanics, the students were taught to build a 3D Finite Element model to conduct a series of computer simulation and finite element analysis of the human motion to predict and determine the locations, and mechanical loads acting in a specific structure of the human body. This paper is one the example of the simulation relating to injury mechanics projects. Results have shown that students have understood well and better in this area and they did well in the final project presentations.

Falling is a common accident that has seen in construction works and more importantly in worker compensation cases. People can fall while they are at work and could be involved in serious injuries and death. Center for disease control (CDC) estimated that "one million people suffered a slip, trip or falling injury, and over 17,000 Americans died as a result in 2004. Of the estimated 3.8 million disabling injuries each year in the work force,15 percent are due to slips, trips, or falls, which account for 12 to 15 percent of all Workers' Compensation costs" [1]. Injury mechanics is the field of bioengineering that describes exactly how injuries were received and what is the biomechanics behind the injury. The basic idea that influences the severity of injury sustained is the amount of energy absorbed by the musculoskeletal system [2]. The higher the energy absorbed the more damage the human body will sustain and could be a leading factor in deciding between life and death. In 1996, the National Safety Council estimated that the comprehensive cost of unintentional injuries was more than $1.2 trillion dollars [2]. Furthermore, injuries accounted for 40% of the visit to the emergency room [2]. This study analyzes the forces and torque associated with the falls and slips and how they damage the lumbar and thoracic vertebrae.

BACKGROUND

The thoracic region is the area of the spine that is located around the chest region and it makes up the ribcage. As shown in figure 1, the thoracic region is the second major region of the spinal column and is beneath the cervical

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[1] Mercer University, 1400 Coleman Avenue, Macon, GA 31207, vo_hv@mercer.edu

[2] Mercer University, 1400 Coleman Avenue, Macon, GA 31207, radharaman_r@mercer.edu

spine column. The spinal column is composed of 33 vertebrae for the human body [3]. Of the 33 vertebrae, the thoracic region usually consists of 12 vertebrae. These regions are labeled: T1-T12.

The lumbar region is the area of the spine that is typically recognized as the lower back. As shown in figure 1, the lumbar region is the third major region of the spinal column and supports approximately 60% of the body weight. Therefore, they are the joints besides hip, knee and ankle that are subjected to larger load bearing application. They are located beneath the thoracic regions of the spine and directly above the Sacrum region. Of the 33 vertebrae, the lumbar region usually consists of five vertebrae and in a few individuals the lumbar region has six vertebrae. The region is labeled: L1-L5

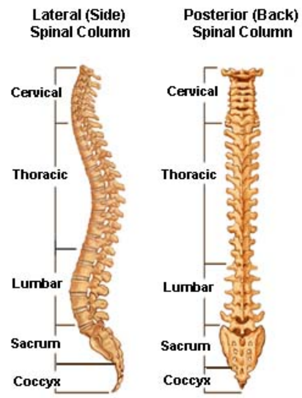

Figure 1: The general structure of the human spine

The spinal column is held together by a series of ligaments and tendons. The ligaments are used to connect the various bones together while the tendons function is to connect muscle to vertebrae. Each vertebrae are stacked on top of one another with a series of disc in between them. These gel-like discs function as cushions between the spinal columns to help absorb the impact during compression. The discs also serve to help distribute stress and keep the vertebrae from grinding against each other [4].

The lumbar region is the area of the spine that carries the most amount of body weight [3]. Therefore this is the region that has to deal with the most stress and has to be able to deal with a variety of forces that affect the body. This will explain why many people suffer lower back pains and injuries.

The various lower back injuries that can occur to a person are herniated discs, spinal stenosis, spinal fracture and various types of arthritis. A herniated disc, spinal stenosis and spinal fracture are sometimes caused by falls especially in the elderly.

A herniated disk happens when a disc degenerates into the spinal canal [5]. The weak spot in the disc is under a nerve root and when the disc is herniated, the area is places pressure on the nerve causing severe pain. Spinal Stenosis is a pain caused by a narrowing of the spinal canal [6]. This narrowing of the spinal canal causes the nerves that travel through the lower back to become compressed leading to pain for the individual. A spinal fracture usually occurs in individuals who have thinning bones [7]. When these thinning bones weaken over time they cause a compression which can lead to the bones in the spinal column collapsing.

Some of these problems can lead to life long problems like paralysis.

> "Spinal cord injury (SCI) involves damage to the nerves within the spinal canal; most SCIs are caused by trauma to the vertebral column, thereby affecting the spinal cord's ability to send and receive messages from the brain to the body's systems that control sensory, motor and autonomic function below the level of injury" [8].

Permanently damaged nerves can lead to paralysis [8]. The nerves around the lumbar region control the signals that are sent to the legs and hips. Damage to these nerves can lead to loss of control in the same areas. After an injury, the nerves that can send signals to their limbs are able to repair themselves over time. However completely injured nerves usually do not regenerate. Nerves that fail to regenerate cannot send signals to areas below the injury.

MATERIALS AND METHODS

The main goal of this study was to analyze the forces that are developed at the anatomical joints at the time of impact during a slip, trip, and fall injuries. These forces can be calculated numerically by developing a mathematical model or by using a computational model by performing computer simulations. This study focused on using a computational software modeling called Lifemod [9], which can be used to predict human motion when subjected under loading conditions. In order to use the software correctly, four steps were followed to arrive at the results: create 3D skeletal model, attach muscles and skin to the skeleton, assign materials property and boundary conditions, and run the simulation.

The Skeletal body was created for a 170 pound person with a height of 5’5”. The units were set to foot, pound mass, and pound force. The center of gravity (COG) is located 2 inches anterior to sacrum S2. The joint stiffness is 1 ksi. Figure 2 shows the skeletal system along with joints that were created to simulate the injury mechanics of a slip, trip and fall injuries. The muscles were then added to the skeletal body and it was finally covered with skin as shown in Figure 3. The limbs were then positioned such that the human body mimics the ideal position during the fall as shown in figure 4. The cases were carried out for COG angles 15°, 25°, 35°, 45°, and 60°.

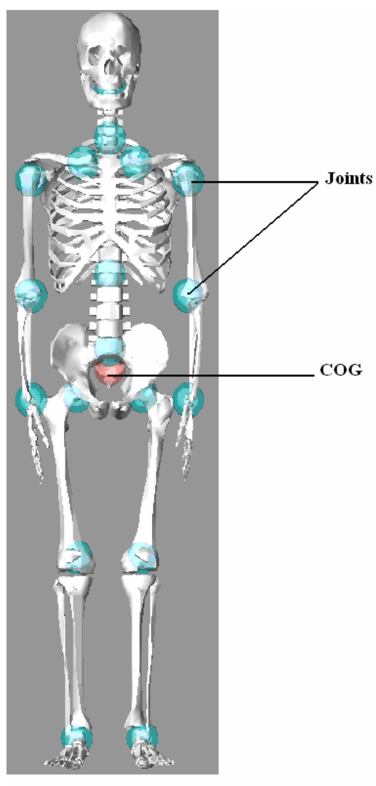

Figure 2: 3D model of the human skeletal system using for simulations.

Figure 3: The complete human body with muscles and skin attached using to create slip and fall.

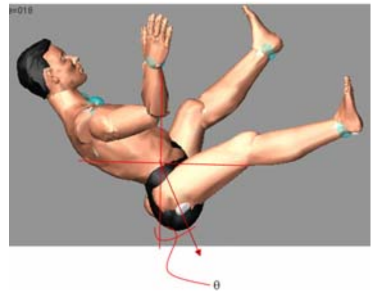

Figure 4: Ideal falling position with center of gravity angle (θ) shown

It was assumed that the person starts from a height of 3ft (COG height) and lands on the concrete slab with a thickness of 1 inch. This material was selected because it is the most common material that is encountered during construction and worker compensation related environments. The parameters for the contacts used were: Stiffness = 1E11 psi; Exponent = 3; Damping = 250 lb-s/in; Damping depth = 0.005” and Friction coefficient = 1. Time dependent simulations were run for a total of 2.0 seconds and data were collected every 0.02 seconds. Forces were measured around the hips, lumbar, thoracic and neck region.

Results and Discussions

During a slip, trip and fall injuries the first joints that are severely affected are the lumbar joints. This is because it is the first joint that comes in contact with the concrete surface and suffers the most amount of injury. The other joints that are commonly affected are the hip, the thoracic, and the cervical spine (upper neck and lower neck).

For the lumbar vertebral injuries, the following diagrams (figures 5-9) show the forces distributed over the lumbar region simulations for the falling position angle θ at 15^o, 25^o, 35^o, 45^o, and 60^o. The solid red line shows the forces while the dashed and dotted lines represent the torques in the sagittal, transverse and frontal planes correspondingly.

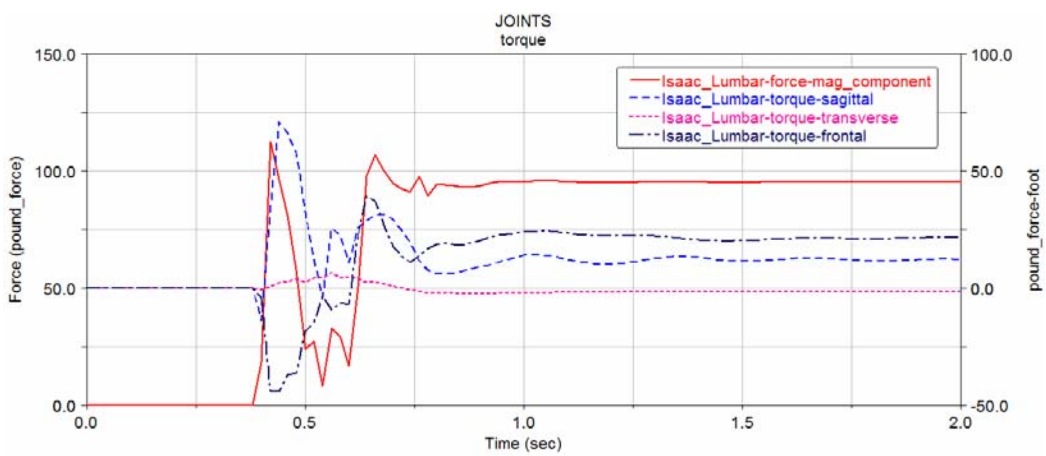

Figure 5: Lumbar force distribution at 15 degree angle of slip

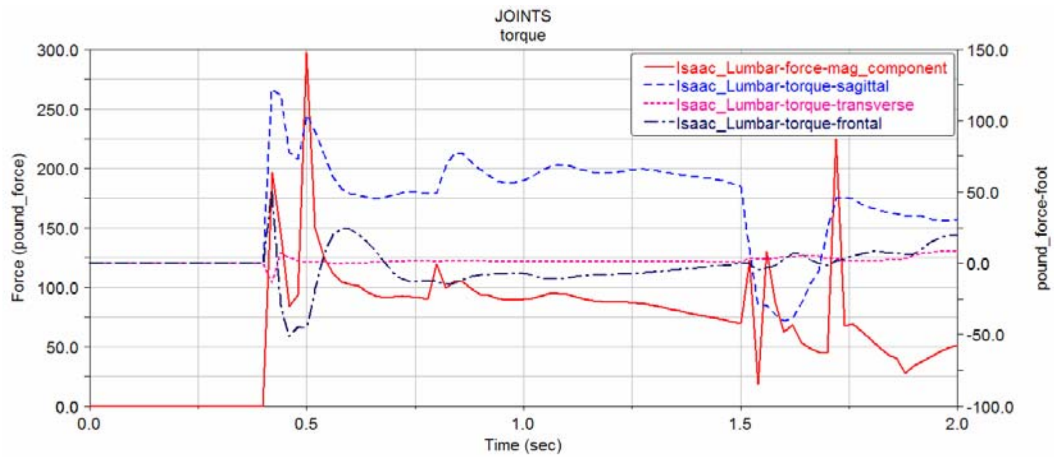

Figure 6: The lumbar force distribution at 25 degree angle of slip

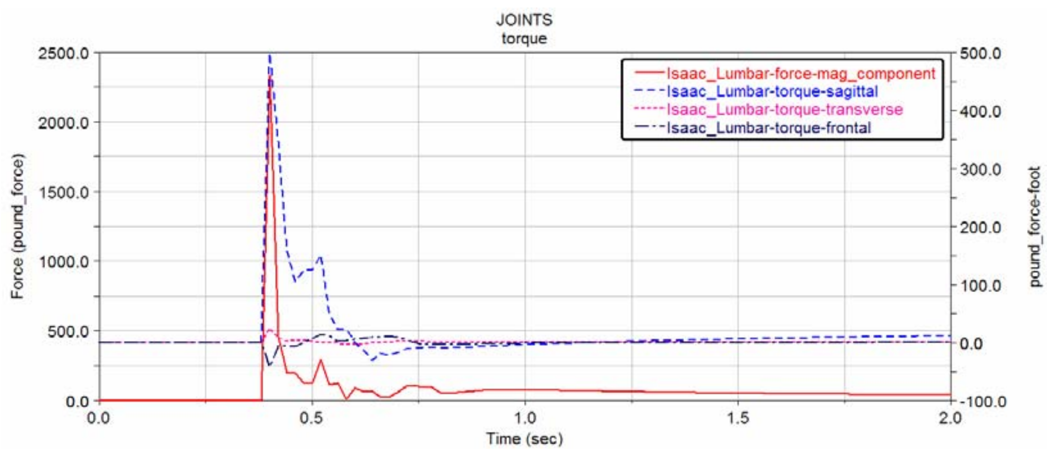

Figure 7: Lumbar force distribution at 35 degree angle of slip

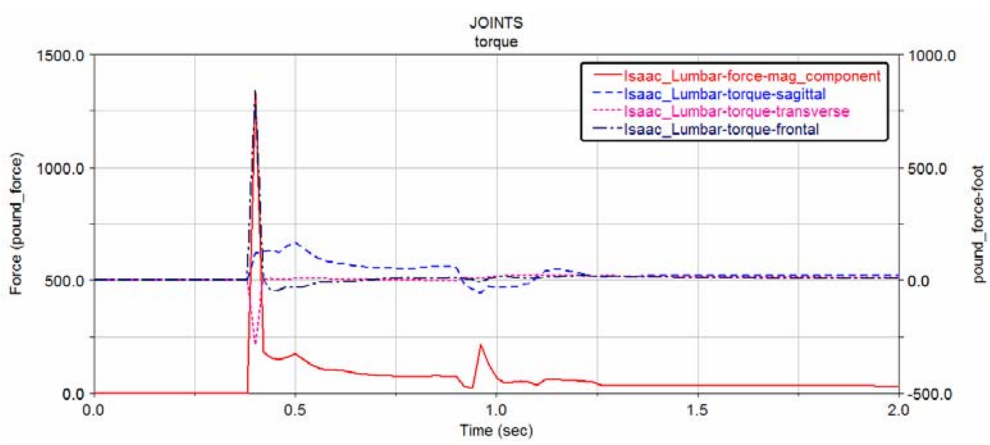

Figure 8: The lumbar force distribution at 45 degree angle of slip

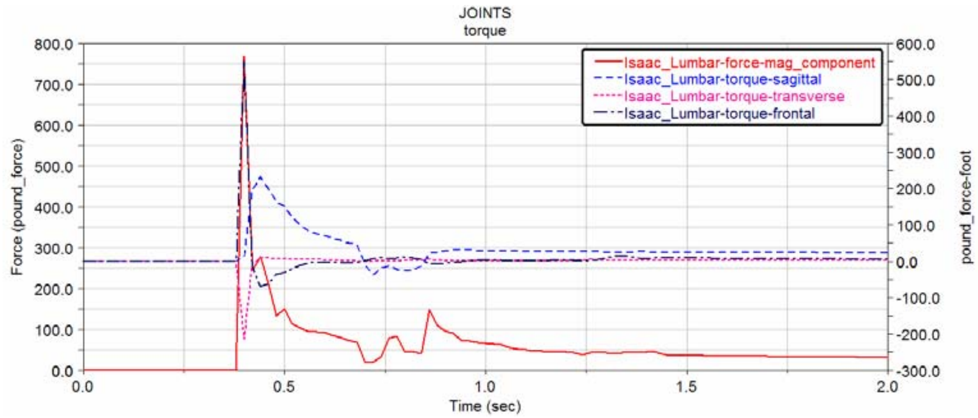

Figure 9: The lumbar force distribution at 60 degree angle of slip

For thoracic vertebral injuries, the following diagrams (figures 10-14) show the forces distributed over the thoracic region simulations for the falling position angle θ at 15°, 25°, 35°, 45°, and 60°. The solid red line shows the forces while the dashed and dotted lines represent the torques for the sagittal, transverse and frontal planes.

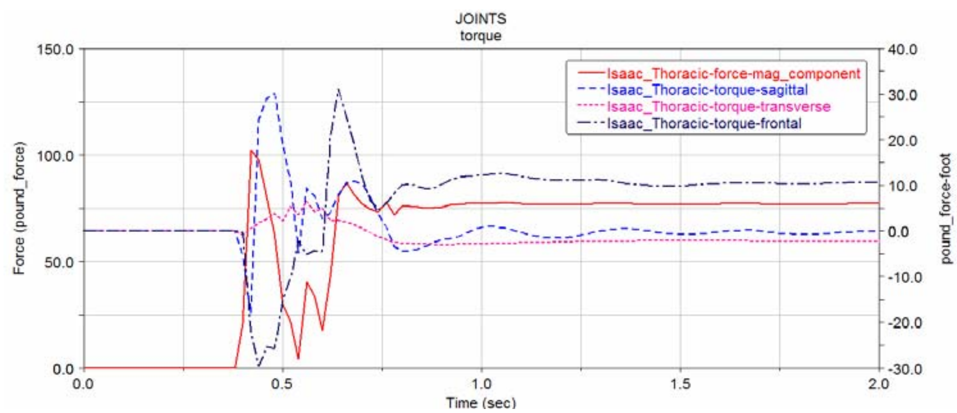

Figure 10: The thoracic force distribution at 15 degree angle of slip

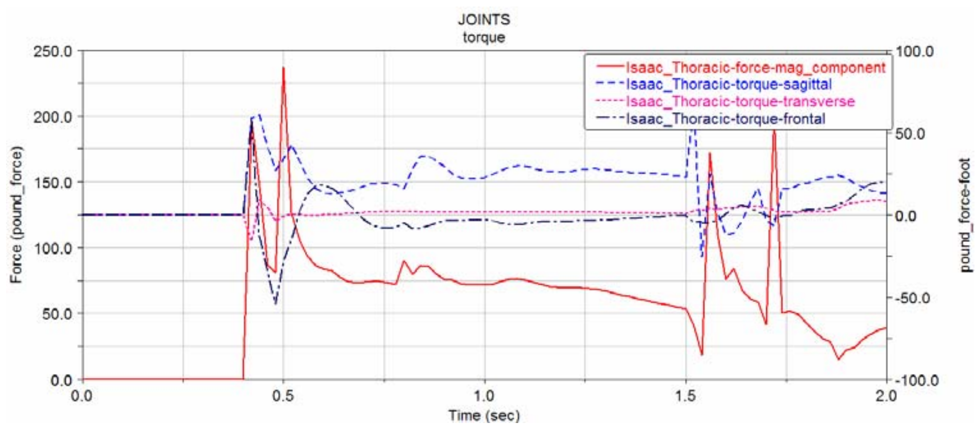

Figure 11: The thoracic force distribution at 25 degree angle of slip

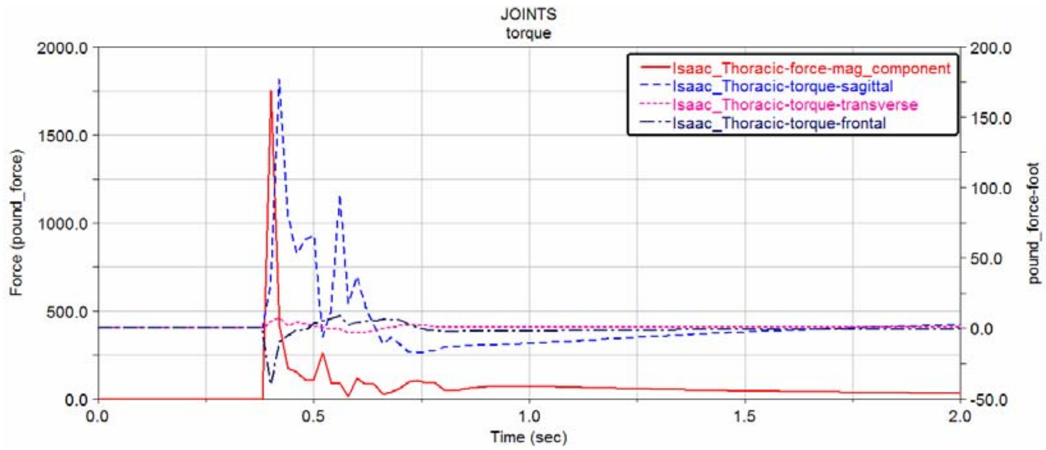

Figure 12: The thoracic force distribution at 35 degree angle of slip

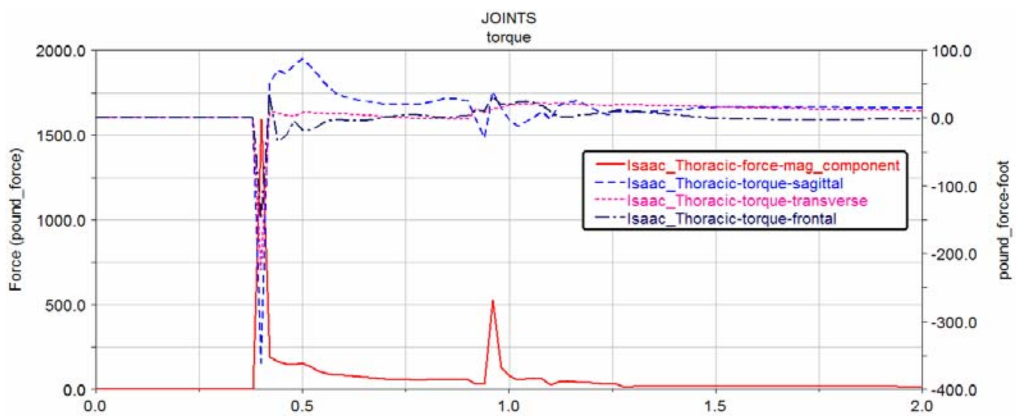

Figure 13: The thoracic force distribution at 45 degree angle of slip

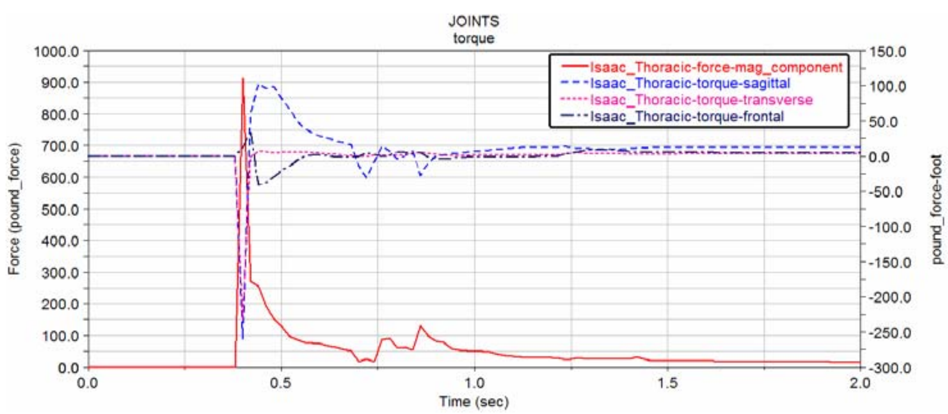

Figure 14: The thoracic force distribution at 60 degree angle of slip

Figure 15 summarizes the relationship for figures 5-14 by determining the maximum reaction force at each angle. Lumbar vertebrae have experienced much higher compressive force of falling position angle θ at 35^o, and since the θ reaches 45^o the thoracic region has experienced higher compressive load than the lumbar region due the COG moved up to the thoracic region.

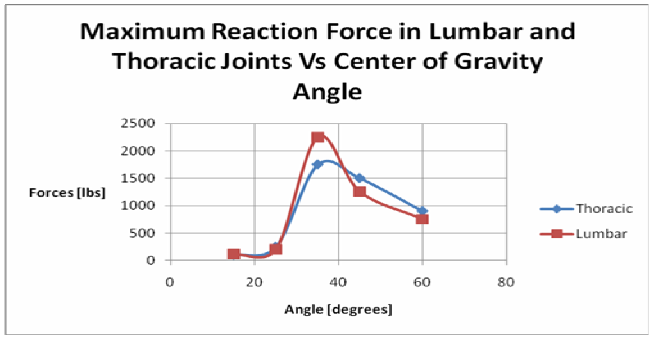

Figure 15: Reaction force and center of gravity relationship in thoracic and lumbar vertebrae

From figure 15, it can be inferred that the magnitude of the force increases rapidly until the angle is 35 degree. After this point, the magnitude of the force decreases rapidly and would eventually reach zero. This is because the spine is made up of four natural curves-two lordotic and two kyphotic. The cervical and lumbar curves are lordotic whereas the thoracic and sacral curves are kyphotic .These curves along with the surrounding ligaments and muscles keep the joints intact, prevent injury and dislocation, and distribute stress as the body undergoes a wide range of motion. Lordosis is the curvature of the spine when a person is facing up to pray and kyphosis is the curvature of the spine when a person is riding a horse. Figure 16 shows a free body diagram of the lumbar joint.

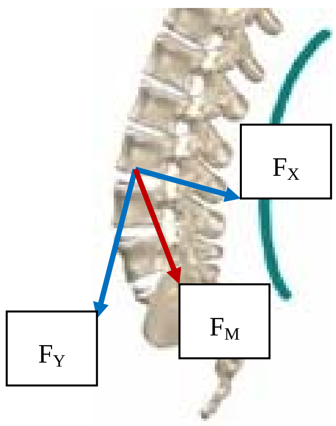

Figure 16: A free body diagram of a lumbar vertebral joint

In figure 16, F_M represents the magnitude of the reaction force that is exerted at the joints, F_Y represents the vertical component of the F_M, and F_X represents the horizontal component of F_M. Any change in the lumbar joint angle will change the magnitude of $F_{M,}$ which arises primarily because of changes in normal curvature of the spine, that is changes lordotic angle. Therefore referring back to figure0 10-14, as the angle is increased the magnitude of the vertical component reaction force dominates in the axial direction until the angle is 45 degree. The horizontal component of the reaction force at the point is very small or no longer exists. As the angle is increased further, the joints are not aligned any more and the curvature changes from lordosis to kyphosis. The vertical component of the force gradually decreases and the horizonal shear plays a major role in determining the magnitude of reaction force. This explanation holds true for thoracic joints except the curvature of the thorax changes from kyphosis to lordosis. Also as the angle is increased beyond 45 degree, the thoracic curve is more open to the ground and therefore more prone to the injuries. Therefore this produces a slightly higher reaction force as compared to lumbar joint as the angle is increased in figures 5-9.

Research suggests that the ultimate stress for a cortical bone is 180 MPa [10]. Also the surface area for lumbar joint is approximately 10 [cm^2] [11]. From figure 15, the maximum force in the lumbar joint is calculated to be 2250 pounds. Using the equation for stress ($\sigma = F/A$), the stress in the lumbar joint is calculated to be 10.01 MPa. Evaluating the same equation for thoracic region, the stress is calculated to be 7.78 MPa.

Both these values are signinificantly lower than the ultimate stress value of the cortical bone. However, this does not hold true for each and every person as different people have different anatomical characteristics such as height, weight, sex, age, bone density, and medical history. Another important factor that Lifemod model does not assume is that at the time of the fall, different person will land in different position and will try to adjust by themselves in order to reduce the amount of injury. Also it should be mentioned that the Lifemod software only applies on a theoretical basis and not enough data has been accumulated that can validate the injury mechanics data. Therefore one of the goals for future studies would involve creating a mathematical model that will attempt to validate the data produced by Lifemod and that it will provide a better approximation for each and every individual.

CONCLUSIONS

The lumbar force magnitude increases with increasing in angle of slip from 15^o to 35^o and decreases with increasing in angle of slip from 35^o to 60^o. The maximum lumbar force magnitude occurs at a slip and fall at 35^o angle. The magnitude of the lumbar force decreases from 35^o to 60^o angle of slip due to the increasing in moment arm in the x-axis which decreases the vertical lumbar force impact in the y-direction. Similar biomechanical forces are acting on the thoracic region.

Slip and fall injuries will be more severe when the reaction forces are maximum and this will happen when the curvature of spine changes such that all vertebrae in that specific joint will be stacked on top of each other. In order to reduce the expenses incurred due to fall related lower back injuries, it is recommended that fall protection and fall prevention measures be put into place.

The purpose of fall prevention is to reduce the amount of falls that occur by doing proper planning. Many of the prevention techniques are already the policy for protection agencies like Occupational Safety and Health Administration (OSHA). Some of the best ways to workers from falling is to make sure that they are wearing shoes and boots with slip resistant soles [12]. The shoes that are worn should also be in good condition. Worn out shoes or boots can cause workers to slip and fall so supervisors should inspect their workers clothing over time.

Another good way to prevent falls is routine cleaning and maintenance [13]. Oil or water spills should be marked by using a sign or a warning label. These spills should be cleaned up as soon as possible to reduce the risk of workers slipping. If workers are working at night or dimly lit conditions then supervisors should make sure that work areas are well lit. Areas that are too dark limit the field of vision of the worker which could cause them to slip. Areas that are typically walked on should be inspected for loose items or cables. If there are cables in the way, make sure that they are covered. Walkways should also be cleared of dust and debris daily so that workers do not lose their footing when walking on floors. If possible flooring should be either replaced or modified. Recoating, repainting, or matting non-slip flooring can be very helpful in reducing the number of slips that occur in the workplace.

The purpose of fall protection is to protect workers from injury in the instance that they do fall. There are numerous ways to protect a worker when they fall [14]. Placing guardrails is a way to protect worker from falling since it can be used to catch a falling worker. Items that can attach to the worker can also be used to protect workers from falls. Body harness, safety belts, and lanyards can be used to attach to the worker to catch them when they fall. Also making sure other workers and supervisors on hand can help to assist injured workers and make sure that they are working in safe working conditions.

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Biography

Ha Van Vo

Dr. Ha Van Vo is an Assistant Professor in the Department of Biomedical Engineering and Physician, Mercer University, Macon, GA. His main teaching and clinical research focus on sport medicine biomechanics, accidental injury biomechanics, rehabilitation engineering, medical devices, laser guide for surgery, orthopedic implants, and biomedical mater

R. Radharamanan

Dr. R. Radharamanan is a professor in the Department of Mechanical and Industrial Engineering at Mercer University in Macon, Georgia. He has thirty five years of teaching, research, and consulting experiences. His previous administrative experiences include: President of International Society for Productivity Enhancement (ISPE), Acting Director of Industrial Engineering as well as Director of Advanced Manufacturing Center at Marquette University, and Research Director of CAM and Robotics Center at San Diego State University. His primary research and teaching interests are in the areas of manufacturing systems (CAD/CAM and Robotics), modeling and simulation, quality engineering, and product and process development. He has organized and chaired/co-chaired five international conferences on CAD/CAM, Robotics and Factories of the Future, and organized and chaired one regional seminar on Operations Research. He has received two teaching awards, several research and service awards in the United States and in Brazil. His professional affiliations include ASEE, IIE, ASQ, SME, ASME, and ISPE.