THESIS

LOW BACK BIOMECHANICS DURING MANUAL MATERIALS HANDLING OF BEER KEGS

Submitted by

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ABSTRACT

LOW BACK BIOMECHANICS DURING MANUAL MATERIALS HANDLING OF BEER KEGS

Biomechanical risk factors such as heavy loads and awkward trunk postures have been associated with occupational low back pain. Those same risk factors are commonly experienced among workers handling beer kegs. The present study used a 3-dimensional motion capture system as a tool to investigate the low back biomechanics during keg handling at a working brewery. Specifically, five workers transferred spent kegs from a pallet to a conveyor to be cleaned and filled with beer in the present study. Data was collected during the portion of the shift workers handled kegs. Low back angular displacements were assessed during keg handling at two heights. Kegs originated from a high or low position and were defined as a high or low lift. Kinematic data from the study was used to estimate compressive and shear forces at the lumbosacral joint from a 2-dimensional static biomechanical model. Repeated measures analyses were performed with each low back angular displacement variable as a function of lift condition.

Differences in low back biomechanics between high and low lifts were identified. During low lifts, torso flexion was significantly greater than high lifts. The magnitudes of flexion achieved during low lifts significantly exceeded those of high lifts. Differences between left axial rotation where significant with larger magnitudes of rotation occurring during high lifts. A broader range of angular displacements was observed in high lifts. In both lifting conditions, estimated kinetics exceeded recommended action limits, potentially putting workers at an increased risk for developing low back pain. Work design (lift condition) influenced low back motion during keg handling. Data collection during operational hours was feasible due to the portability and small design of inertial measurement units. Results from the study can help improve workplace design in a craft brewery, reduce risk, and create safer work.

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DEFINITIONS OF TERMS

Axial rotation	Lumbar motion in transverse plane.
Barrel	The primary beer container before kegs were invented. Now barrels are the standard unit of measurement for beer quantities (1 barrel = 31 gallons = 117.35 liters).
Compressive force (spinal context)	A force that acts parallel to the long axis and is transmitted through the vertebral bodies and intervertebral discs of the spine.
Craft brewery	An independently owned facility that produces 6,000,000 barrels (2,000,000 gal. or 7,570,824 L) of beer or less annually. Craft breweries often emphasize high quality brews, community engagement, and philanthropy (Brewers Association, 2016)
Drift (IMU context)	Over repetitive integration of angular rates from gyroscopes, orientation errors. (Sun, Meng, Ji, Wu, and Wong, 2010). Magnetometers and accelerometers offer complementary information to compensate for drift (Roetenberg, Luinge, Baten, and Veltink, 2005) .
Euler angles	True values of XYZ roll pitch yaw are integrated from gyroscope signals (Sun et al., 2010).
Extension	Motion corresponding to when the angle between two adjacent segments increases in sagittal plane (approaching upright posture). Additional extension (past upright posture) is hyperextension (bending backwards, or returning to neutral from flexion).
Flexion	Motion corresponding to when the angle between two adjacent vertebral bodies decreases in sagittal plane (forward bending).
Frontal axis	A line passes horizontally in left to right direction and is formed by intersection of frontal and transverse planes. By conventional usage, values to the right of the subject's center of mass are positive and to the left are negative (Steindler, 1973).
Frontal plane	A plane running perpendicular to the transverse and sagittal planes and divides the person into anterior and posterior halves (Steindler, 1973).
Half barrel keg	The most common size keg used to transport and store beer (15.5 gal. = 58.67 L). In the present study, a keg represents a half barrel keg. Half barrels are 59.4 cm high, 41.9 cm diameter. Half barrels weigh 13.6 kg. empty (30 lbs.) and 73.6 kg. (160 lbs.) when full.
Homebrew (distribution)	Beer that is brewed at a private residence is refered to as homebrew. This is typically done on a small production scale. The ability to sell (and tax) homebrew is known as legal homebrew distribution (Alworth, 2015).
Keg	A pressurized aluminum container that holds beer is called a keg. Keg specifications are available in the Appendix 8.1. Half barrel, slim quarter barrel, and sixth barrel are common keg sizes. The act of filling beer into kegs is referred to as 'kegging'

Lateral flexion	Motion corresponding to side-to-side bending in the frontal plane.
Long axis	A line formed by the intersection of frontal and sagittal planes. Distances superior to the subject's center of mass are assigned positive values and values below are negative (Steindler, 1973).
Low back pain (LBP)	Discomfort that feels as though it is arising from the lumbar and/or sacral spine regions is referred to as low back pain. According to the International Association for the Study of Pain, this definition does not include the actual pain origin and whether or not the pain radiates (Grieve, 1997).
Lumbosacral joint	The articulation between the fifth lumbar and first sacral bone of the spine.
Range of motion	The full movement potential of a joint is referred to as the range of motion. For the present study, range of motion was represented by estimated angular displacement of the lumbosacral joint.
Sagittal axis	A line that passes horizontally in posterior to anterior direction and is formed by the intersection of sagittal and transverse planes. By conventional usage, distances in front of the person are positive and behind are negative (Steindler, 1973).
Sagittal plane	A plane that is perpendicular to the transverse plane and divides the body into right and left halves (Steindler, 1973). The plane itself runs in an antero-posterior direction.
Shear force (spinal context)	A force that acts perpendicular to the long axis and parallel to disk mid-plane.
Slim quarter barrel keg	An alternative size keg used for smaller quantities of beer can be a slim quarter barrel (29.3 L = 7.75 gal.). While available at the craft brewery in the present study, quarter barrel kegs were not included in analysis.
Spent keg	Kegs that are returned from bar or restaurant (often by a third-party distributor) with varying amounts of residual beer. Spent kegs need to be properly sanitized before they can be refilled with beer.
Transverse plane	A plane that is perpendicular to the sagittal plane, passes horizontally through a person's center of gravity and separates the body into superior and inferior halves (Steindler, 1973).

1. INTRODUCTION

1.1. Background

Occupational related back pain is the most common work-related illness in the U.S. (Gatchel and Schultz, 2014; Marras, Granata, Davis, Allread, and Jorgensen, 1999). In 2015, occupational back injuries in the U.S. had an overall incidence rate of 17.3 per 10,000 full time workers (Bureau of Labor Statistics, 2016). Most occupational back injuries have high recovery rates with minimal treatment. Approximately 80% of injured workers return to work within a month and over 90% return within three months (Gatchel and Schultz, 2014). However, those that do not recover quickly may require extensive treatment and support. Of all the occupational back injuries, five percent of the cases are responsible for 75% of the expenses (Frank et al., 1996; Gatchel and Schultz, 2014). The overall economic impact of low back pain (LBP) in the U.S. (direct costs such as lost wages and rehabilitation plus indirect costs such as retraining, and reduced efficiency and quality) exceeds $200 billion annually (Dagenais, Caro, and Haldeman, 2008; Marras, Knapik, and Ferguson, 2009).

Causation of occupational LBP has been extensively researched. Despite the abundance of these investigations, the causes of occupational LBP in terms of exposure are still poorly understood in many occupational groups (Amell, Kumar, and Rosser, 2001; Gatchel and Schultz, 2014; Jones and Kumar, 2001; Putz-Anderson, Bernard, and Burt, 1997). One approach to characterize and evaluate levels of risk of experiencing LBP is to assess low back kinematics (linear displacement, velocity, and acceleration). Job design, alternative redesign and intervention effectiveness can be quantified using kinematic data as well (Bergquist-ullman and Larsson, 2014; Campbell-Kyureghyan, Jorgensen, Burr, and Marras, 2005; McGill, 1997). Optical camera systems and low back monitoring devices are examples of typical kinematic measuring devices, most of which are only practical in a lab. Lab studies of occupational tasks are limited in their ability to represent the actual work practices, demands, conditions and environment (Kim and Nussbaum, 2013; van Dieën et al., 2010). Unexperienced subjects are often recruited to perform simulated work tasks. The experimental setup is often oversimplified, strictly controlled, and often not applicable to the work environment. The ability to use 'wearable technology' directly in the workplace is an emerging technology that enhances our ability to characterize and study workers in the field. Inertial measurement units (IMUs) provide an opportunity to collect continuous human motion data throughout lifting and normal work tasks in the actual work environment. Subjects can move freely throughout the workplace without concern about exceeding instrument ranges and lines of site. Inertial measurement units combine convenience with an abundance of information related to segment and joint kinematics. Low back pain continues to be an issue in the workplace, but with portable, lightweight measurement tools in field studies, we can increase our understanding and therefore increase the efficacy of interventions to reduce risk of low back pain and increase productivity.

The association between manual materials handling (MMH) tasks and LBP has been studied in numerous occupations (Faber, Kingma, and van Dieën, 2007; Lavender, Marras, Ferguson, Splittsteosser, and Yang, 2012; Magora, 1975; Marras et al., 1993; van Dieën et al., 2010; Zurada, Karwowski, and Marras, 2004). However, there have been few studies related MMH or LBP in the brewing industry (Abaraogu, Okafor, Ezeukwu, and Igwe, 2015; Jones, Strickfaden, and Kumar, 2005). The U.S. brewing industry is experiencing a 21st century surge that resembles the rapid brewery growth in 1933, after the repeal of U.S. Prohibition. In response to the legalization of homebrewing in 1978 and commercial success of fermentation beverages in the U.S, popularity of craft breweries increased (Alworth, 2015). Craft breweries emphasize unique quality brews with renewable business practices. These breweries often start as small businesses without resources to invest in expensive automated MMH equipment, thus, the majority of MMH is performed by workers. The challenges and injuries plaguing modern craft breweries mimic those that breweries experienced following the repeal of the U.S. Prohibition. In the 1940s, these new breweries had a disproportionately high accident rate compared to general industry, with 9.2 injuries per 100,000 hours worked (1.8 per 100,000 higher than other manufacturing). Due to the high accident rate, a special task force was assigned to investigate accidents in breweries (Swellenbach and Clague, 1946). This report identified washing, loading, and barrel handling as areas of elevated risk. Barrels, the original vessel for beer transport, hold 117-liters (31 gallons),are 45.4kg (100lbs) empty, and are over 272.2kg (600lbs) full (Alworth, 2015). As of 2015, brewery injuries averaged 4.2 injuries per 100,000 hours (Brewers Association, 2016). Aluminum kegs replaced wooden barrels as the primary vessel in the 1950s (Figure 1.1.). Half the size of barrels, aluminum kegs weigh 13.6kg (30lbs) empty and 72.6kg (160lbs) full (Alworth, 2015; Jones et al., 2005). Transporting beer in kegs decreased the weight of the load, but increases the number of kegs to hold the same quantity of beer. The smaller but more numerous kegs increased the duration of worker MMH. The act of filling beer into kegs is referred to as 'kegging'. If financial resources and production demands allow, kegging may be automated or semi-automated. Today, new craft breweries may not have the production scale to economically justify automated kegging. Brewing schedules and job rotation dictate the frequency and duration that a worker may have to handle kegs. During large brew batches, a keg line operator may handle more than 600 kegs over the eight-hour shift. In contrast, during smaller brew batches, the kegging tasks can be completed in two hours or less (personal communication). Flexion, lateral flexion, and axial rotation are examples of awkward trunk motion experienced by the worker while they handle kegs.

Figure 1.1. Empty (spent) half barrel kegs arranged on a pallet to be cleaned and filled with beer

2.1. Purpose of the study

Awkward postures, long durations, and high frequency of MMH are occupational risk factors associated with LBP (Basahel, 2015; Coenen, Kingma, Boot, Bongers, and van Dieën, 2014; de Looze, Kingma, Thunnissen, van Wijk, and Toussain, 1994; Potvin, 2008). Examples of common materials handled in breweries included bags of grain, hoses, and kegs. There is very little literature of musculoskeletal risk assessments in craft breweries. Inertial measurement units (IMUs) have been validated to measure human motion, with an emphasis on MMH (Faber, Chang, Dennerlein, and van Dieën, 2016; Kim and Nussbaum, 2013; Schall, 2014). The present study was conducted using IMUs as a tool to assess low back biomechanics when craft brewery workers handle kegs. Workers in the present study transferred incoming, spent, dirty kegs from pallets to a conveyor roller where the kegs were cleaned internally, externally, then filled with beer. Kegs originating from high or low positions were defined as high or low lifts. Low back kinematic information can be used to improve workplace design in a craft brewery, reduce risk, and create a safer workplace or environment. A 2-dimensional biomechanical model estimated compressive and shear forces at the lumbosacral joint during different keg height positions. Estimating resultant forces can be used for risk assessments of low back pain (Gallagher, Marras, Litsky, and Burr, 2005; Marras et al., 1993; Waters, Putz-Anderson, Garg, and Fine, 1993).

3.1. Aims

Aim 1:

Assess displacement of the trunk during manual materials handling of beer kegs.

Objective 1: Characterize trunk flexion in the sagittal plane during keg handling tasks.

Objective 2: Characterize trunk lateral flexion in the frontal plane during keg handling.

Objective 3: Characterize axial rotation in the transverse plane during the keg handling.

Aim 2:

Evaluate changes in low back kinematics for handling kegs at different origin positions (high and low lifts).

Aim 3:

Evaluate changes in low back kinetics during keg handling at high and low lifts using a static compressive and shear forces biomechanical model.

Aim 4:

Assess kinematics and kinetics of keg handling tasks in the context of risk for pain or injury.

2. REVIEW OF LITERATURE

2.1. Overview

The following chapter addresses literature relevant to occupational low back pain, craft breweries, and human motion measurement techniques**.** Many associated risk factors for developing low back pain occur with occupational lifting. Craft breweries' recent growth and development will also be summarized, highlighting the lack of literature on risk research in this occupational field.

2.2. Work related musculoskeletal disorders

Injuries that affect a worker's physical body that occur at the work place are referred to as work related musculoskeletal disorders (Putz-Anderson, Bernard, and Burt, 1997; Tores, 2015). Work related musculoskeletal disorders are estimated to be responsible for worker compensation claims exceed $1 billion every week (Liberty Mutual Research Institute for Safety, 2017). The Bureau of Labor Statistics (BLS) reported in 2015 that work related musculoskeletal disorders had an incident rate of 32.2 per 100 full-time workers (Bureau of Labor Statistics, 2016). Overall, musculoskeletal disorders accounted for over 30% of all reported illnesses and injuries and 35% of all workers compensation costs (Dagenais et al., 2008; Pandalai, Wheeler, and Lu, 2016). Occupational low back pain accounted for over half of the reported musculoskeletal injuries in 2015 (BLS, 2016).

2.3. Occupational low back pain

Low back pain is a common work related musculoskeletal disorder that generates between $50 and $200 billion annually in indirect costs (including lost time, absenteeism, disability, retraining, and additional medical attention) (Dagenais et al., 2008). Low back pain is the most common cause of disability in industrialized countries for people younger than 45 years of age (Odole, Akinpelu, Adekanla, and Obisanya, 2011). The World Health Organization estimates that 37% of all back injuries occur at the workplace (Punnett et al., 2005).

Each day, 6.5 million American workers, or five percent of the workforce, will miss work due to low back pain (Gatchel and Schultz, 2014). In 2015, the incidence rate of back injuries that resulted in days away or restricted transfer (DART) was 16.75 per 100 full time workers (BLS, 2016). Back injuries had a higher incidence rate in men than women (19.4 and 14.6 per 100 full time workers). Workers between 35 and 44 years of age had the highest incidence rate at 20.0 per 100 full time workers (BLS, 2016).

2.4. Risk factors for low back pain

Three categories of risk factors for LBP include biomechanical, psychosocial, and individual (Gatchel and Schultz, 2014). Biomechanical risk factors include repetition, awkward postures, duration, and intensity (Gatchel and Schultz, 2014; Marras, Granata, Davis, Allread, and Jorgensen, 1997). High levels of work demand, low job control, and low social support are psychosocial risk factors. Personal characteristics such as age, gender, genetics, and lifestyle are individual risk factors. Theories for the causation of work related musculoskeletal disorders (such as LBP) include multivariate interaction, differential fatigue, cumulative load, and overexertion (Amell, Kumar, and Rosser, 2002; Jones and Kumar, 2001; Jorgensen, Marras, Granata, and Wiand, 2001b).

Many risk models for LBP identify certain work and individual factors as key contributors. Lifting frequency, axial rotation, load magnitude, forward flexion, trunk lateral velocity, symmetry, load height, and horizontal distance traveled all have been identified as explanatory variables in various models assessing causes of LBP (Jorgensen, Marras, Granata, and Wiand, 2001a; Marras et al., 1997; Potvin, 2008; Snook and Ciriello, 2002; van Dieën, Hoozemans, and Toussaint, 1999; Waters, Putz-Anderson, Garg, and Fine, 1993). Certain variables in the risk models for LBP are associated with occupational lifting and MMH: the weight of the object, bulkiness, origin and destination locations, lift frequency, and asymmetric nature of the lift (Waters et al., 1993; Zurada et al., 2004). An increase in the magnitude (intensity, frequency, duration) of kinematic variables (such as segmental angular displacement, velocities, angular velocity, acceleration, and angular acceleration) in flexion, lateral flexion, and axial rotation are associated with an increased risk of sustaining injury and developing LBP (Magora, 1975; Waters et al., 1993; Zurada et al., 2004). The speed of the lift (dynamic or static), weight of the load, asymmetry all may influence the body's response to the lift (Marras et al., 1999).

Low back pain may be caused from a single incident, resulting in acute injury, or be chronic from repetitive trauma and stress (Potvin, 2008). It is often impossible to identify the exact cause, therefore it is important to look at all the factors of a lift (including the person and the job) (van Dieën et al., 1999). During a lift, the added weight of the external load and angle of displacement (flexion, lateral flexion, or axial rotation) increases the downward force of the upper body, and the stabilizers at the base of the spine must counteract that force to maintain balance. Failure of these mechanisms to react to added loads can cause an onset of pain.

In a neutral upright posture, the weight of the upper body is evenly distributed across intervertebral discs and facet joints. Three joints are created by two articulating lumbar vertebrae; one joint between the vertebral body discs and two between the facts (zygapophysial joints). The facets provide stabilization and restrict axial rotation while permitting flexion (Grieve, 1997; Wong, 2010). Approximately 20% of the height of the vertebral column is due to intervertebral disc height (Grieve, 1997). Intervertebral discs absorb shock and distribute weight evenly across the horizontal vertebral surfaces (Chaffin, Andersson, and Martin, 1999). Abdominal pressure and muscular activation maintain this alignment.

During spinal flexion, abdominal weight is shifted forward and the body reacts to control this motion and maintain balance. Ligaments around the vertebral body and spinous processes (anterior and posterior longitudinal ligaments, ligamentum flavum, and interspinous ligaments) stabilize the trunk during trunk movement (Grieve, 1997; Netter, 2011). Spanning the sacrum and vertebrae, the erector spinae muscle activates, providing support and controlled motion of the torso. Other muscles involved in trunk stabilization during bending and lifting tasks include the rectus abdominus, internal and external obliques, and latissimus dorsi muscles (Chaffin et al., 1999). Resistance to flexion consists of intervertebral discs (29%), supraspinous and interspinous ligaments (19%), ligamentum flavum (13%), and facet joint capsules (39%) (Grieve, 1997). A lever arm is generated about the lumbosacral joint to counteract the downward forces from the abdomen bending forward. Increases in flexion, external load weight (such as during a lift), or a combination of the two create a longer lever thereby creating a larger moment arm and resultant torque about the lumbosacral joint. Injury can occur when the generated force exceeds the control of the stability mechanisms. Ligaments may sprain, muscles may strain or discs may rupture.

Quantifying the forces where LBP can occur is a significant area of interest in occupational ergonomics and safety. A spinal compressive force limit of 3400N has been recommended by the National Institute for Occupational Safety and Health (NIOSH) (Putz-Anderson et al., 1997; Waters et al., 1993). Axial rotation while lifting can further increase estimated spinal compressive forces (Chaffin et al., 1999; Marras and Granata, 1995; Miller, Schultz, Warwick, and Spencer, 1986). The lower action limit of shear force at the lumbosacral joint is 500 N (Gallagher and Marras, 2012; McGill, 1997). Depending on the frequency of shear loading, shear force limits between 700 N and 1000 N have been recommended (Gallagher and Marras, 2012). Mathematical, biomechanical models have been developed (and continue to be revised) to estimate compressive and shear forces that a worker may experience during a task. The earliest models were coplanar, static, symmetrical lift equations (Chaffin et al., 1999). Five components are considered in these simple, 2-dimensional static models: the erector spinae muscle force, subject’s upper body mass, load mass, angle of forward sagittal flexion, and the distance between the load and the lumbosacral joint. Additional models expanded on this approach by considering multiple muscle groups of the trunk, contraction and activation sequences, intrabdominal pressure, torso postures and stresses (Chaffin et al., 1999). Accepting the limitations of models (from the simplest to the most sophisticated versions), researchers and ergonomists can estimate compressive and shear force values experienced by workers during occupational lifting tasks (Greenland, Merryweather, and Bloswick, 2011; Lavender et al., 2012; van Dieën et al., 2010).

Manual materials handling has been found to have a strong association to LBP (Abaraogu et al., 2015; Ferguson and Marras, 2013; Kim and Nussbaum, 2013; Marras et al., 1997; Odole et al., 2011; Panel on Musculoskeletal Disorders and the Workplace and Council, 2001). Repetition, weight, acceleration (slow sustained pull or quick jerk), and awkward postures of lifts are all common factors for LBP that are frequently seen in occupational lifting. Risk assessments from multiple industries and occupations have consistently identified manufacturing and warehouse workers as a population with overall higher rates of musculoskeletal disorders, including low back pain (Ferguson, Marras, Allread, Knapik, and Splittstoesser, 2012; Gatchel and Schultz, 2014; Magora, 1975).

Extensive research has been conducted on evaluating musckuloskeletal disorders and discomforts related to MMH in various industries. However, few of these studies have been perfomed beverage industries, and even less in breweries. To the author's knowledge, there have been four studies. The prevalance of work related musculoskeletal disorders and awkward postures at an Eastern Nigerean beverage factory used observation-based methodology (Abaraogu, Odebiyi, and Olawale, 2016; Abaraogu et al., 2015). Physical demands of brewpub staff were analyzed using various observation based tools (Jones et al., 2005). Researchers concluded that the bartender's task of keg handling exceeded the permissible exposure limit for lumosacral joint compressive forces and was considered hazardous for most workers (Jones et al., 2005). NIOSH conducted a risk assesment and released a safety report on a large Colorado brewery in 2011. NIOSH focused on the workstation design and safety culture. The can-line and bottle depalletization areas were identified as higher risk of developing upper limb musculoskeletal disorders (Ramsey, Wiegand, and Loren, 2011). There is little literature on exposure assesment of worker demands in craft breweries.

Beverage manufacturing has some of the highest incidences of work related lost time injuries in all of private industry in the U.S. Out of 20 private industries, beverage manufacturing placed in the top five highest incidences of injuries with DART (Bureau of Labor Statistics, 2016). In the 1990s, there were 12.0 injuries for every 100,000 hours worked. Despite the increase in craft breweries and workers, the 2015 injury rate decreased to three per 100,000 hours worked (Brewers Association, 2016). This is an improvement from the 1944 reported incidence rate of 9.24 injuries per 10,000 hours. Technological advancements and safety awareness have contributed to this overall decrease.

2.5. Breweries

As of 2015, the craft beer industry represented over 20% of the $105.9 billion beer market in the U.S (Beer Institute, National Beer Wholesalers Association, 2015; Brewers Association, 2016). One job in a brewing industry creates 34 additional jobs including, but not limited to, wholesale, retail, manufacture, and farming (Beer Institute, National Beer Wholesalers Association, 2015). The overall beer industry represents $252.6 billion in economic output in the U.S. (Beer Institute, National Beer Wholesalers Association, 2015). From the agricultral industry to distribution and supplier firms, the brewing industry is an intricate part of the US economy. Over the past 200 years, beer per capita consumption in the U.S. increased from 3.79 liters (one gallon) to 75.7 liters (20 gallons) (Beer Institute, National Beer Wholesalers Association, 2015).

Homebrew distribution was legalized when the 39th U.S. President, Jimmy Carter, and Califronia senator Alan Cranston signed bill H.R. 1337, which revised federal tax codes to permit homebrewing in 1978 (https://www.congress.gov/bill/95th-congress/house-bill/1337). This legistaltion led to renewed interest in beers that differed from those produced at traditional large breweries. As demand for these unique craft brews grew, these homebrew operations expanded into craft breweries.

The craft brewing industry emphasizes a combination of traditional and modern ingredients to produce a unique beer that customers cannot find at traditional large breweries. Craft breweries produce less than 6,000,000 barrels (2,000,000 gal. or 7,570,82 L) annually (Alworth, 2015; Brewers Association, 2016). These independently owned facilities emphasize philanthropy and community engagement. The number of craft breweries in the U.S. increased from 1,500 to 5,000 between 2006 and 2016 (Brewers Association, 2017). Craft breweries are a rapidly growing industry, especially in Northern Colorado (Alworth, 2015; Associates, 2014; Brewers Association, 2016). Colorado has the second most craft breweries in the United States, with 284 craft breweries (Brewers Association, 2017).

Most craft breweries started as small homebrew operations that grew with popularity. (Alworth, 2015). Demand drives breweries to increase production, often still using small scale manually intensive processes. Increased production drives up packaging requirements. Beer can be packaged in cans, bottles, or kegs. Kegs are pressurized containers used to transport beer from breweries to bars, restauraunts, and private events. Machinery exists to automate cans, bottles, and even full kegs. The action of handling and loading empty kegs is typically the last component to be mechanized and automated as breweries grow and invest in more automated technologies. Thus, keg handling in craft breweries is usually manual. A common clean and fill line in breweries is shown in Figure 2.1. Spent kegs are delivered arranged on pallets, typically stacked two pallets high. Workers invert the kegs from the pallet to the conveyor. The conveyor delivers kegs through equipment and machinery that cleans the kegs externally, internally, and fills the kegs with beer. Full kegs are arranged on pallets for customer delivery.

Figure 2.1. Keg-line workstation
Craft brewery workers transfer spent kegs onto the conveyor by lifting and inverting the kegs. There are eight kegs per pallet. After clearing a pallet, the worker manually removes the empty pallet. The speed of the clean and fill line dictates how much space is available on the conveyor for the worker to add kegs.

2.6. Approaches to quantify worker motion

Current methods to assess low back kinematics include direct and indirect methods. Direct methods consist of attaching instruments to the human body, either in the form of superficial sensors or sensors inserted into spinal intervertebral discs. The most invasive direct measurement system includes inserting pressure transducers directly into the spinal discs (Wilke, Neef, Caimi, Hoogland, and Claes, 1999). Intervertebral pressure transducers provided direct measurements of compressive forces occurring within the spine (Oxland, 2016; Wilke et al., 1999). Invasive approaches are infrequent and have small sample sizes (van Dieën et al., 1999). Another in vivo technique includes modified vertebral body replacements to study low back demands (Dreischarf, Rohlmann, Graichen, Bergmann, & Schmidt, 2016).

Observation-based ergonomics tools and static models are noninvasive low back kinematic assessment methods that often focus on the origin and destination of lifts. Concentrating on the postures at the origin and destination of the lift only considers the peak postures and does not include intermediate postures and movements that contribute to overall spinal demands. Visual obstructions, either environmental or the subject's clothing, further limit observational techniques. The 2-dimensional nature of these observation methods can oversimplify human motion (Godwin, Agnew, and Stevenson, 2009). The consequences of these errors are misrepresentation and underestimation of the risk for LBP and injuries. Validation of these models through comparisons with other model estimations is an ongoing challenge (Oxland, 2016).

2.7. Inertial measurement units

Inertial measurement units are small, inexpensive, and portable devices that allow human motion studies to be conducted outside of a lab setting (Cutti, Giovanardi, Rocchi, Davalli, and Sacchetti, 2008; Ertzgaard, Ohberg, Orn Gerdle, and Grip, 2016). Wireless IMUs provide a quantitative measure of human movement, allowing for a kinematics based characterization (Lin and Kulić, 2012). This technology combines data from an accelerometer, gyroscope, and magnetometer to measure position, orientation, and determine joint angles (Banos, Toth, Damas, Pomares, and Rojas, 2014; Lin and Kulić, 2012; Roetenberg, Luinge, and Slycke, 2013; Zhang, Novak, Brouwer, and Li, 2013). Accelerometers measure acceleration (velocity and position are integrated). The gyroscope calculates orientation by directly measuring angular velocity that is integrated to determine angular position (orientation) and to overcome drift (Godwin et al., 2009). Gyroscopes are less effected by displacement anomalies because they measure angular velocity and do not record rotations (Banos et al., 2014). The same study describes how, due to a rigid body segment approach, the placement of a gyroscope on a body segment does not influence its measurement abilities (Banos et al., 2014). Kalman filtering is used to calculate joint angles based on information for the accelerometer and gyroscope to account for drift (Lin and Kulić, 2012; Roetenberg, Luinge, Baten, and Veltink, 2005). Inertial measurement units that consisted solely of accelerometers and gyroscopes illustrate joint angles and angular velocity patterns, but encounter drift along the gravitational vector. The addition of a magnetometer helps account for this gravitational vector drift by aligning with the magnetic north (Ertzgaard et al., 2016). Magnetometers can be vulnerable to environmental ferromagnetic interference or certain electronic devices (Luinge, Veltink, and Baten, 2007; Roetenberg et al., 2005). This can be an issue when recording in a facility with ferromagnetic structural beams and reinforcing bar (rebar). Sensor fusion algorithms were applied to address magnetic disturbances (Luinge et al., 2007; Roetenberg et al., 2005). Updated sensor fusion algorithms and dynamic calibration techniques are actively being developed to reduce dependency on the magnetometer, thereby reducing the influence of ferromagnetic interference on final position data (Xsens.com).

Calibration procedures of IMU systems allow for flexibility of sensor placement. However, sensors should not be adjusted after calibration is complete. Any sensor shifting post calibration can disrupt the rigid segment assumptions (Schall, Fethke, Chen, Oyama, and Douphrate, 2016). Inertial measurement units are used in human motion modeling by treating the body as a series of rigid segments to approximate motion interactions (Banos et al., 2014).

Inertial measurement units have been recently used in basic movement, sports medicine and clinical research (Kim and Nussbaum, 2013). They are also a promising tool with strong clinical applicability and the possibility for further kinematic analysis in various locations (Ertzgaard et al., 2016; Ha, Saber-Sheikh, Moore, and Jones, 2013). Inertial measurement units do not suffer from obstruction or line of sight issues, making them ideal for field research (Luinge et al., 2007; Splittstoesser et al., 2007). Previous studies have simultaneously recorded MMH task simulations in a lab with IMU systems and optical motion capture systems, concluding that IMUs are acceptable (Berthouze and Mayston, 2011; Cutti, Giovanardi, Rocchi, Davalli, and Sacchetti, 2008; Faber, Chang, Dennerlein, and van Dieën, 2016; Mancini et al., 2012; Roetenberg, Luinge, and Slycke, 2013; Saber-Sheikh, Bryant, Glazzard, Hamel, and Lee, 2010; Zhang, Novak, Brouwer, and Li, 2013).

Inertial measurement units can facilitate human motion monitoring in diverse environments. These sensors provide a novel opportunity to measure worker motions and exposures in the field, eliminating error from oversimplified lab simulations or non-experienced lifters. They have been called the next generation of noninvasive kinematic motion assessment and analysis tools, being portable, lightweight and having strong usability (Cutti et al., 2008). The small, wireless, and lightweight design of each sensor and its (flexible) placement allow for minimal interference with the worker's normal activities. Their robust structure can facilitate monitoring body kinematics in a diverse work environment, even in non-routinized tasks (Kim and Nussbaum, 2013; Miezal, Taetz, and Bleser, 2016; Picerno, Cereatti, and Cappozzo, 2008). During simulated MMH tasks with asymmetric lifting, lowering, pushing, and pulling, IMUs have been confirmed as an acceptable form of human motion measurement after multiple studies compared IMUs to the gold-standard optical motion capture (OMC) and the Lumbar Motion Monitor (LMM) with subjects standing on a force plate (Faber et al., 2016; Kim and Nussbaum, 2013; Miezal et al., 2016; Schall, Fethke, Chen, and Gerr, 2015; Schall et al., 2016). In a study simulating depalletization, the authors suggested that multiple IMUs generated a more robust model of thoracolumbar motion than a single accelerometer-gyroscope-magnetometer IMU device (Ramsey, Davis, Kotowski, Anderson, and Waters, 2014).

Kim and Nussbaum (2013) described a potential use of IMUs as assessing human motion differences in work conditions. Sensors are placed in unobtrusive locations that allow the subject to perform normal behaviors naturally (Banos et al., 2014). Data collected from the field using IMUs would aid in understanding the ecologic validity of laboratory mock-ups. Overall, it was recommended that IMUs be utilized in future studies (Kim and Nussbaum, 2013; Splittstoesser et al., 2007; van Dieën et al., 2010).

Human motion measurement tools are not without their limitations. Inertial measurement systems are expensive and complex (depending on the software). Some systems use raw coordinate data while others include biomechanical models to translate the sensor data into human motion information (Roetenberg et al., 2013; Xsens, 2015). Depending on the sensor fusion algorithm, the body is broken into numbers of segments, reducing the organic flow of natural movement. A biomechanical model may include an anatomical database in order to estimate body segment coordinates (Roetenberg et al., 2013). Anatomical databases are limited in their size and applicability to the general population. The reliability of IMU's external placement (using bony landmarks) and noninvasive attachment methods (straps and Velcro) continues to be evaluated (Banos et al., 2014; Godwin et al., 2009; Schall et al., 2016; Theobald, Jones, and Williams, 2012). Regardless, current validation studies and diverse applicability of IMUs suggest that they are an acceptable tool for occupational research in the field.

2.7.1. Xsens MVN Biomech

The Xsens MVN Biomech movement analysis program was applied in the present study (Xsens, Enschede, NT). The system, Xsens MVN BIOMECH Awinda, consisted of 17 wireless IMUs and a wireless USB transmitter linked to a computer. Each sensor, shown in Figure 2.2., contains a magnetometer, triaxial accelerometer, 3-dimensional angular velocity gyroscope, and barometer with a mass of 16 grams, and dimensions of 55 x 40 x 10mm (Xsens, 2015). The Awinda protocol creates 3-dimensional drift-free orientation measurements of 23 human body segments from a combination of subject-specific measurements, biomechanical models, and sensor fusion algorithms (including Strap Down Integration and Relative Frequency components). The role of Relative Frequency is to store information in the MTw itself. In the cases of temporary relative frequency loss, the system continues to track 3-dimensional inertial motion. The kinematic coupling algorithm (KiCTM) was enabled to address problems with magnetic disturbances (Kim and Nussbaum, 2013). Xsens Kalman Filter for Human Movement (XKF-HM), the Extended Kalman Filter (EKF) and 'settling time' were applied for magnetometer and gyroscope application. Anatomical landmark position is extrapolated from orientation angles of body segments. Euler angles are used to calculate joint angles relative to the distal and proximal segment reference frames (Khurelbaatar, Kim, Lee, and Kim, 2015). Linear acceleration and angular velocity is calculated from sensor data using manufacture-provided software that used a series of rigid body calculations (Lin and Kulić, 2012). Each joint is specified by statistical parameters for six degrees of freedom joint laxity (Roetenberg et al., 2013). The same manufacturer-provided software applies algorithms that compute the kinematics of the spine and additional body segments (Xsens, 2015). Estimated kinematics included segment position, velocity, acceleration, orientation, angular velocity and angular acceleration, and joint angle (angular displacement) (Roetenberg et al., 2013; Xsens, 2015). Sensor collection is recorded at 60Hz in the U.S. Recording frequencies of 60Hz have been determined sufficient for recording human activity in Europe and the U.S. (Banos et al., 2014). Data capture was done using a graphical interface (MVN Studio 3.0, Xsens technologies B.V., Enschede, NT).

Figure 2.2. Xsens IMU sensor and antennae dongle (Xsens, 2015)

3. METHODS

3.1. Keg MMH task

The present study focused on the handling of half barrel kegs at the craft brewery in Colorado. Before kegs can be filled with beer, they must be cleaned. Depending on the size of the brewery, different stages of the keg cleaning process may be automated. The design of the kegging line at the craft brewery were data was collected required kegs to be cleaned upside down. At the craft brewery in the present study, the task of transfering spent kegs from the pallet to the clean and fill line was manual. Eight kegs were positioned on each pallet. Forklift drivers delivered pallets stacked two high. The worker must grab kegs from both high and low pallet origin positions. After workers flipped spent kegs onto the conveyor, kegs were transported through a series of machines that cleaned the kegs externally, internally, and filled with beer. The duration of this task varied depending on the type and and quantity of beer. A worker might handle over 600 kegs during a typical eight hour shift. On a slower shift, a worker may handle fewer than 100 kegs overall. Data was recorded in a craft brewery during for the duration it required a worker to handle 64 kegs, or 32 kegs from each lift condition.

3.2. Subjects

All experienced keg line operators were recruited from a craft brewery in Northern Colorado. Letters of support from the brewery were obtained before engaging in direct employee involvement. The researchers received University Internal Review Board approval for this project (16-6819H, available at the end of the Appendix). All regular keg handlers, five healthy males between 28 and 39 years of age, participated in the study. Subjects self-reported that they were free of LBP at the time of study. Anthropometric measurements (age, body mass, body height, foot size, arm span, ankle height, hip height, hip width, knee height, shoulder width, and shoe sole height) of each participant were acquired, recorded, and inputted into the biomechanical model.

3.3. Experiemental procedures

Data was recorded in a craft brewery during typical working hours. All subjects read and signed informed consent and photograph permission forms that were approved by the Colorado State University Institutional Review Board prior to the subject's participation. These documents detailed that their participation was purely voluntary and that they were free to withdraw participation at any time without penalty. Upon request, personal study results were shared with participants for their personal benefit. Analyzed, de-identified data was available to the company upon completion of the study.

Subjects were introduced to the IMU sensors and briefed on the purpose of the study. Anthropometric dimensions were measured and inputted directly into the IMU software. Worker measurements and sensor attachment were in accordance with the system manual. Study participants were fitted with seventeen Xsens Biomech Awinda sensors (Xsens, Enschede, NT). Manufacturer supplied materials plus additional straps ('Applied Technology International LTD Fabrifoam Products NuStim) secured the sensors to the body, as shown in Figure 3.1. Latex tape ('Powerflex by Andover') was used to secure foot sensors to the subject's shoes. Upper arm sensors were secured bilaterally on the lateral proximal side of the humerus. Forearm sensors were bilaterally secured on the anterior distal third of the forearm, just proximal to the wrist joint. Subjects maintained unrestricted range of wrist motion when the lower arm sensor was secured. Upper leg sensors were placed bilaterally along the iliotibial tract (IT band) on the lateral aspect of the femur and halfway between the greater trochanter and lateral epicondyle of the femur. Lower leg sensors were secured on the proximal third medial surface of the tibia bone, just distal to the knee joint. Subjects maintained unrestricted range of motion of their knee joint after sensor securement. The sternum and shoulder sensors were secured to the body using Velcro attachments in the custom Lyrcra shirt. The sternum sensor was secured in a pocket of the shirt on the medial region of the manubrium of the sternum. The shoulder sensors were placed between the superior angle of the scapula and scapular spine. The head sensor was placed in a custom headband, worn with the sensor on the posterior lateral aspect of the head. When secured in custom gloves, hand sensors were positioned on the dorsal surface of the hands. The pelvis sensor was placed on the center of the sacrum. The central location was identified by palpating the posterior superior illiac spines of the subject’s pelvis and placing the sensor at the midpoint. Sensor dislocation was minimized by placing the sensor on the flattest region of the relevant limb. The rationale was that flatter zones have more consistent surface area contact, so sensors secured there would be resistant to involuntary skin movement. The pelvis sensor was secured two layers of wide Lycra straps wraped around the torso in opposing directions (in order to self-tighten).

Figure 3.1. Sensor attachment
Inertial measurement unit sensors were attached to the subject using a combination of straps, a custom shirt, a head band, and gloves designed to contain the sensors.

The IMU suit was worn for approximately 90 minutes, including calibration and recording the 64 lifts. Data was collected on an HP laptop at 60Hz with MVN 4.3 and 4.4 software. The prop sensor was not used to collect data, but was on standby as a replacement sensor if another IMU's battery level fell below 40%. Calibration was conducted using standard Xsens MVN procedures in a region of the work area with minimal ferromagnetic interference. Figure 3.2 shows the 'N-pose' workers stood in for ten seconds during calibration. The software scored calibrations as one of four levels (good, acceptable, fair, and poor). Acceptable or good levels were used for collecting data. The range of the wireless sensors inside a typical warehouse environment was 50 m (Xsens, 2015). Even if they stayed within range of the sensors while checking tanks, workers passed multiple tanks and pipes that had high ferromagnetic inteference. Whenever a subject exited the immediate kegging area due to additional shift requirements (i.e. check tank pressure in the cellar), recording was paused and resumed when they returned. To maintain sensor fusion algorith integrity, it is critical that the sensors do not adjust after calibration. During recording, ferromagnetic interference and pelvic sensor position were monitored. Procedural details of ferromagnetic interference and pelvic sensor position monitoring are included in Appendix 8.2 and 8.3.

Figure 3.2. 'N-pose' during system calibration

During calibration, the subject assumed a neutral posture ('n-pose'), with an upright stance and hands relaxed at the side. Study participants held this pose for approximately ten seconds.

The workers were recorded while they handled kegs from approximately eight pallets. Half of the kegs originated from high pallets and the other half from lower pallets. A small wireless camera (GoPro Hero 3.0) was set up for visual comparison to the 3-dimensional avatar generated in MVN Studio BIOMECH software.

Forklift drivers delivered spent kegs on pallets stacked two high, as shown in Figure 3.5. The workers grasped kegs located at the heights 69.8 cm (low pallet) or 139.5 cm (high pallet). The top end of kegs has two 11 cm wide by 3 cm tall handles that are 4 cm below the upper lip on either side. Workers typically grasp kegs on the upper lip instead of the handle. During the lift, the workers first grasped the edge of the keg with one hand (alternating right and left, depending on worker's preference and typical work practice), inverted it and then placed the keg nozzle-end down onto the roller conveyor. The roller conveyor was 104.1 cm high and 50.8 cm wide. For the present study, a lift started at the point of the initial hand contact with the keg and ended when the hands released the keg onto the conveyor. All five participants handled 32 kegs from each lift condition (high and low origin positions). Data recording occurred during the work shift. The sequence that workers grasped kegs on the pallet was up to their discretion. Keg height origin position was noted as high or low.

Figure 3.3. Stacked pallets of spent kegs
Eight kegs are placed on a pallet. Forklift operators deliver spent kegs stacked two pallets high.

Data for the present study was recorded in MVN Studio BIOMECH software on an HP laptop. The file type, MVN (".mvn"), is named after Xsens' original name, Moven. After recording was completed, data was compressed and exported as a Moven export file ("mvnx"). Video of the 3-dimensional avatar was directly exported from the MVN Studio BIOMECH software as a Moving Picture Expert Group 4 file ("mp4"). Lumbosacral joint information was exported as a comma separate value file (".csv") using manufacturer provided software and R studio. Individual keg lifts were marked in the MVN software (using the keystroke '+' key and 'space bar'. Releasing their hands from the keg signaled the end of the lift. Time was represented by frame number in MVN studio but exported as seconds. Time (in seconds) corresponding to a specific posture in the MVN was calculated by dividing the specific frame by 60Hz.

Peak torso angular displacement values were identified from dynamic recordings to characterize low back motion for each lift condition. A 2-dimensional biomechanical model was applied to the peak scenarios to estimate compressive and shear forces experienced by the spine. The model used was a static, coplanar model developed by Chaffin at Michigan University and was a component of the 3DSSPP (three-dimensional static systems posture predictor) software package. Estimated forces included compressive forces (total compressive forces, compressive forces due to load and due to upper body weight) and shear forces (total shear forces, shear forces due to load and the erector spinae muscles).

Torso angular displacement during keg handling was assessed by calculating the maximum, average, and minimum values for the lumbosacral flexion, lateral flexion, and axial rotation. Due to the IMU system coordinates and sensor fusion algorithm, the peak right lateral flexion angle was represented by minimum X-values. The peak left lateral flexion angle was represented by maximum X-values. The peak right axial rotation corresponded to the minimum Y-values and the peak left axial rotation corresponded to the maximum Y-values. Peak extension was represented by minimum Z-value and peak flexion corresponded to a maximum Z-value. Averages represented the average, or dominant, direction and degree of angular displacement during the lifting tasks. For example, a positive value for average axial rotation during corresponds to more frequent left axial rotation. If the average lateral flexion angular displacement has a negative sign, then the worker experienced more left lateral flexion than right during the keg handling. An image of the Xsens avatar with planes and axis of motion is shown in figure 3.6.

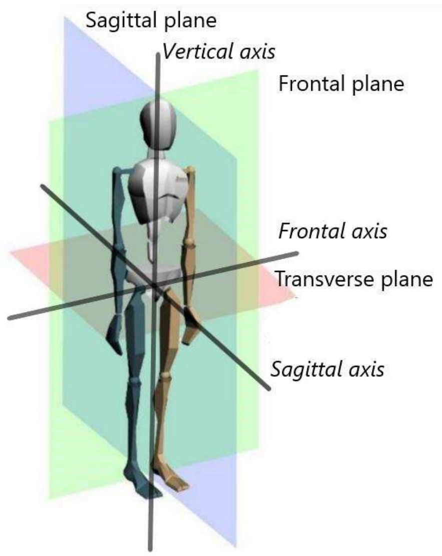

Figure 3.4. Xsens avatar with planes (Xsens, 2015)
Planes of motion are highlighted in accordance with the sensor fusion algorithm. Z-values represent motion in the sagittal plane, shown in blue. Frontal plane (X-values) is shown in green. Transverse plane (Y-values) is shown in red.

3.4. Data analysis

Results of the present study were analyzed in RStudio Version 1.0.136, 2016 (R Core Team, 2016). Descriptive statistics were calculated for the anthropometrics of the subjects (height, age, hip width, knee height, foot length, ankle height, hip height, shoulder width, arm span, and weight) (Bates, Maechler, Bolker, and Walker, 2015; Kuznetsova, Bruun Brockhoff, and Haubo Bojesen Christensen, 2016; Wickham, 2011). Kinematic data was analyzed and compared for each recorded lift. Sensor fusion data corresponding directly to the lift was extracted from the entire recording (Wickham, 2016; Wickham and Francois, 2016). After individual lift kinematics were analyzed, results were grouped into high and low lifts (per subject) and summary statistics were generated. Summary statistics (minimum, average, maximum, and standard deviation) for torso angular displacement of the lift conditions were calculated. The minimum, average, and maximum torso joint angular displacements were calculated for each lift by flexion, lateral flexion, and axial rotation. Values in the sagittal plane represented trunk flexion and extension. The lateral plane values represented lateral flexion. Values in the transverse plane represented axial rotation. A 2-dimensional biomechanical forces model was used to estimate compressive, lateral, and shear forces experienced by the worker's spine during the recorded tasks. A descriptive assessment of techniques was also conducted. Observed trends during lifts were also noted and summarized in the results.

To determine if the data of the present study fit a normal distribution, residual versus fitted plots of angular displacement in each plane were assessed using a treatment-subject interaction model. Independence of cases (temporality causes the lift data to be independent of each other) and equal variance were identified through the same plots. The data was determined to be normally distributed, therefore no data transformation took place prior to statistical analysis. The present study had equal sample sizes between high and low lifts, so it was a balanced model. Residual plots for each variable (minimum lateral flexion, mean lateral flexion, maximum lateral flexion, etc.) are available in the Appendix 8.4.

A repeated measures design with replicates and univariate analysis of variance (ANOVA) test was performed for each torso angular displacement as a function of lifting height origin. The lift height was the condition (low and high) and the within-subject factor. Subjects were treated as a random factor to account for inherent subject to subject variability or variability due to individual differences. Lifts were averaged across subjects for high and low origin positions separately. The interaction between subject and lift condition was investigated. Post hoc analysis consisted of least square means (*Lsmeans*) to examine significant effects. Significance was determined if $p \leq \alpha = 0.05$.

4. RESULTS

All workers at the craft brewery who regularly operated the keg clean and fill line participated in the present study. Five healthy males between 28 and 39 years of age participated in the study. Subjects were free of pain (including LBP) at the time of study. Anthropometric information applied to the biomechanical model is shown in Table 4.1.

Table 4.1. Anthropometric data of study participants.

Variable	Units	Mean	SD	Minimum	Maximum
Age	years	31.0	4.5	28.0	39.0
Body mass	kg	5.9	74.8	88.9	78.8
Body height	cm	179.0	5.6	173	186
Foot size	cm	31.6	1.3	30.3	33
Arm span	cm	174.5	4.8	168	181
Ankle height	cm	10.7	1.0	9.5	12
Hip height	cm	93.4	3.4	90	99
Hip width	cm	27.5	1.9	26	30.5
Knee height	cm	51.2	2.6	47.5	54.5
Shoulder width	cm	36.4	5.3	27	40
Shoe sole height	cm	3.7	1.	2	4.8

Apart from age and body mass, all the above variables were included in the sensor fusion algorithm for the IMU system.

4.1. Angular displacement

The IMU sensor fusion algorithm estimated lumbosacral joint angular displacement while workers handled kegs on the clean and fill line. While workers had different techniques and methods for handling kegs, patterns were observed during the different lift conditions. Maximum and minimum angular displacement values corresponded to peak angular displacement values in different directions. For example, peak left lateral flexion corresponded to minimum X-values (coordinates associated with the frontal plane). Positive and negative values of average angular displacements identified the dominant direction of the angular displacement. A negative average X-value corresponded to an overall lateral flexion to the left. Average and peak angular displacement values were estimated for motions in all three planes.

4.1.1. Observed trends during lift

Workers handled kegs with varying techniques, but a few patterns of angular displacement emerged over the course of data collection. Graphs of typical lifts from low and high conditions are shown in Figures 4.1 and 4.2.

Degrees of torso angular displacement during flexion exceeded those of lateral flexion and axial rotation throughout low lifts. Workers spent much of the duration of low lifts in some degree of forward sagittal flexion. Peak flexion occurred at the start or during the first portion of the low lifts when workers initially grasped the keg. Lesser degrees of flexion were observed throughout high lifts.

Throughout both lift conditions, workers started the lift with their torso in a right lateral flexion position. After lift initiation, workers transitioned to left lateral flexion. Right to left lateral flexion sequences were observed in both lift conditions. Peak right lateral flexion was observed at the start of the lift cycle. Peak left lateral flexion was often observed at the termination of the lift.

Peak right rotation of the torso was observed during the early stages of high lifts when workers are initially grasping kegs during high lifts. A smooth axial rotation to the left was observed as the worker would lift and invert the keg onto the conveyor roller. Peak left axial rotation was observed towards the end of the high lifts. Greater degrees of axial rotation were observed during high lifts. Axial rotation remained around a neutral position (zero) during low lifts. Left axial rotation would increase slightly during the middle of the low lift.

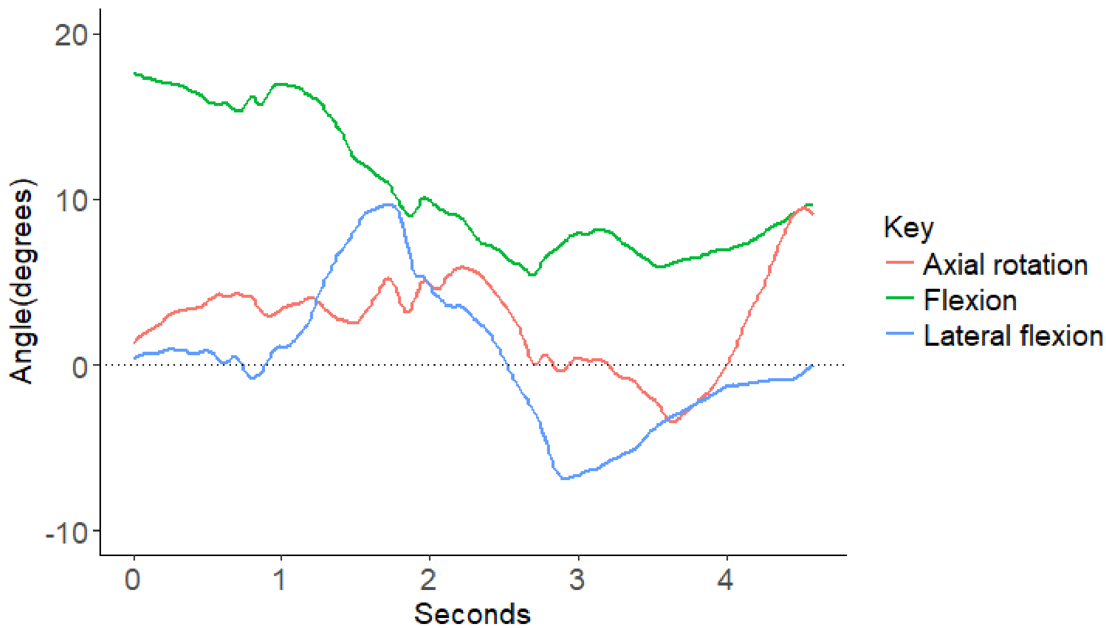

Figure 4.1. Typical graph of low lift
The above graph is an example of a typical lift from a low positioned keg. Lateral flexion (blue), axial rotation (red), and flexion (green) angular displacement change during the lift-cycle (seconds). Torso flexion peaks at the start of the lift. Torso lateral flexion starts neutral then the worker side bends to the right and concludes the lift with left lateral flexion. Torso axial rotation is slightly to the right, deviated to some left axial rotation at the end of the lift-cycle.

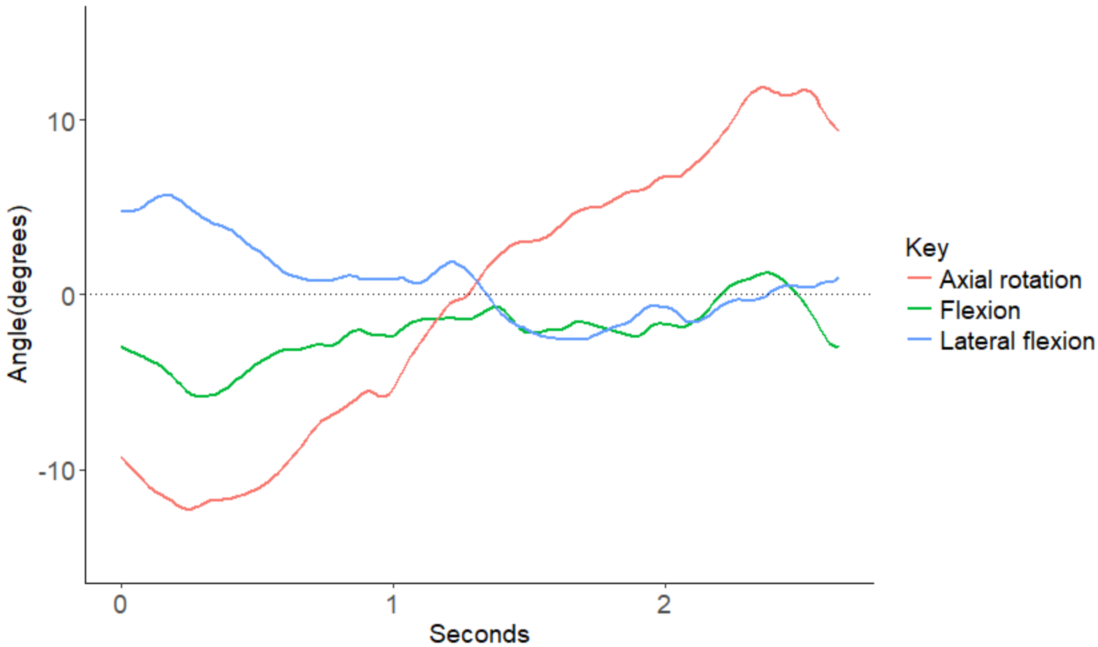

Figure 4.2. Typical graph of high lift
The above graph is an example of a typical lift from a high positioned keg. Lateral flexion (blue), axial rotation (red), and flexion (green) angular displacement change during the lift-cycle (seconds). The lift begins with right axial rotation and transitions to left axial rotation of the equal opposite magnitude at the end of the lift cycle. Lateral flexion begins to the left then transitions to neutral with some right lateral flexion at the conclusion. Extension is observed during high lifts.

4.1.2. Sagittal plane

Flexion and extension of the torso occurred in the sagittal plane (Z-values), shown in Figure 4.3. A neutral upright posture was assigned a value of zero degrees. Deviation in the form of flexion was assigned a positive value. Deviation in the form of spinal extension was assigned a negative value. The average degree of flexion during high lifts was 6.34 (with a 95% confidence interval of 2.10, 10.58) degrees and 10.18 (5.95, 14.42) degrees during low lifts. The difference between dominant flexion during high and low lifts was statistically significant with $p < 0.05$ ($p = 0.02$). Peak flexion during high lifts was 9.75 (4.80, 14.71) degrees and 15.85 (10.89, 20.08) degrees during low lifts. The difference between peak flexion angular displacement during high and low lifts was significant with $p < \alpha = 0.05$ ($p = 0.01$). Extension was negative motion in the sagittal plane. Peak extension during high lifts was 3.55 (0.44, 7.53) degrees and

1.51 (0.66, 3.68) degrees during low lifts. Differences between peak extension angular displacement values were not significant with p = 0.08 > α = 0.05.

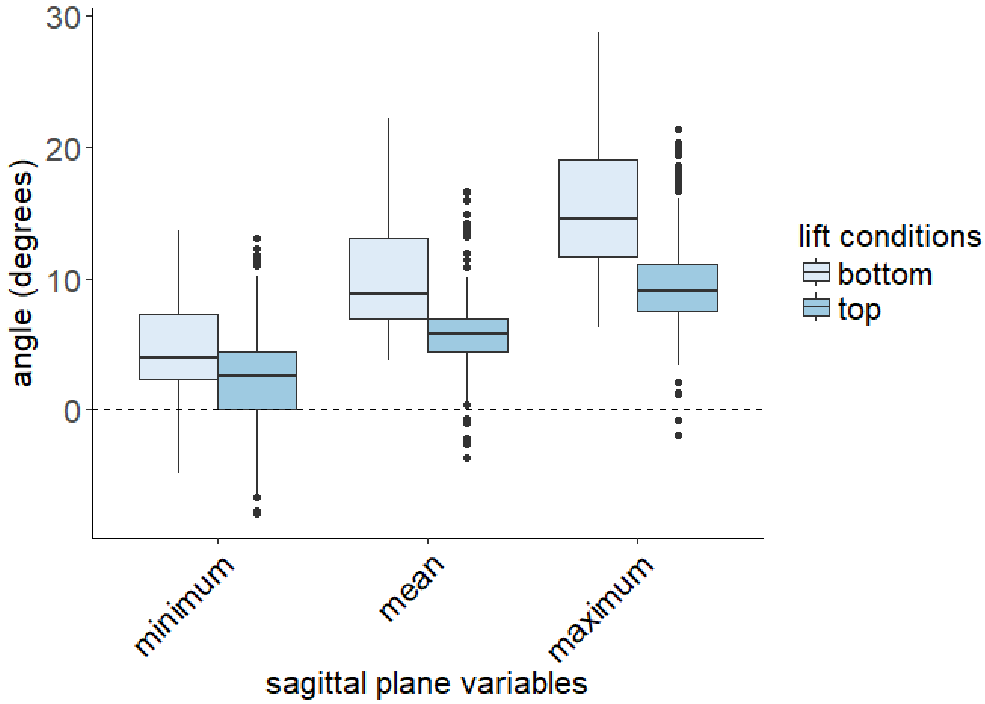

Figure 4.3. Flexion by lift conditions
A box and whiskers plot shows the range of degrees of flexion during high and low lifts averaged across all subjects. larger magnitudes of average and peak flexion occurred during low lifts. Angular displacement values less than zero correspond to hyperextension.

Magnitudes of torso flexion varied between subjects, as shown in Figure 4.4. Degrees of flexion were greater during low lifts than high lifts across all subjects. Worker 2 had the largest range of flexion angles experienced during keg handling for both high and low lifts. Worker 5 had the lowest flexion angular displacements while worker 3 experienced the highest degrees of flexion during low lifts.

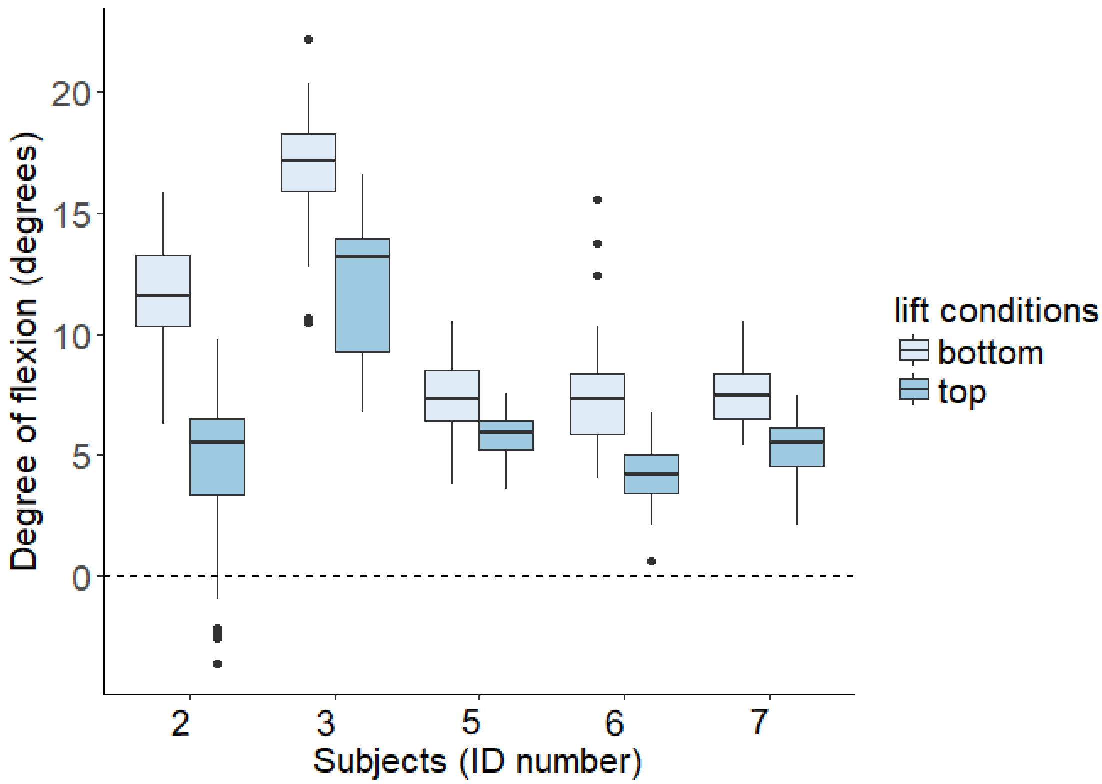

Figure 4.4. Flexion by subject
The box and whiskers plot above shows the range of trunk flexion by lift conditions and each subject. Positive degrees indicate forward flexion in the sagittal plane. Zero represents the upright posture during calibration procedures. Negative values indicate spinal hyperextension.

4.1.3. Frontal plane motion

Right and left lateral flexion of the torso occurred in the frontal plane (X-values). Zero degrees represented a neutral upright posture. Deviation in the form of right lateral flexion was assigned a positive sign. Left lateral flexion was assigned a negative value. The average lateral flexion was to the right for both lifting conditions. During low lifts, the average lateral flexion was 1.07 (-0.7, 2.8) degrees. The -0.7 of the lower confidence interval indicates that there was some left lateral flexion but the lateral flexion was more often to the right. The average lateral flexion during high lifts was 1.2 (-0.51, 3.09) degrees. As in low lifts, there was some left lateral flexion but mostly right lateral flexion during low lifts. The peak left lateral flexion angular displacement during high lifts was 3.40 (0.85, 5.95) degrees and 4.61 (2.06, 7.16) degrees during low lifts.

Peak left lateral flexion angular displacement differences between lift conditions were not significant as $p > \alpha = 0.05$. The peak right lateral flexion angular displacement was 5.62 (3.56, 7.67) degrees during high lifts and 7.42 (5.36, 9.47) degrees during low lifts. Peak right lateral flexion angular displacement differences between high and low lifts were not significant as $p > \alpha = 0.05$.

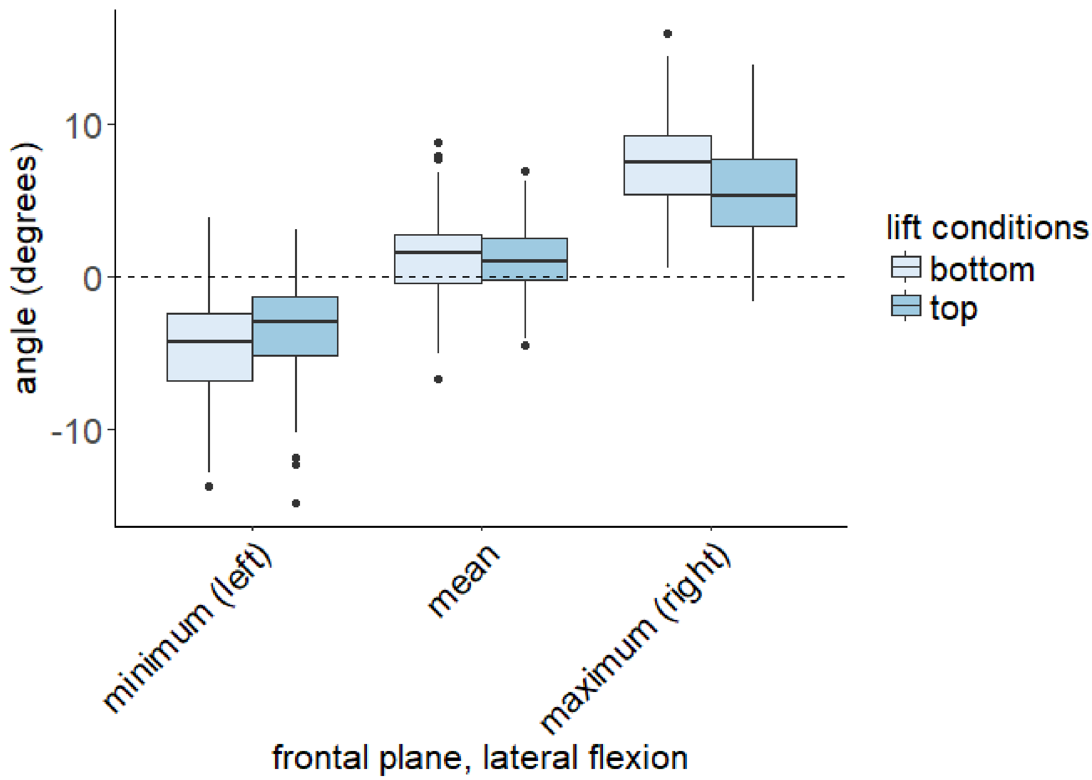

Figure 4.5. Lateral flexion by lift conditions
A box and whiskers plot shows the range of degrees of lateral flexion during high and low lifts averaged across all subjects. True left lateral flexion is represented by values less than zero. Overall lateral flexion for both lift conditions was to the right, indicated by the positive values in 'dominant LF.'

Variations of torso movement in the frontal plane existed between the subjects, as shown in Figure 4.6. No patterns between lateral flexion were observed between high and low lifts, aside from right lateral flexion being the more frequent lateral flexion posture overall. Worker 3 had overall right lateral flexion during bottom lifts and left lateral flexion during high lifts. Worker 7 had the smallest range of lateral flexion angular displacement.

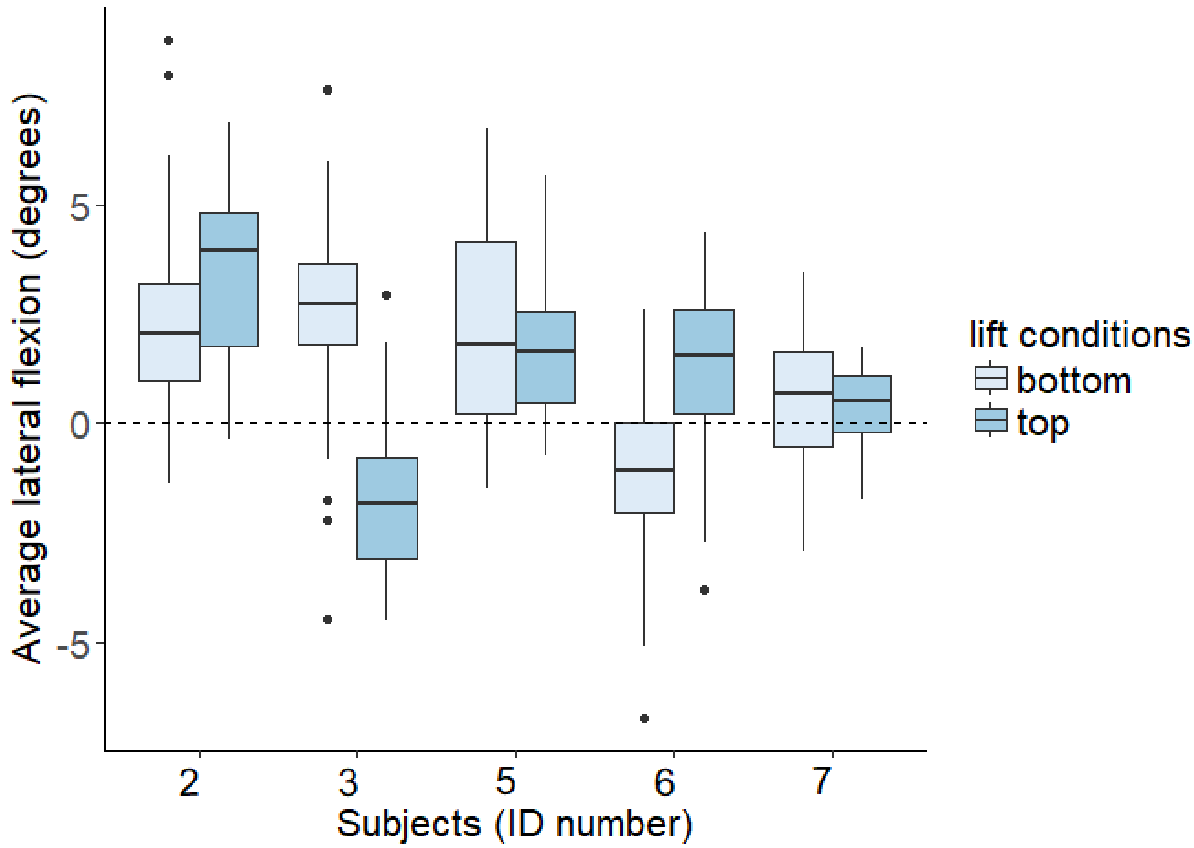

Figure 4.6. Lateral flexion by subject
A box and whiskers plot shows the range of degrees of average lateral flexion during high and low lifts per subject. True left lateral flexion is represented by values less than zero. Overall lateral flexion for both lift conditions was to the right, indicated by the positive location of the boxplots.

4.1.4. Transverse plane motion

Axial rotation of the worker's torso occurred in the transverse plane (Y-values). Zero degrees represented a neutral anatomical posture with the worker facing directly forward. Left axial rotation was represented with a positive sign. Right axial rotation was assigned a negative sign. The dominant, or average, axial rotation for lift cycles was positive for both high and low lifts, indicating overall twisting to the left, as seen in Figure 4.7. The average axial rotation during high lifts was 3.35 (0.34, 6.36) degrees to the left. During low lifts, the average axial rotation was 2.49 (-0.52, 5.50) degrees to the left. The -0.52 degrees in the lower confidence interval indicates that workers conducting low lifts experienced minor right axial rotation. The confidence interval of axial rotation during high lifts is strictly positive, indicating that 95% of the average axial rotation was left axial rotation. The differences between dominant axial rotation during high and low lifts was statistically significant with p = 0.04. Peak left axial rotation during high lifts was 9.37 (5.70, 13.03) degrees and 8.10 (4.44, 11.76) degrees during low lifts. However, the differences between peak left axial rotation during high and low lifts were not statistically significant as p > α = 0.05 (p = 0.16). Lesser degrees of right axial rotation were observed during both high and low lifts. Peak right axial rotation during high lifts was 2.58 (0.12, 5.28) degrees and 2.82 (0.13, 5.52) degrees during low lifts. The differences between peak right axial rotation during high and low lifts were not statistically significant as p > α = 0.05 (p = 0.79).

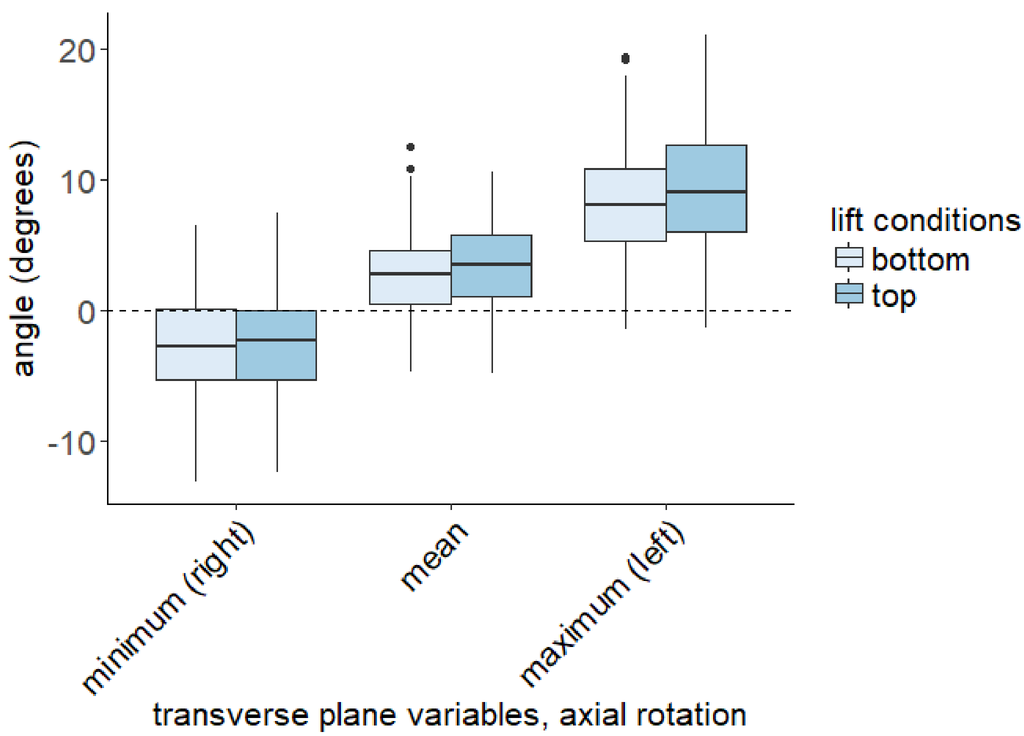

Figure 4.7. Axial rotation by lift condition
A box and whiskers plot shows the range of degrees of axial rotation during high and low lifts averaged across all subjects. True right axial rotation is represented by values less than zero. Greater degrees of left axial rotation occurred during high lifts.

Degrees of torso axial rotation, both right and left, varied across subjects, as shown in Figure 4.8. Left axial rotation (represented by positive angular displacement values) is greater during high lifts than low lifts. Worker 6 experienced more right axial rotation than any other worker.

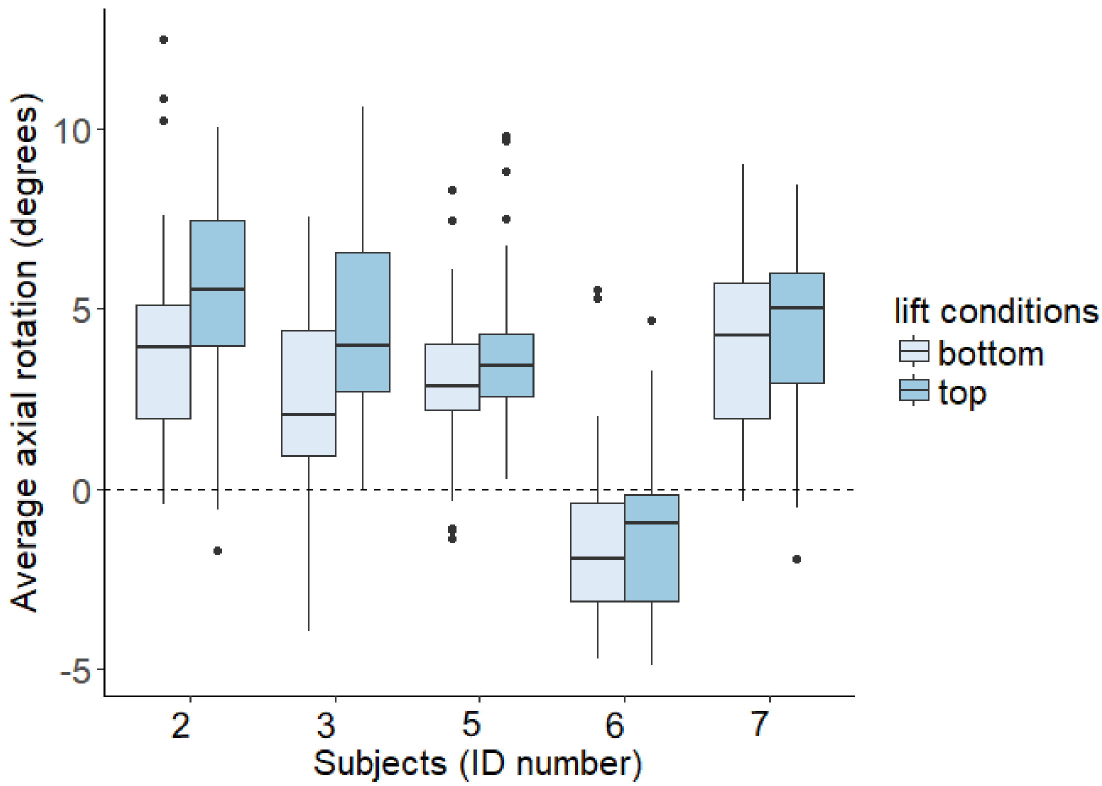

Figure 4.8. Axial rotation by subject
The box and whiskers plot above shows the range of axial rotation of the trunk experienced during the lift conditions by each subject. Worker 6 experienced greater right axial rotation than any other worker.

A summary of all peak ranges of torso motion under the different lifting conditions is shown in Table 4.2. Estimated averages are listed in Table 4.3.

Table 4.2. Peak lumbosacral joint angles

Axis	Estimation	High lift	Low lift	SE	p-value
X	Peak left lateral flexion	3.40 (0.85, 5.95)	4.61(2.06, 7.16)	1.05	0.31
	Peak right lateral flexion	5.62 (3.56, 7.67)	7.42 (5.36, 9.47)	0.88	0.19
Y	Peak right axial rotation	2.58 (0.12, 5.28)	2.82 (0.13, 5.52)	1.07	0.79
	Peak left axial rotation	9.37 (5.70, 13.03)	8.10 (4.44, 11.76)	1.39	0.16
Z	Peak extension	3.55 (0.44, 7.53)	1.51 (0.66, 3.69)	1.51	0.08
	Peak flexion	9.75 (4.80, 14.71)	15.85 (10.89, 20.80)	1.92	0.01

Values presented as mean (confidence interval)

Table 4.3. Average lumbosacral angular displacement in degrees

Axis	Estimation of average	High lift	Low lift)	SE	p-value
X	Lateral flexion (right)	1.2 (-0.51, 3.09)	1.07 (-0.7, 2.8)	0.78	0.19
Y	Axial rotation (left)	3.35 (0.34, 6.36)	2.49 (-0.52, 5.50)	1.10	0.04
Z	Flexion	6.34 (2.10, 10.58)	10.18 (5.95, 14.42)	1.64	0.02

Values presented as mean (confidence interval)

4.2. Lift frequency and operator responsibilities

Workers were recorded for 64 lifts: 32 high lifts and 32 lifts low lifts regarding pallet level. Recording occurred during a portion of operational hours. Lifting frequencies of keg handling differ if calculated from direct observations or integrated over the entire shift. Based on lifting speeds during observations, the estimated lifting rate was 19.98 lifts per minute (3.0 seconds per lift). However, if 600 kegs (the maximum workers will handle in a shift) is factored over a shift, the time weighted average lifting frequency becomes 1.25 lifts per minute (48 seconds per lift). This difference is due to the keg line operator's responsibility to monitor the cleaning and filling equipment and be prepared to troubleshoot should problems arise. Over the course of the actual work shift, the worker is not constantly handling kegs. A list the keg line operator's responsibilities and their relative demands is listed in Table 4.4.

Table 4.4. A list of other tasks keg line operators are responsible for during their shift.

Task	Demand
Directing/guiding forklift driver to deliver kegs on pallets	Every two to four double pallet stacks
Removing plastic wrap around kegs	Once every 16 kegs as the plastic wrapping encases double pallet stacks
Removing plastic keg caps	Every keg nozzle
Removing debris on the tops of the kegs	Varies, but workers check every eight kegs (one pallet)
Removing old keg labels (scrape and burn)	Varies, often occurs with older kegs after being inverted on the conveyor roller
Applying new keg labels	Varies, often occurs on kegs after being inverted on the conveyor roller
Checking/monitoring keg line computer	Frequently
Monitoring speed of conveyor	Frequently
Managing sensor-keg	Once per beer run a keg with sensors is placed on the conveyor to run through the filling line
Troubleshooting robotic keg palletizer	Varies
Handling general computer trouble/glitches	Keg caps, incoming pallets
Check tank pressures	Requires crossing to other side of brewery, occurs two to three times per beer run
Collecting samples from points along the fill line	Happens at least two times per beer run
Managing and draining spent kegs with residual beer	Depends

4.3. Estimated compressive and shear forces

Evaluating torso peak flexion of workers helps characterize the spectrum of work-related postures during the different lift conditions. Peak postures for lateral flexion, axial rotation, and flexion angular displacements were identified. A 2-dimensional biomechanical analysis was conducted to estimate various forces experienced by the worker while lifting an empty (13.6kg) keg, as shown in Figure 4.9. during a high lift and Figure 4.10. during a low lift (2DBiomechanics Analyst, NexGen Ergonomics, QC).

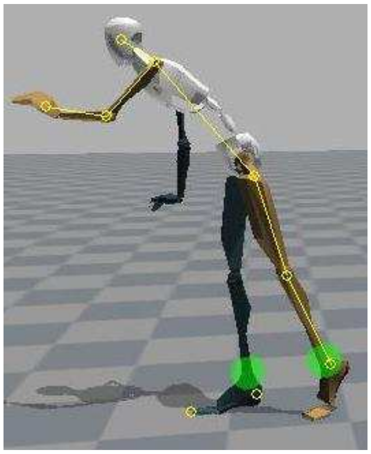

Figure 4.9. Example of peak flexion during a high lift

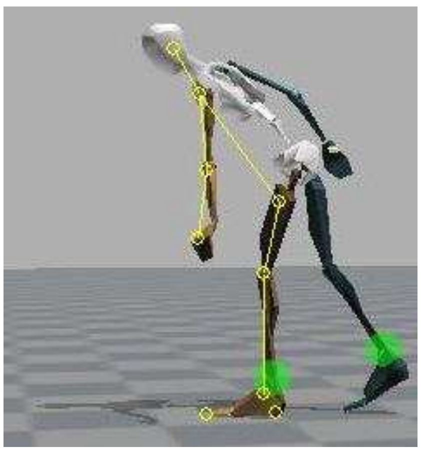

Figure 4.10. Example of peak flexion during low lift

Peak torso flexion cases from high and low keg lifts were analyzed using a 2-dimensionial biomechanical model that estimated compressive and shear forces. As shown in Table 4.5, differences between estimated forces were not statistically significant for both compressive and shear forces ($p > \alpha = 0.05$).

Table 4.5. Summary of 2-dimensional biomechanical model

Condition	High lift	Low lift	p-value
Compressive (N)	2448 (1149, 4750)	2745 (2431, 3147)	0.99
Shear (N)	410 (130, 1000)	667 (555, 756)	0.54

5. DISCUSSION

5.1. Overview

The following chapter addresses the impact that torso angular displacement and estimated shear and compressive forces have on the risk of developing LBP. The effect of additional operator responsibilities is followed by study limitations and future study recommendations. Measured values for joint angles are comparable to similar studies that assessed joint range of motion using IMUs, OMC, and other measurement devices during manual handling task simulations (Ha et al., 2013; Jorgensen, Handa, Veluswamy, and Bhatt, 2005; Knapik, Mendel, and Marras, 2012; Splittstoesser et al., 2007). Ranges of motion are a common metric for describing kinematic and biomechanical spine behavior. Some differences in angular displacement in lateral, axial, and sagittal planes were observed between lift conditions. While estimated compressive and shear forces experienced during both height conditions of keg lifting task were potentially hazardous, the low frequency was a protective factor (Marras et al., 1993; Putz-Anderson et al., 1997; Waters et al., 1993).

5.2. Angular displacement

Peak and average lateral flexion and peak axial rotational angular displacements of the torso did not significantly differ between high and low lifts. The workstation remained the same design except for the vertical position of the lift condition. The average horizontal distance between the pallet and conveyor roller varied equally during both lift conditions. The pallet distance depended on the forklift driver.

There was a significant difference in average axial rotation of the torso between the lift conditions ($p = 0.04$). Workers experienced greater degrees of left axial rotation during high lifts than low lifts. In the workstation setup, the destination (conveyor roller) was to the left of the worker and the spent kegs arrived on pallets on their right. By positioning themselves closer to the pallet for the initial lift, the worker would rotate their torso to invert the keg and place it on the roller. Standing closer to the pallet positioned the workers so that the initial load was closer to their torso's center of mass, therefore decreasing the length of the primary moment. Axial rotation while lifting or carrying a load increases compression on the spine, thus increasing risk of injury (Marras and Granata, 1995; Panel on Musculoskeletal Disorders and the Workplace and Council, 2001; Waters, Putz-Anderson, and Garg, 1994). In an effort to decrease axial rotation of the torso, increasing the horizontal travel distance between a pallet and destination was studied as an engineering control, but did not change worker behavior during manual palletizing loading tasks (Jorgensen et al., 2005). Changing the orientation of the pallets could reduce the magnitude of axial rotation because the worker would not stand between the origin and destination. Consistent pallet orientation could be a total quality control intervention to address the magnitude of axial rotation.

Peak right lateral motion of the torso was slightly greater during high lifts than low lifts, possibly due to the workers having to brace and lean over the pallet to reach kegs. When initiating low lifts, workers often walked around the pallet, whereas with high lifts they were more likely to pull kegs across the pallet.

Forward sagittal flexion of the torso is a significant variable when characterizing task demands and quantifying risk of LBP. Even without a load, bending the torso forward generates large primary moment arms and reactant forces about the lumbosacral joint (Grieve, 1997; Littlewood and May, 2007). The degree of forward flexion is accounted for in simple 2-dimensional compressive force models, rapid assessment tools, complex biomechanical software and complex measurement devices (Chaffin et al., 1999; Jones et al., 2005; Marras et al., 1997; Marras, Lavender, Ferguson, Splittstoesser, Yang, et al., 2010; Merryweather, Loertscher, and Bloswick, 2009; Vignais et al., 2013). In the present study, differences in flexion angular displacement between the lifting conditions were significant ($p = 0.01$). Workers experienced approximately six degrees of additional flexion angular displacement when lifting kegs from low height conditions.

A difference of six degrees of lumbosacral flexion angular displacement was estimated in the present study between high and low lifts. For lumbar spinal flexion, the normal range of motion is defined as 60 degrees (Grieve, 1997; Panjabi, Oxland, Yamamoto, and Crisco, 1994; White, 1971). However, there are five articulating surfaces between vertebral bodies in the lumbar spine (including the first sacral bone). During flexion, forward bending in the lumbar spine starts at the first lumbar vertebrae and progresses inferiorly to the lumbosacral joint (Steindler, 1973). This sequence is reversed during extension. The range of motion is not evenly distributed across these joints at vertebral bodies and intervertebral discs (Grieve, 1997; Troke, Moore, Maillardet, and Cheek, 2005). For example, the L5S1 and L4L5 joints have greater ranges of motion in the sagittal plane, but less ranges of axial rotation compared to L1L2 and L2L3 (Grieve, 1997; Ha et al., 2013; Panjabi et al., 1994). Previous studies estimated the average lumbosacral joint flexion range of motion as between eight and fifteen degrees (Ha et al., 2013; Panjabi et al., 1994; Wong, 2010). In the present study, peak flexion was estimated at 15.9 degrees (occurring with low lifts). The six degrees of flexion difference between high and low lifts is over 35% of the lumbosacral joint's average range of motion.

Observed values of lateral flexion and axial rotation of the lumbosacral joint deviated from estimated ranges of motion in other studies. In the present study, average lateral flexion was estimated 1.7 degrees (with an observed peak of 7.4 degrees). Previous studies estimated 4.5 degrees of lateral flexion (Grieve, 1997; Panjabi et al., 1994; Wong, 2010). Average axial rotation was estimated to be 3.4 degrees (with an observed peak of 9.4 degrees). Previous studies have estimated average axial rotation of the lumbosacral joint to be 0.5 to 1.5 degrees (Grieve, 1997; Panjabi et al., 1994; Wong, 2010). Validation studies between IMU, OMC, and electromyography systems have identified IMU accuracy strengths in estimating flexion angular displacement, but identified weaknesses regarding lateral flexion and axial rotation (Karatsidis et al., 2016; Zhang et al., 2013).

5.3. Lift frequency and operator responsibilities

The difference between expected lifting rate and actual lifting rate is due to the additional task demands of operating the keg-line. Observing and measuring keg line operators revealed that approximately six percent of the eight-hour shift is direct handling of the keg (lifting from the pallet and inverting onto the conveyor) keg lifting. Task frequency and duration are risk factors for developing LBP (Marras et al., 1993; Putz-Anderson et al., 1997; Waters et al., 1993). While some of the postures and estimated compressive and shear forces experienced during the keg lifting task are potentially hazardous, the low frequency is a protective factor.

The remaining 94% of the kegging shift is spent doing other necessary tasks. Additional tasks can include draining full kegs, taking quality-assurance-samples of the beer, handling pallets and packaging material and more.

The weight of the keg is not accounted for in the estimated lift frequency model. Depending on the amount of residual beer in the keg, the worker may choose to do a 'team lift.' The keg line is an individual task, so the worker would have to leave the workstation to recruit help. Once the non-empty keg is on the ground, the residual beer must be drained. This requires an additional set of steps that distract the worker from additional keg lifting. Workers must monitor the draining process and find space to store the partially full keg until it can be added to the conveyor roller. Draining a full keg can take over 15 minutes. This does not include the ten minutes required to wait for the overflow tank to drain so that another keg can be emptied. Workers balance draining spent kegs while continuing to load spent kegs.

Samples of beer are regularly taken throughout the brewing process for microbiological tests for quality assurance purposes. The keg line is part of packaging, so beer is sampled before it is filled into kegs and after. The keg line operator is responsible for taking these samples throughout their shift.

Spent kegs arrive eight per pallet held in place with a plastic film wrapping. After the pallets are delivered to the workstation, the plastic wrap must be removed. Next, keg caps must be removed from the keg nozzle and any additional trash that is on the top of the kegs. After moving the kegs, each empty pallet must be removed so that the next pallet of kegs can be accessed.

Empty pallets are manually transferred from the workstation to a designated storage area. Pallets are moved either using an overhead carry or dragged along the floor, as shown in Figure 5.1. The worker then inspects the pallet and places it on a stack of other pallets. Wooden pallets typically are between 14.97 kg and 21.77 kg (33lbs to 48lbs). If a worker flips 600 kegs during a shift, they will handle 75 pallets. If all the spent kegs are empty, the worker has moved 8,164.7 kg (18,000 lbs.) of kegs. Assuming a pallet has a mass of 18.37 kg. (40 lbs.), the worker has moved 1,377.75 kg. (3,000 lbs.) of pallets. Depending on the brewing schedule, the stacks of empty pallets can exceed waist height before the forklift operator can remove them. When this happens, awkward postures and extensions are necessary to throw the pallet onto the top of the stack.

A forklift operator removes the stacked pallets and loads them onto the robotic palletizing line. Labeling and palletizing of full kegs is performed? robotically. Pallets loaded with kegs full of beer move along a larger roller conveyor, are automatically wrapped in plastic, and stacked two high. A forklift operator then removes the full pallets and transfers it to an outgoing delivery zone at the brewery.

Figure 5.1. Worker maneuvering an empty pallet

5.4. Estimated compressive and shear forces

A 2-dimensional static model was applied to estimate compressive and shear forces from extracted peak torso flexion during the lifting tasks. The static, coplanar model considered the muscle force of the erector spinae muscle and the downward force of the upper body and external load (Chaffin et al., 1999). While additional torso stabilizing muscles and dynamic components were not included, the simple model can be used to assess basic differences in estimated compressive and shear forces between the two lift conditions.

NIOSH recommends that estimated compressive forces over 3400 N may put some of the working population at risk for developing LBP (Chaffin et al., 1999; Gatchel and Schultz, 2014; Panel on Musculoskeletal Disorders and the Workplace et al., 2001; Waters et al., 1993). The average values of both conditions were less than the NIOSH recommended limit. However, the maximum estimated total compressive for high lifts exceeded 3400 N. While the total compressive forces were typically similar, there was a larger range in kegs from high lifts.

The action limit for shear force is 500 N (Gallagher and Marras, 2012; McGill, 1997). Authors in a 2012 review on lumbar responses to shear forces recommended revised limits from 500 N to of 700 N for frequent tasks and 1000N for occasional loading tasks (Gallagher and

Marras, 2012). If a worker conducted a loading task 100 times a shift or less, that was considered occasional. In a craft brewery setting, the kegging demand is highly variable. If the beer schedule is slower, a worker may move only six pallets, or 48 kegs. During a busy shift, a worker may handle over 600 kegs. Workers must also lift and maneuver empty pallets after they finish unloading the kegs onto the conveyor. The mean estimated shearing force during low lifts exceeded 500 N. The maximum estimated shearing force during low lifts exceeded 700 N, or the frequent loading recommended value. High lifts generated estimated total shear values with a mean that was below the 500 N action limit, but a maximum value that exceeded the occasional loading recommended value of 1000 N. As observed in estimated total compressive forces, high lifts had greater variance in estimated total shear forces than bottom lifts.

The amount of estimated total compressive and shear force of the lumbosacral joint varied more during high lifts than low lifts. The applied model emphasized flexion and hand (load) location relative to the lumbosacral joint. Moments of peak flexion from each subject and lifting condition were identified, with varying amounts of horizontal distance between the hands and lumbosacral joint. Workers consistently would pull a high keg to the edge of the pallet during a lift. For this study, a lift started at the point of the initial hand contact with the keg and ended when the hands released the keg onto the conveyor. This definition included the worker pulling the keg across the pallet. Kegs located on the far edge of the pallet would require the worker engage in forward flexion over the pallet to reach and grasp the keg. Accounting for keg horizontal placement could generate better understanding of estimated compressive and shear levels when handling high level kegs.

Regardless of the causes of the varying estimated compressive and shear forces at the lumbosacral joint during high lifts, variation increases the probability that a worker may position themselves such that recommended total compressive (3400 N) and total shear values (500 N, 700 N, or 1000 N depending on task details) are reached or exceeded. Surpassing the recommended forces does not automatically guarantee an injury, but puts the worker at an increased risk of sustaining injury and developing LBP (Waters et al., 1993).

Estimated compressive and shear forces of the lumbosacral joint were calculated assuming the load was an empty keg. Residual beer in non-empty kegs increases the weight of the external load, thereby increasing the reacting forces at the lumbosacral joint. Full kegs can mass up to 72.6 kg, or five times the weight of an empty keg. Lifting with unknown loads can cause a 'jerking' motion that increases the moment at the lumbosacral joint (Butler, Andersson, Trafimow, Schipplein, and Andriacchi, 1993). However, the extent of this jerking motion as a risk for LBP is debated (Heiss, Shields, and Yack, 2002; Korkmaz et al., 2006; Mawston, McNair, and Boocock, 2007; Van der Burg and Van Dieën, 2001; Van Der Burg, Van Dieën, and Toussaint, 2000). An airline baggage handling study investigated how labeling the luggage with weight values would affect handling techniques (Korkmaz et al., 2006; Splittstoesser et al., 2007). Weight class identification tags were not found to decrease spinal loads, but did help in sequential placement of the luggage during the task (Korkmaz et al., 2006). Developing a procedure that measures the keg weight without interrupting that natural work flow would be beneficial to further estimating compressive and shear forces occurring at the lumbosacral joint.

5.5. Limitations

There were several limitations to this study. Limitations due to subjects, study environment, and equipment will be analyzed.

5.5.1. Subject limitations

Only young healthy men participated in the present study. The results are not generalizable to the entire MMH population, which could include women and older men. Men and women have different ranges of lumbar motion and different lifting techniques, suggesting that interventions might vary between the two (Cook, Yeager, and Cheng, 2015; Plamondon, Larivière, Denis, Mercheri, and Natasia, 2017). Currently, young males are the predominant demographic in brewery's manual materials handling areas. As the craft brewing industry expands, so will the amount of people working manual materials handling tasks and their demographics.

The present study had a small sample size (n = 5). While the participants represented all the keg line operators at the craft brewery when the study was conducted, all subjects had similar anthropometrics. The largest difference was 13 cm in body height. Different anthropometrics would alter how the worker interacts with the keg line environment; handling kegs on the first pallet level might require less flexion for a worker with a shorter stature and more lateral flexion or axial rotation compared to a taller worker. Different magnitudes of angular displacement would generate different primary moments, exposing the spine to varying compressive and shear forces. Most keg handling in craft breweries is delegate to a small group of staff. Studying multiple craft breweries that have similar keg line operations or procedures could generate a larger, more diverse sample size in regards to anthropometry and gender. A study on the recommended number of subjects to characterize a repetitive task in an industrial setting determined three participants to be necessary (Allread, Marras, and Burr, 2000). The authors argued that three trials of three employees generated enough data to characterize the demands and LBD risk. They concluded that job design is a more influential factor than individual behavior for characterizing a repetitive task's risk for LBP (Allread et al., 2000). Regardless of how many particpants are recommended, expanding the present study to other breweries with similar keg handling practices could increase the generalizability to other brewery workers and MMH. While the brewery in the present study represents common keg handling practices, breweries with different keg handling procedures should be studied to investigate the scope of muscloskeletal demands with different levels of automation and kegging.

5.5.2. Environmental limitations

Keg weight was assumed to be constant at 13.6 kg (empty keg weight) for the present study. Spent kegs arriving on pallets are usually empty, but could have enough beer left over to exceed 72 kg. The amount of residual beer in kegs is highly variable. For the scope of this study, only kegs the workers could lift onto the conveyor belt themselves were included in analysis. Operating the keg line has more autonomy compared to other repetitive brewery tasks such as the can line. A worker can lift kegs they feel comfortable handling. This autonomy means that workers may lift kegs with different amounts of residual beer, therefore lifting with loads exceeding 13.6 kg. The resulting range of motion values and estimated compressive and shear forces may not reflect lift patterns for lifting kegs over 13.6 kg.

A static, coplanar model was applied to estimate total compressive and shear forces at the lumbosacral joint during peak flexion moments of the keg lift. The static approach to a dynamic task does not consider the role of acceleration or muscle activation patterns (Chaffin et al., 1999). Research using OMC and force plates during lifting tasks in lab settings identified peak acceleration values occurring before peak flexion, suggesting the role of acceleration values on injury causation (Dreischarf et al., 2016; Greenland et al., 2011; Shahvarpour, Shirazi-Adl, Larivire, and Bazrgari, 2015). Furthermore, the erector spinae were assumed to be the only counter force to the primary load moment plus external weight loads. In reality, many primary, secondary, and tertiary anatomical structures in the human body are involved in trunk stability during a lift (Campbell-Kyureghyan, Jorgensen, Burr, and Marras, 2005; Chaffin et al., 1999; Jorgensen et al., 2001b; Knapik et al., 2012). The model used a rigid two body segmental approach that calculated trunk flexion based on the greater trochanter of the femur and the acromion process. Complex models factor in multiple spinal segments to generate more accurate postural estimates (Campbell-Kyureghyan et al., 2005; Marras, Lavender, Ferguson, Splittstoesser, Yang, et al., 2010; Roetenberg et al., 2013). The static model generates a biomechanical assessment of the body to estimate compressive and shear forces relative to the different keg lifting conditions. Additional analysis with more sophisticated models is recommended.

The horizontal distance between the pallet (origin) and the conveyor (destination) was not controlled for in the present study due to data collection occurring during a typical work shift. Manipulating horizontal distance or measuring each delivery would have disrupted the worker's normal work habits. Typically, pallets were located to the right of the conveyor with enough space for the worker to step between the two to access the other side of the pallet. Occasionally pallets were delivered such that the incoming pallet was pushed forward, decreasing the space between the pallet and conveyor. Under these circumstances, the keg line operator would have to walk the pallet. These additional steps could modify the time spent moving kegs from the pallet to the conveyor roller and increase risk of the worker developing LBP.

Controlling the sequence that the workers handled kegs and measuring each keg's horizontal position was not monitored during the present study. Doing so would have interfered with the actual workflow. Kegs were observed and classified based on their vertical location. Eight kegs were placed on a pallet. Depending on the positioning of other pallets, the worker may pull kegs starting from the right side of the pallet or walk around to access kegs from the other side, as shown in Figure 5.2. The worker might brace themselves against the pallet to reach the kegs located on the far end of the high pallet. The keg would then be tipped towards the worker and pulled across the pallet. Unexpected loading could occur if the worker is in a rhythm and grasp a keg that is full and begins to pull it closer.

Figure 5.2. Keg placement on a pallet

The Hawthorne effect, or observer effect is another limitation to the present study. Data were collected as employees did their work at the jobsite while wearing a series of IMU sensors. While the sensors were small, lightweight, and less bulky than alternative motion monitoring systems, the workers were still aware of the suit. Some workers wore hats while working, so the headband was not a foreign sensation. Participants reported the shirt being tight and warm. Data collection took place during the winter and spring months, so overheating was not a concern. Furthermore, data collection was only for the duration of 64 lifts and approximately 30 minutes. The hand sensors were in gloves worn underneath typical rubber work gloves. Some workers wore a larger size glove than what they normally work with to accommodate the sensor gloves. Workers were filmed during the lifts. The researchers attempted to minimize the amount of interferences with the lifting tasks, but occasionally work had to be paused for 30 seconds for recalibration. All of these interferences could remind the worker that they are being observed and that can modify their behavior (McCarney et al., 2007).

The weight of the keg was not controlled for due to the same limitations that prohibited measuring the horizontal positions of kegs on pallets in the present study. Spent kegs are not synonymous with empty kegs. When a worker encounters a partially full keg, they may choose to flip it onto the conveyor roller or pull it aside, as shown in Figure 5.3. Kegs set aside require an additional set of processes to drain the beer into a tank below the conveyor roller. This extra step slows down the work flow, especially if a worker encounters multiple partially full (or completely full) spent kegs. Not only do they have to monitor the ‘draining’ process, they must find space to store the partially full spent kegs until they can be inverted onto the keg line. Draining a full keg can take over 15 minutes. This does not include the ten minutes required to wait for the overflow tank to drain so that another keg can be emptied. Workers must deal with the inconsistencies of residual beer in spent kegs.

Figure 5.3. Non-empty keg management
A worker grasps a keg from a bottom pallet (right) to lift and invert the keg onto the roller conveyor (right). The three kegs in the foreground have residual beer. The center keg is being drained.

While the present study was a repeated measures design with multiple lifts recorded per subject, data was collected one day per subject. Short term cross-sectional studies are limited in that only a portion of the shift is observed. While some patterns of lifting behavior can be gathered from multiple lifts under defined conditions, the variation from the start to end of the shift or variation over multiple work shifts could provide valuable postural information. The present study did not include fatigue because only 64 lifts were monitored. Repetitive lifting can cause fatigue which has the potential to change lifting coordination, load control and movement techniques resulting in low back failure, pain and injury (Chaffin, Andersson, and Martin, 1999)s. Fatigue can also interfere with a worker’s judgement (Panel on Musculoskeletal Disorders and the Workplace et al., 2001). This would be especially important when a worker comes across a keg with residual beer and must decide if a solo lift is feasible.

Data for the present study was collected in a working craft brewery. Field work sacrifices control for ecologic reliability (Allread et al., 2000). Issues that would be controlled for in a lab setting (including duration, frequency, number of subjects, and exact load conditions) are determined by the work environment. The present study design guaranteed experienced workers and all the psychosocial variables that occur alongside the keg lifting tasks. Factors associated with the work environment can influence work flow and therefore the postures and movements a worker may experience.

5.5.3. Equipment limitations

Low back kinematics can be assessed through in vivo, in vitro, mathematical estimations, or a combination of models. Radiographs and magnetic resonance imaging (MRI) allow the angular displacement between subject specific vertebrae to be measured (Grieve, 1997; Panjabi et al., 1994). Imaging provides detailed, static information that provides information that can be compiled into mathematical models. These models provide an opportunity to estimate angular displacement occurring in environments where radiographs are not practical.

The present study assessed lumbosacral joint angular displacement as a representation of torso movement during keg handling. The estimated joint angles were derived from the sensor fusion algorithm of the IMU system. Seventeen IMU sensors were secured to the subject. Kinematic information for 23 body segments were estimated. Five additional body segment kinematic information (angular displacement, segmental velocity, segmental angular velocity, segmental acceleration, and segmental angular acceleration) were estimated from MVN segments to match segment definitions in the sensor fusion algorithm (Tafazzol, Arjmand, Shirazi-Adl, and Parnianpour, 2014). Segment definitions in the current sensor fusion algorithm were based off a modifications of segmental masses and gyration points created in 1990 using gamma ray scans (Leva, 1996). Samples were collected from Caucasian college students using bony landmarks to direct the scans. A few years later, different bony landmarks were applied to redefine relative body segments of mass and radii of gyration (Leva, 1996). The algorithm is constrained by body segment length (both subject specific and empirical database) and joint range of motions (empirical database).

While validation studies have been conducted, and established the accuracy of the Xsens IMU system, there are inherent limitations in IMUs and biomechanical models. Sensor placement was performed in accordance with system provided instructions. There currently exists no standard method or indicator to alert the researcher to sensor dislocation. Accurate joint angle estimates are dependent on secure sensor attachment after calibration procedures. If a sensor adjusts or becomes dislocated, the algorithms cannot accurately estimate kinematic data. Recording information following sensor dislocation generates unreliable estimates from the biomechanical model (Banos et al., 2014; Schall, Fethke, and Chen, 2016; Schall et al., 2015). Researchers in the present study monitored pelvis position for sensor dislocation during recording. Position information output was presented in terms of meters. The effects of a few centimeters of sensor dislocation are unknown at the time of the present study. Future studies should further assess the impact of minor sensor dislocation during recording.

The results of the present study are encouraging, but there are several practical factors to consider regarding the feasibility of using IMUs and a biomechanical model in the field. The cost of the full body IMU system can be a significant barrier to implementation. The wireless sensors and biomechanical model are significantly more expensive than single IMU worker devices (Lee, Seto, Lin, and Migliaccio, 2017; Schall et al., 2015). Although previous studies recommended using multiple IMU systems to measure body kinematics (Kim and Nussbaum, 2013; van Dieën et al., 2010), a full body suit of 17 sensors could be excessive if a single body region is of interest. Future studies should investigate reliability of simplified multiple IMU systems to measure specific body regions (Vignais et al., 2013). Alternatively, the full body suit generates large, vast amounts of data. Task-specific information captured with full body IMU systems in the field could generate databases that can be used to characterize multiple components of the body during a work task. During a validation study between OMC and IMUs using gate analysis, differences were observed between OMC and IMU for rotation and some lateral motions (Zhang, Novak, Brouwer, and Li, 2013). These differences could be due to varying reference axis definitions. The authors concluded that sagittal plane motions (flexion and extension) could be directly compared between OMC and IMU, but rotations and lateral flexion might not be directly comparable (Zhang et al., 2013). If IMUs are to be considered validated against a gold standard OMC, these axis definitions and differences need to be addressed (Karatsidis et al., 2016; Zhang et al., 2013).

Although the present study had many limitations, the results provide valuable documentation and insight into torso kinematic demands of a keg handling task in a craft brewery. Given the positive reception to the IMUs use in breweries, further research is hopeful. Many of the limitations discussed in this study can be addressed in future investigations.

5.6. Future studies

Results of the present study introduced basic information on the torso angle (represented through lumbosacral joint angular displacement) during keg handling tasks. The data generated during this study can be used for many different studies, from lumbosacral kinematics as a function of exact keg weight to a characterization of other brewery tasks to other anatomical biomechanics studies.

5.6.1. Keg weight

The present study assumed kegs to be empty, or 13.6 kg. Future studies could consider how different keg weights impact the torso joint angles and peak loading.

The physical layout of the workstation and time pressures of keg handling present a challenge to the added chore of weighing individual kegs. Since data was collected during an actual work shift, individual kegs were unable to be measured prior to keg handling without severely interrupting work flow. Future studies could devise a method to pre-measure the kegs before they are lifted. A perceived exertion scale could be verbally administered to the keg line operator during each lift. There are limitations to perception-based scales and conversing with the worker during their task may alter results. Workers could keep a log where workers record how many kegs were not completely empty.

A controlled single blind lab experiment could have participants lift kegs with designated weights. This would allow researchers to measure how different weighted kegs influence torso angular displacement and peak loading. Joint patterns when lifting unknown and unexpected (to the participant) weights could be evaluated. To limit strain on participants in designed studies, the amount of weight in each keg would be restricted. An empty keg has a mass of 13.6 kg and can exceed 72.6 kg when full, but designed lifting experiments may define a ‘heavy load’ as 15 kg, 19 kg, and 24.7 kg depending on the conditions (Beach, Frost, and Callaghan, 2014; Knapik et al., 2012; Merryweather et al., 2009). Controlling keg weight would reduce unexpected loading and joint reaction forces. Unexpected loading can initiate a chain reaction of reflexive involuntary muscle contractions that increase spinal compression to increase stability and regain balance (Heiss et al., 2002).

If measuring individual kegs is not feasible, the body’s reaction to different weights could be measured using a force plate or in-shoe pressure (Khurelbaatar et al., 2015; Kim and Nussbaum, 2014; van Dieën et al., 2010). An inverse dynamics approach could estimate moments about the lumbosacral joint based on ground reaction forces (Faber et al., 2016).

5.6.2. Compressive force modeling

A static, coplanar 2-dimensional biomechanical analysis was applied to peak flexion postures in the present study. This simple model provided sufficient information to compare the estimated compressive and shear forces occurring at the two lifting techniques (Chaffin et al., 1999). This was a static interpretation of data that was collected under dynamic conditions. The multifactorial and multidimensional nature of a lift is not addressed in the coplanar static model. Complex motions and combinations of sagittal bending with axial rotation coupled with lateral movements were observed during keg lifting tasks. The researchers recommend additional analysis with sophisticated 3-dimensional biomechanical models and regression models to further investigate the keg lifting task demands. The IMU system records at 60Hz, providing information on estimated segmental acceleration values to input into a 'real time' moment calculator. Kinematic data (acceleration, angular acceleration, velocity and angular velocity) for multiple body segments, shown in Table 5.1, that can be combined into biomechanical models (Greenland et al., 2011; Kim and Nussbaum, 2013). Trunk inclination can be challenging to accurately estimate in the field, but IMUs offer a solution (Faber et al., 2016; Kim and Nussbaum, 2013; Splittstoesser et al., 2007; van Dieën et al., 2010).

5.6.3. Alternative biomechanical variables

The incorporation of complex modeling would enable researchers to investigate further kinematic variables of the lumbosacral joint and biomechanical variables of other joints. The Xsens MVN Biomech Awinda sensor fusion algorithm and biomechanical model generated multiple kinematic values to model the spine along with many other body segments and joints outlined in Table 5.1. (Xsens, 2015).

Table 5.1. All segment and joint output from the IMU system

Pelvis	L3	L3	T12	T8
Neck	Head	Right Shoulder	Right Upper Arm	Right Forearm
Right Hand	Left Shoulder	Left Upper Arm	Left Forearm	Left Hand
Right Upper Leg	Right Lower Leg	Right Foot	Right Toe	Left Upper Leg
Left Lower Leg	Left Foot	Left Toe	jL5S1	jL4L3
jL1T12	jT9T8	jC1Head	jRightC7Shoulder	jRightShoulder
jRightElbow	jRightWrist	jLeftC7Shoulder	jLeftShoulder	jLeftElbow
jLeftWrist	jRightHip	jRightKnee	jRightAnkle	jRightBallFoot
jLeftHip	jLeftKnee	jLeftAnkle		

'j' represents joint between the two segments; "L" refers to lumbar spine; "S" refers to sacral bone; "T" refers to thoracic spine

Torso estimated angular displacement was the focus in the present study, but angular acceleration has been described as a risk factor for LBP. Recent studies identifiy the importance of including dynamic variables in generating forces on the low back (Greenland et al., 2011; Kim and Nussbaum, 2013). Angular acceleration from the sensor fusion algorithm was calculated with respect to the global reference frame (Xsens, 2015).

Greater shear forces were estimated when the workers initiated contact with the keg and pulled it towards them on the pallet. Anterior posterior shear increases during push and pull activities or demands (Gallagher and Marras, 2012;. Marras et al., 2009). After completeing the keg lift, workers were observerd pushing the kegs forward on the conveyor roller to create space for additional kegs, as shown in Figure 5.4.

Figure 5.4. Post lift completion keg pushing

The focus of the present study was torso angular displacement, but shoulder and elbow motion was very active during the keg handling tasks. The nature of inverting kegs requires workers to grasp opposite ends of the keg, lift, rotate, and place on the conveyor. Tracking hand motion is useful to study workflow (Gilbreth, 1911). Shoulder motion has been studied using IMU technology, but not in a craft brewery (Cutti et al., 2008). Future research of upper limb motion in keg handling tasks is recommended. A recent study interfaced trunk flexion and upper limb movement with the Rapid Upper Limb Assesment tool to generate an audio-feedback system for workers regarding their body positioning (Vignais et al., 2013). The combination of additional lumbosacral joint kinematic variables plus additional body parts with sophisticated models creates the ability to study multiple factors and biomechanical relationships during keg handling tasks.

5.6.4. Keg and pallet horizontal location

The relationship between torso angular displacement and keg horizontal position was not evaluated in the present study, but could be investigated for future studies. This could be accomplished by monitoring only lifts from a certain region of the pallet or by instructing workers to grasp kegs in a specific sequence. Previous studies on pallet unloading have broken a loaded pallet into multiple regions: front and back horizontal locations and low, middle, and top vertical positions with similar conclusions of low positions' influence of posture (Jorgensen et al., 2005; Marras et al., 1997).

The exact positioning of the pallet in proximity to the loading conveyor roller was not evaluated in the present study, but could be in future studies. When the forklift driver delivers multiple pallets of spent kegs, the keg line operator must navigate around stacks of pallets accumulating around the conveyor roller. Pallet delivery location could be controlled for the study by applying floor demarcations and communicating with forklift operators to deliver pallets to set conditions. Alternatively, pallets could be labeled as near or far from the conveyor (similar to the approach of defining pallet regions).

5.6.5. Time spent in postures

Duration spent in certain spinal postures has been associated with risk of developing LBP. Regardless of the weight of a load, upper body weight contributes to significantly the moment generated around the lumbosacral joint. Depending on the degree of flexion, this moment increases and the low back muscles must exert more force to balance out the moment generated by the torso. Cumulative exposure in different levels of forward flexion has been studied by classifying the degrees of flexion into categories: mild (20 to 45 degrees), severe (45 to 60 degrees), and extreme (over 60 degrees) (Campbell-Kyureghyan et al., 2005; Jorgensen et al., 2005; Merryweather et al., 2009). These categories are defined for total trunk flexion. To integrate information from the IMUs into existing ranges, translation must occur. Outputted segments from the sensor fusion algorithm must be compiled (L5S1, L4L3, L1T12) to estimate total trunk flexion or the provided ranges must be classified into segmental variations.

5.6.6. Workplace implications

A fully automated keg clean and fill line would eliminate the risks of LBP observed in the present study. Larger craft breweries often have the resources to implement this technology. Kegs arrive pre-positioned upside down and eight to a pallet. A forklift operator loads entire pallets of kegs onto the conveyor line. Kegs returned from distributors are inspected and flipped at a separate facility to increase efficiency (personal communication). While full level of automation eliminates keg handling at the craft brewery, it is very expensive and the act of keg handling still occurs. In traditional large breweries, the clean and fill line itself is designed to properly orient incoming kegs. This completely automated line requires a very large production scale to justify the costs. Often this type of technology is outside the scope of craft breweries, especially when they are starting small.

Given the nature of craft breweries, it is reasonable to expect that some amount of keg handling will continue to occur during the brewing process. The following keg handling workstation suggestions are based on results of the present study. Keg weight, torso angular displacement kinematics, and workstation layout are addressed.

Greater torso flexion was observed in low lifts than high lifts in the present study. Elevating low lift origin height could decrease the amount of torso flexion when workers handle kegs. However, extension was observed during high lifts, which is also a risk factor for occupational LBP. During flexion, many anatomical components (facets, abdominal pressure, and musculotendon structures) work in unison to support the upper body. However, few of these structures support the upper body during extension (Grieve, 1997; Wong, 2010). Risk of sustaining low back injury and developing LBP has been associated with spinal flexion and extension (Jones and Kumar, 2001; Marras et al., 1993; Marras, Lavender, Ferguson, Splittstoesser, and Yang, 2010; Putz-Anderson, Bernard, and Burt, 1997; Waters et al., 1993). To decrease the magnitude of extension, the researchers recommend lowering the origin height of high lift conditions. Both magnitudes of flexion and extension can be decreased by modifying the workstation to deliver kegs at a single pallet level that is elevated off the ground. Forklift operators could separate loaded pallets into single levels. At the time of the present study, kegs were periodically delivered stacked three pallets high and would be separated by forklift when delivered to the workstation. Alternatively, a modified roller conveyor system could deliver loaded pallets and remove empty pallets.

Removing empty pallets from the workstation required awkward handling postures while workers lifted and carried pallets. Installing a conveyor system that removes the pallets is one possibility to reduce pallet MMH. Alternatively, the workstation layout could be modified to include the empty pallet pile. Moving the designated pallet pile would decrease the distance workers transfer empty pallets.

At the time of the present study, the warehouse corner next to the clean and fill line occasionally served as storage for damaged kegs and assorted materials. Storage would often overflow into the keg handling area, impeding a worker's ability to access and handle spent kegs. Organizing the corner, perhaps by redefining it as an empty pallet place, could improve the efficiency of workers operating the keg clean and fill line.

The location of loaded pallets was not included in the present study due to placement variation with each delivery. Sometimes pallets were delivered too close to the conveyor, preventing workers from quickly accessing the other side of the line. Occasionally pallets would arrive farther from the conveyor roller, requiring workers to carry kegs from the pallet to the conveyor roller, increasing the handling time. Installing mirrors and floor demarcations, coupled with forklift driver training, could standardize the placement of spent kegs on pallets for the kegging line.

Based on IMU data for both lift conditions, workers experienced greater degrees of right lateral flexion and left axial rotation than left lateral flexion and right axial rotation. Workers would experience greater lateral flexion angular displacement of the torso towards the pallet (origin) then greater axial rotation towards the conveyor roller (destination). Coupled motion of axial rotation, lateral flexion and/or flexion while lifting significantly increases the risk of sustaining injury and developing LBP (Allread et al., 2000; Badger, 1981; Grieve, 1997; Ha et al., 2013; Kumar, Narayan, Stein, and Snijders, 2001).

Lateral flexion and axial rotation most likely varied depending on the location of the pallet relative to the conveyor roller, however this was not analyzed specifically in the present study. Orienting the pallet of spent kegs slightly offset of the conveyor roller (so the worker does not stand in directly between the origin and destination) could reduce the magnitude of torso axial rotation. If the front edge pallet is delivered in line with the bottom edge of the conveyor, a 90-degree corner 'zone' would be created where the worker could stand and transfer kegs. Consistent pallet orientation could be a total quality improvement measure to address the magnitude of axial rotation. Consistent pallet delivery location could regulate and reduce the magnitude of torso lateral flexion and axial rotation.

The installation of floor demarcations with an elevated mirror could help ensure that pallets are consistently delivered to the same location. This approach would ensure a predictable distance between the pallet and conveyor roller as well as designated walking access around the workstation, as shown in Figure 5.5. Additionally, regulating pallet placement would reduce the risk of a worker getting caught between pallets of kegs when a forklift adds additional pallets, often pushing existing pallets forward.

Unknown weights of spent kegs are due to inconsistent amounts of residual beer. Unexpected loading (as a result of lifting unknown weight) creates a risk of LBP (Amell et al., 2002; Badger, 1981; Bergquist-ullman and Larsson, 2014; Gatchel and Schultz, 2014; W.S. Marras et al., 2009; Waters et al., 1993). Ideally, spent kegs would be assumed empty when returned to the brewery. A variation of 'be kind, rewind' programs could encourage and incentivize spent kegs to be returned empty. Developing and implementing a program that encourages or requires distributors return empty kegs could reduce current weight variability in keg handling. When kegs are picked up from restaurants and bars, a simple gravity-based tool can estimate the amount of residual beer in a keg (http://www.kegcheck.com/). Additional tools exist to estimate the amount of residual beer in kegs, from disposable temperature sensitive stickers to scales (http://www.kegerators.com/articles/keg-meter.php).

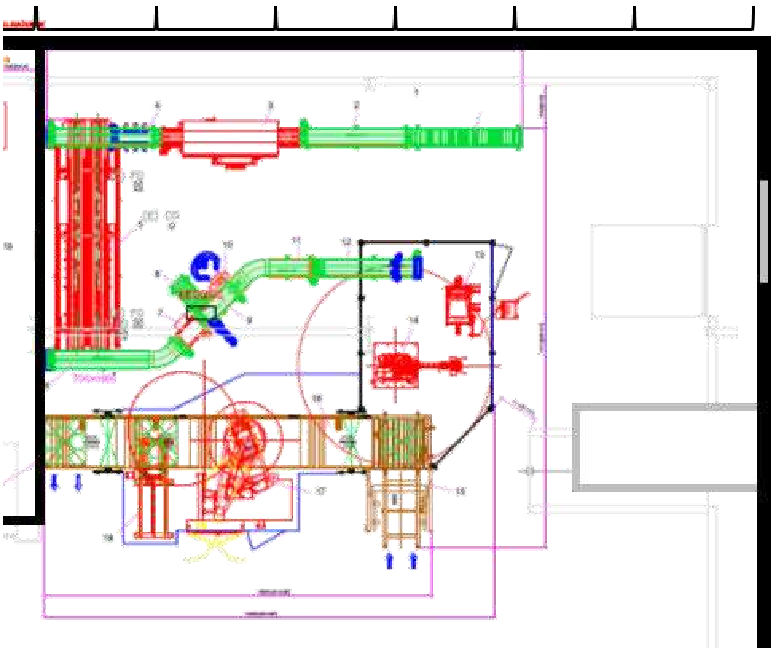

Figure 5.5. Craft brewery kegging line floorplan
The layout of the keg line machinery is illustrated above, operating in an "S" pattern. Empty kegs are loaded onto the top right region of the line and clean full kegs exit at the bottom left. Incoming pallets and assorted materials storage occurs in the open space on the right. Empty pallets could replace assorted materials storage to reduce duration of pallet handling. Additional organization of the top right corner would help regulate incoming pallet placement and increase accessibility to pallets and the far side of the clean fill line.

Recommendations for keg handling in a craft brewery address keg weight, low back angular displacement kinematics (flexion, extension, lateral flexion, and axial rotation) as well as organization and design. Regarding expense, design suggestions range from floor layout modifications to additional conveyor roller installations.

5.6.7. Post interventions

Keg lifting was recorded with the existing clean and fill line. The craft brewery used in the present study is in the process of redesigning this area to reduce the musculoskeletal demands. Results from this study will be shared to assist in that design process. Examples of potential modifications regarding conveyor roller design or keg delivery methods were outlined in 5.6.6. Regardless of how the workstation is redesigned, this study serves as a baseline dataset. After the workstation is redesign or updated, researchers can revisit the area and use IMUs to study worker torso angle movements. Results can be compared and the efficacy of the intervention can be assessed. The quick set up and portability of the IMU sensors enable feasible follow-up studies to quantify the effectiveness of interventions.

6. CONCLUSIONS

Many risk factors associated with occupational LBP exist in MMH jobs. Effectively quantifying trunk kinematics during task performance helps researchers understand how work design influences worker movement. Accurately measuring workplace trunk kinematics can be challenging due to tools' limitations. Video and OMC are limited by field of view obstructions. An extensive camera setup may not be practical in the work environment. Equipment used in lab based studies can be expensive and challenging to setup in a workplace, especially MMH facilities. Inertial measurement units are lightweight, noninvasive instruments that, when secured to a worker, record movements without disrupting their natural movements. When combined with a biomechanical model, IMUs' coordinate data can be used to estimate whole body kinematics. Reliability of sensor fusion algorithms and filters for IMUs continues to be a challenge. Current validation studies, algorithm developments, and high portability suggest that IMUs continue to be applied in future studies. While the scope of this study was lumbosacral joint angular displacement, many other approaches and levels of analysis are possible.

Craft breweries are a rapidly growing yet under-studied industry. Using IMUs, we effectively characterized low back angular displacement of kegging tasks. Specifically, we compared lumbosacral joint displacement when workers handled kegs from different pallet heights. A 2-dimensional biomechanical forces model was applied to estimate compressive and shear forces at peak flexion postures. While the overall duration of the handling task is low compared to a complete eight-hour shift, the workers could be exposed to angular displacements that are associated with a risk of developing LBP. Results from this study will be shared with the brewery as they work to redesign the keg line. Due to the portability and simplicity of the IMU system, we will be able to return and measure the efficacy of the intervention in the future. Body and joint kinematic information can be used to improve workplace design in a craft brewery, reduce risk, and create safer work.

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8. APPENDIX

8.1. Supplemental keg information

Name	Height cm(in)	Diameter cm(in)	Capacity L (gal/oz.)	Empty kg(lbs.)	Full kg(lbs.)
Half barrel	59.4 (23.4)	41.9 (16.5)	60 (15.5/1984)	13.6 (30)	72.6 (160)
Slim quarter barrel	59.4 (23.4)	28.4 (11.2)	29.3 (7.75/992)	11.3 (25)	40.8 (90)
Sixth barrel	59.4 (23.4)	23.5 (9.25)	(5.16/661)	8.6 (19)	27.2 (60)

Depending on the geometry dimensions of these smaller kegs, they are called slim quarter, quarter, or pony kegs. Beer weighs approximately 8.34 lbs per gallon.

Figure 8.1. Cross-section of half barrel keg
The downtube dispenser and spear valve in the center of the keg can be seen in a cros section.
Image source (https://es.wikipedia.org/wiki/Barril_de_cerveza)

8.2. Ferromagnetic interference monitoring procedure

Ferromagnetic interference could compromise the IMU sensor fusion algorith's accuracy in estimating low back kinematic data. As shown in Figure 3.3, the illustrated box highlights an instance when ferromagnetic interference increased. If ferromagnetic interference occured, the subject was asked to pause in a calibration posture for ten seconds to recalibrate the system (MVN User Manual, MV0319P.N, p99).

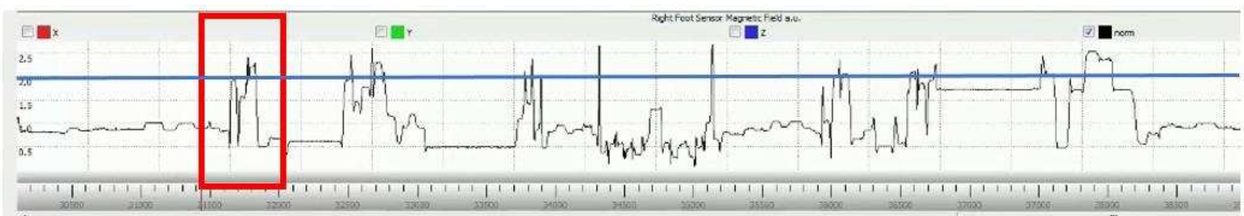


Figure 8.2. Magnetic norm for the right foot sensor
The representative sample graph illustrates magnetic interference for the right foot sensor during recording. Frame number is along the X-axis to represent time. Magnetic units (atomic units, a.u.) on the Y-axis. The blue line at mid-graph level highlights 2.0 a.u. The system requires recalibration if the magnetic normal exceeds 2.0 a.u. for over 30 seconds. The red box highlights one instance when the system exceeded 2.0 a.u. However, the width of the red box spans 580 frames (9.7 seconds) so the system does not require recalibration.

8.3. Pelvic sensor placement monitoring procedure

Pelvic sensor placement was monitored during recording by observing pelvic position estimation from the sensor fusion algorithm and software user interface. If the sensor dislocated from the original calibration position, the sensor fusion algorith became compromised and no longer estimated reliable kinematic values. High levels of superior and inferior movement were indicative of sensor dislocation. Superior and inferior movements were closely monitored throughout recording, as shown in Figure 8.3. If sensor dislocation occurred, the system was recalibrated (with the sensor placement readjusted).

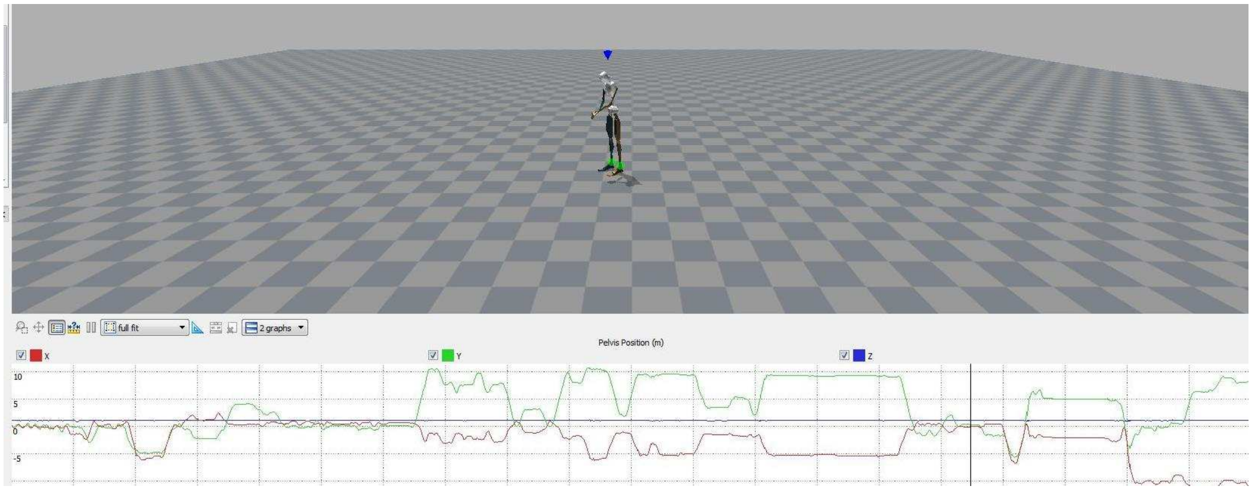
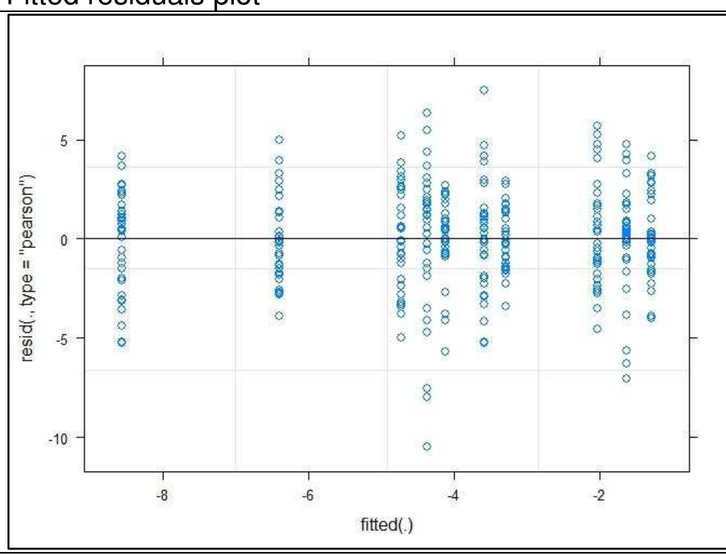
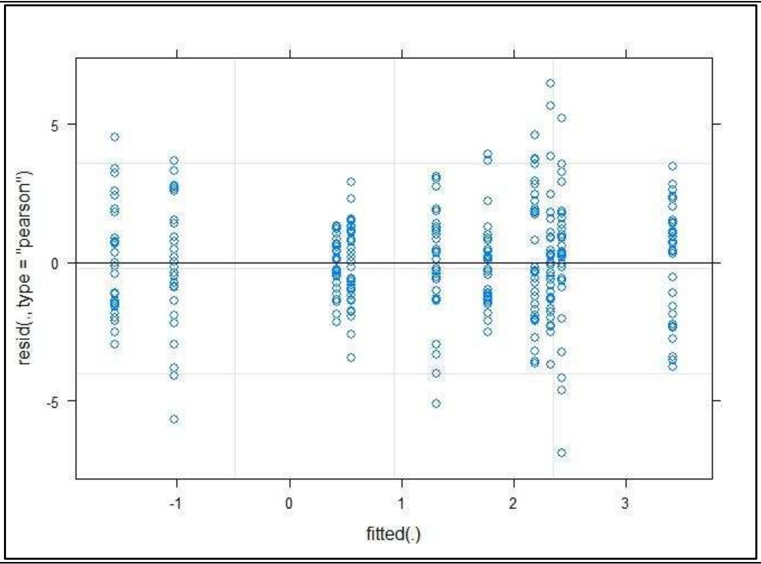
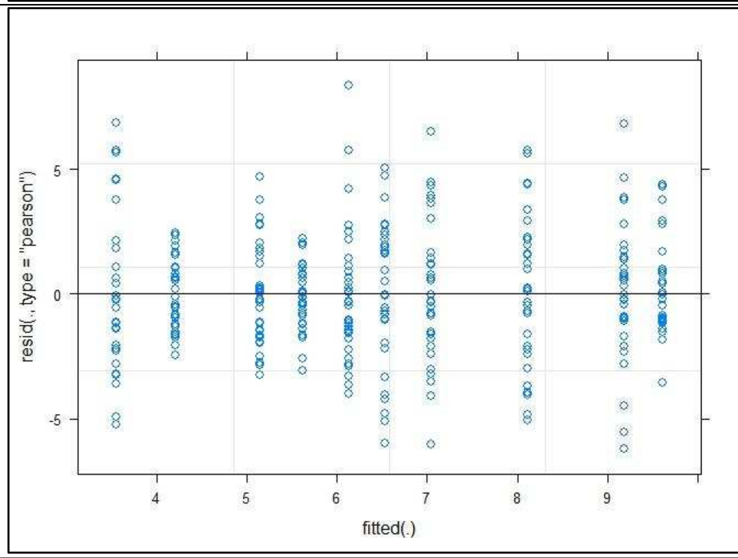
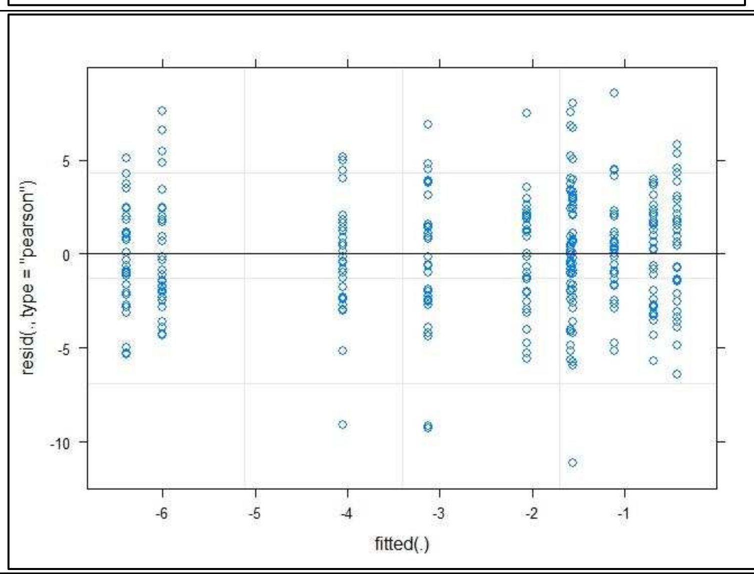


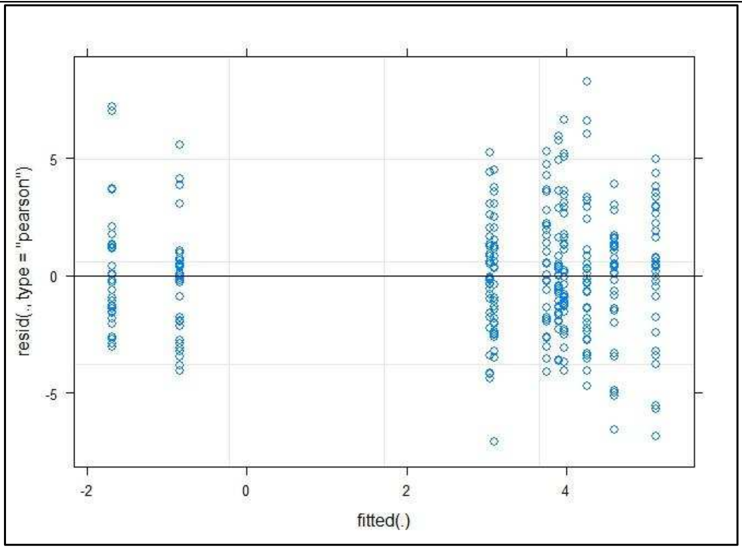
Figure 8.3. Pelvic sensor dislocation monitoring
Pelvic sensor position is displayed in the figure above. Z-values (shown in blue) represent superior and inferior movement. Z-values are consistently around zero meters, indicating normal sensor movement with the trunk. X-values (shown in red) correspond a worker's movements to the east and west of the origin point. Y-values (shown in green) represent a worker's movements north and south of the origin position. Both X and Y-values indicate normal sensor movement with the trunk as the worker walks around the workstation.

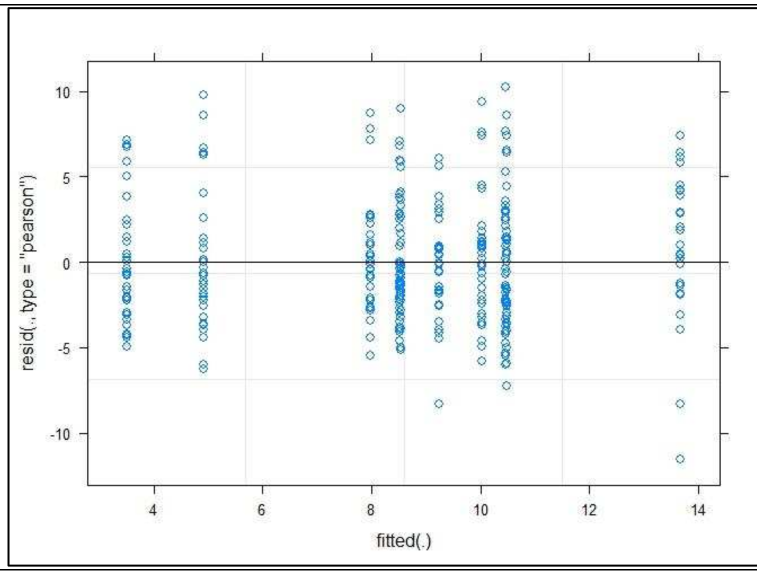
8.4. Variance plots of each angular displacement variable as a function of lift condition and subject in Figure 8.4.

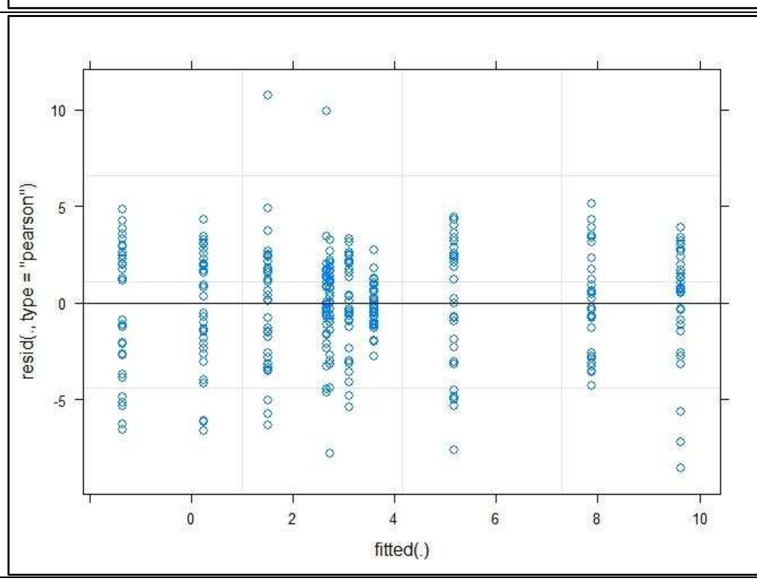
Variable	Fitted residuals plot
Variable: MaxlatR (maximum lateral angle to the right) comments: good variance spread	

Variable: Meanlat (average lateral angle) Comments: Good variance spread, Almost cornucopia if not for edges	
Variable: MaxlatL (maximum lateral angle to left) comments: good variance spread	
Variable: MaxaxialR (maximum axial angle to right) Comments: good variance spread	

<table>
<tr>
<td>Variable:
Meanaxial
(average
axial angle)

Comments;
Concentrated
spread on
the right side</td>
<td>
</td>
</tr>
<tr>
<td>Variable:
MaxaxialL
(max axial
angle to the
let)

Comments:
even spread
of variance</td>
<td>
</td>
</tr>
<tr>
<td>Variable:
Maxextz
(max
extension)

Comments:
Equal
variance, two
outliers</td>
<td>
</td>
</tr>
</table>

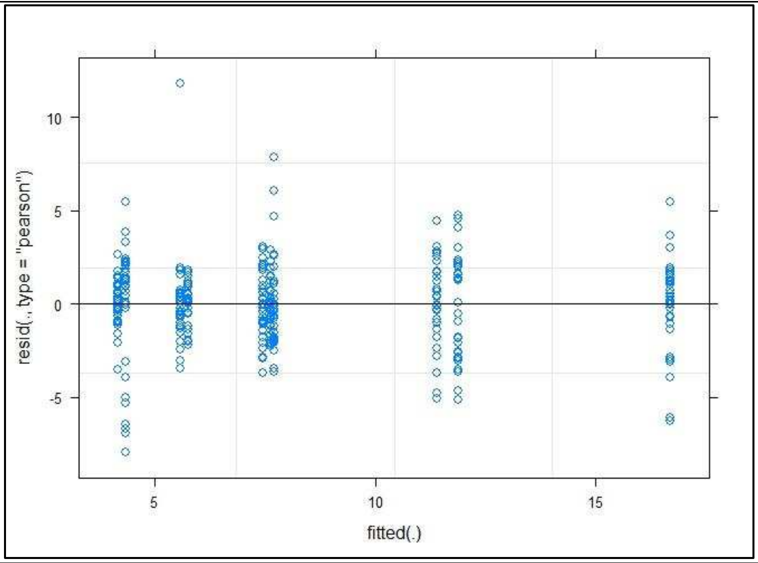
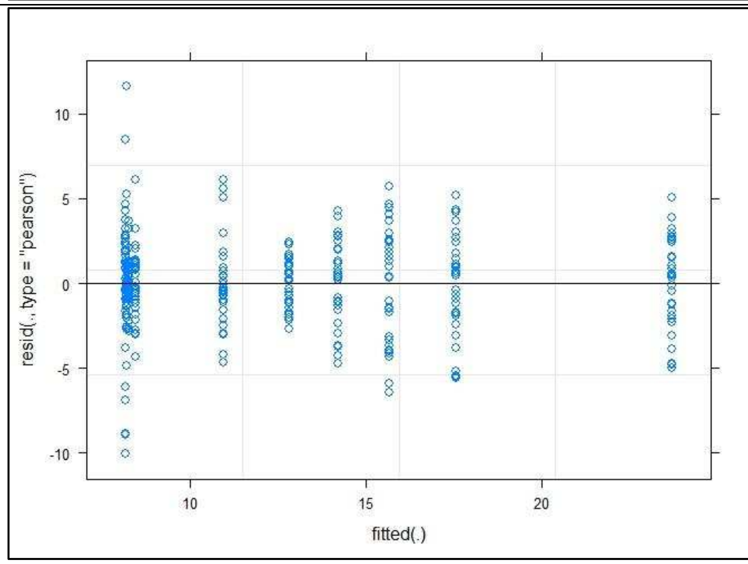
Variable: Meanflex (average flexion) Comments: There's one outlier on the left end and there's a little broader variance on the left edge	
Variable: Maxflex (max flexion) Comments: a little broad variance on far left; no cornucopia	

Figure 8.4. Variance plots of kinematic trunk variables.