



Low Back Biomechanics of Keg Handling Using Inertial Measurement Units

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Abstract. Workers handling beer kegs experience risk factors associated with occupational low back pain (heavy loads, awkward trunk postures). Many breweries are small and lack resources for materials handling equipment, causing much work to be done manually (including keg handling).

Measuring worker motions (kinematics) may aid job design to reduce risk factors associated with lifting. Low back motions may be evaluated using observation techniques and devices which are oftentimes inconvenient in the field. Application of wireless inertial measurement units (IMUs) for human motion provides whole body kinematics information, including low back.

The present study used a 3-dimensional motion capture system to investigate low back kinematics during keg handling at a Colorado brewery. Specifically, five workers lifted spent kegs onto a clean and fill line. Workers wore 17 IMUs as they handled kegs. Low back angular displacements were assessed during keg handling at two heights (low, high). Repeated measures analyses were performed with each trunk angular displacement variable as a function of lift condition.

Differences in low back kinematics between lift conditions were identified. During low lifts, torso flexion was significantly greater than high lifts. A broader range of angular displacements was observed in high lifts. Data collection was feasible during operational hours due to IMU's small design. Data collected from experienced workers provided researchers with information directly applicable to keg handling in small breweries. Results from the study can help improve workplace design in a craft brewery, reduce risk, and create safer work.

Keywords: Craft beer industry · Manual materials handling · Low back pain
Inertial measurement units

1 Introduction

Disability from low back pain (LBP) accounts for one third of disabilities from work related risk factors, according to the Global Burden of Disease 2010 (Driscoll et al. 2014). In 2015, occupational low 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). Furthermore,

the overall economic impact of LBP in the U.S. (direct costs such as lost wages and rehabilitation plus indirect costs such as retraining, and reduced efficiency and quality) exceeded \$200 billion annually (Dagenais et al. 2008; Marras et al. 2009).

Low back pain is the most common work-related illness in the U.S., and its causation 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 research groups (Amell et al. 2001; Gatchel and Schultz 2014; Jones and Kumar 2001; Putz-Anderson et al. 1997). Numerous studies have identified an association between low back injuries and manual materials handling (MMH) tasks (Faber et al. 2007; Lavender et al. 2012; Magora 1975; Marras 1993; van Dieën et al. 2010; Zurada et al. 2004). Awkward postures, long durations, and high frequency of MMH are occupational risk factors associated with LBP (Basahel 2015; Coenen et al. 2014; de Looze et al. 1994; Potvin 2008).

The craft brewing industry is a growing area that relies on manual materials handling, especially small breweries. Within the last ten years, the number of breweries in the U.S. has more than doubled, with over 6,000 breweries in 2017 (Brewers Association 2017). Colorado has the second most craft breweries in the U.S. with over 300 in 2016 (Brewers Association 2016). Craft breweries start as small businesses without resources to invest in expensive automated materials handling equipment, thus, much of materials handling is performed manually by workers. To date, there have been few studies related MMH or LBP in the brewing industry (Abaraogu et al. 2015; Jones et al. 2005). As of 2015, brewery injuries averaged 4.2 injuries per 100,000 h (Brewers Association 2016). The lack of studies and presence of occupational injuries in brewing industry presents a research opportunity on MMH and LBP.

Kegs, a container for beer, are one example of commonly handled materials in craft breweries. Half-barrel kegs were the most commonly used kegs at the craft brewery in the present study. With a capacity of 58.7 L (15.5 U.S. gallons), half-barrel kegs are 59.0 cm high, 41.0 cm wide, and weigh between 13.6 to 72.6 kg (60 to 160 lbs.) when empty or filled with beer. Kegs must be cleaned before they can be refilled with beer.

One approach to study LBP is to investigate the postures and motions (kinematics) workers experience during actual tasks. A way to quantify kinematics in an occupational setting is with 'wearable technology.' Lab studies of occupational tasks are limited in their ability to represent the actual work practices, demands, conditions and environment. Inertial measurement units allow collection of continuous human motion data during work tasks in the actual work environment. Inertial measurement units have been validated to measure human motion, with an emphasis on MMH (Faber et al. 2016; Kim and Nussbaum 2013; Schall et al. 2015). Characterizing trunk motion could be used to improve workplace design, reduce risk, and create a safer workplace in a craft brewery during tasks involving keg handling. The purpose of this research was to assess trunk posture using sternum and pelvic sensor data when craft brewery workers transferred spent kegs from incoming pallets onto a cleaning and filling conveyor.

2 Methods

2.1 Subjects

Five male employees at a craft brewery who regularly operated the keggling line voluntarily participated in this institutional review board-approved cross-sectional study after providing written informed consent. Participants self-reported that they were free of LBP at the time of study.

2.2 Keg Line Process

At the craft brewery used in the present study, kegs were manually lifted and flipped from incoming pallets onto a conveyor roller. Due to the design of the conveyor roller, kegs were placed upside down. Kegs were washed externally, then internally, and finally filled with beer. During an eight-hour shift, a worker may handle as many as 600 or as few as 100 kegs depending on the packaging demands of the scheduled beer. Kegs are transported around the brewery arranged eight to a pallet, often stacked two high (the height of the keg handle at 69.8 or 139.5 cm).

2.3 Instrumentation and Procedure

Study participants were fitted with seventeen IMU sensors (Xsens, Enschede, NT). Worker setup and calibration was done in accordance with the Xsens MVN system manual in an area with minimal ferromagnetic interference. The IMU suit was worn for approximately 90 min while subjects operated the keggling line during operational hours of the craft brewery. Data for was recorded in MVN Studio BIOMECH software



Fig. 1. Workstation setup of the keggling line includes the conveyor roller (A) and incoming spent kegs on a pallet. Kegs are stacked two high on the pallet, high (B) and low (C).

on an HP laptop. Video was simultaneously recorded for the 90 min during keg handling tasks. Due to the variability in the number of kegs handled, present study participants were recorded while they handled 64 kegs, or 32 kegs from each lift condition, which took approximately 90 min. A keg lift was defined as the point of initial grasp to final release of the worker's hands when transferring the keg from the pallet the conveyor. Keg origin height was tagged as a high or low, as shown in Fig. 1.

2.4 Data Processing and Analysis

2.4.1 Peak and Average Trunk Angular Displacement

Lift height condition and initiation/termination time points were identified using the video recordings and sensor fusion data for each subject. In Xsens MVN Studio, data was recorded in Euler angles and exported in quaternions form, which was converted into rotation angles using Matlab 2017b (Roetenberg et al. 2013). Using a custom R code in RStudio Version 1.0.136, 2016, lift time points and rotation angle data were combined to identify descriptive statistics of the trunk angular displacement during keg lifts (R Core Team 2016). Trunk angles were calculated from pelvic and sternum sensor data. Maximum values corresponded to flexion in the sagittal plane. Minimum values corresponded to extension (or minimal flexion) in the sagittal plane. Averages of trunk angular displacement in each plane were identified for all lifts under both height conditions. Evaluating trunk positions of workers assists researchers, clinicians, and other stakeholders to characterize the spectrum of work-related postures for the different lift conditions.

2.5 Statistical Analysis

The data were 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.

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. 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 $p \leq \alpha = 0.05$.

3 Results

All five male workers at the craft brewery who regularly operated the keg line participated and were free of LBP at the time of the study. Anthropometric information inputted into the biomechanical model is shown in Table 1. Two keg lift height conditions were analyzed in the present study and sample graphs of trunk angular displacement are shown in Figs. 3 and 4. Average trunk flexion was significantly greater during low lifts compared to high lifts by an average magnitude of 4.2° ($p = 0.03$).

Minimum flexion was significantly greater during low lifts compared to high lifts, with participants experiencing an average of 3.34° of trunk extension ($p = 0.04$). While not significant, overall magnitudes of maximum flexion were larger while workers handled kegs from low heights. While the differences between maximum flexion were not significant, the confidence interval for high lifts was larger, suggesting there is more variability in trunk motion when workers are transferring kegs from high levels. Estimated trunk angular displacement is shown in Table 2. The difference between high and low keg lift durations was not significant ($p = 0.46$).

Table 1. Anthropometric data of study participants. (All variables except age and body mass, were included in the sensor fusion algorithm for the IMU system)

Variable	Units	Mean	SD	Minimum	Maximum
Age*	<i>years</i>	31.0	4.5	28.0	39.0
Body mass*	<i>kg</i>	5.9	74.8	78.8	88.9
Body height	<i>cm</i>	179.0	5.6	173	186
Foot size	<i>cm</i>	31.6	1.3	30.3	33.0
Arm span	<i>cm</i>	174.5	4.8	168	181.0
Ankle height	<i>cm</i>	10.7	1.0	9.5	12.0
Hip height	<i>cm</i>	93.4	3.4	90	99.0
Hip width	<i>cm</i>	27.5	1.9	26	30.5
Knee height	<i>cm</i>	51.2	2.6	47.5	54.5
Shoulder width	<i>cm</i>	36.4	5.3	27	40.0
Shoe sole height	<i>cm</i>	3.7	1.1	2.0	4.8

Table 2. Estimated angular trunk displacement in both keg lift height conditions. Values reported in angles as mean (lower, upper confidence interval). Significant values have *

Motion	High	Low	p-value
Average flexion	15 (9, 21)	19 (12, 27)	0.03*
Maximum flexion	35 (23, 47)	40 (32, 47)	0.19
Minimum flexion	-1 (-7, 5)	-3 (-10, 4)	0.04*

4 Discussion

The investigators utilized IMUs to characterize trunk motion in keg handling from high and low lifts to improve workplace design and reduce injury risk of the workers. Lift height impacted the amount of flexion experienced by the worker during keg handling.

4.1 Trunk Postures

Workers' average trunk posture in the sagittal plane was significantly greater during low lifts compared to high lifts ($p > 0.05$). When lifting kegs from a low height, workers experienced an average of four degrees of additional forward flexion. Kegs originating

from low positions are 69.8 cm lower than their high counterparts (the height of a keg on a pallet), therefore requiring the worker to bend farther forward when initiating the lift.

Magnitudes of trunk extension were observed to be significantly different between high and low keg lifts ($p > 0.05$). Workers lifting kegs from low heights on average experienced trunk extension three degrees greater than when lifting from high locations. Momentum could be factor when workers are lifting kegs, and trunk extension is a way to maintain this energy.

While the differences were not significant ($p > 0.05$), the confidence interval of trunk maximum flexion was broader during high lifts than low lifts, suggesting workers can experience a more diverse range of motion in the sagittal plane.

Available research on trunk posture exposure during brewing tasks is limited, but measurements collected during keg line operation can be compared to other studies. Trunk motion has been investigated in other industries with known associations to work related musculoskeletal disorders (including LBP). Keg line operators lifting kegs from both height conditions experienced similar peak flexion when compared to a database of 17 distribution centers (37° , Marras, Lavender, Ferguson, Splittstoesser, and Yang, Marras et al. 2010). Keg line operators experienced less peak sagittal flexion than Southeastern reforestation planters (75° , Granzow et al. 2018). Peak sagittal flexion in brewery workers was greater than registered nurses (36° , Schall et al. 2016).

4.2 Limitations

Only five young healthy men participated in the present study. While the participants represented all the keg line operators at the craft brewery when the study was conducted, the results may not be generalizable to MMH workforce. Data was collected at a craft brewery that utilized both manual and automated processes. The keg line required kegs to be manually loaded then were automatically cleaned, filled, and palletized. Therefore, postural patterns may not be generalizable to the full range of kegging demands regarding craft brewery equipment variability.

To minimize task interference, the order in which the worker lifted kegs from the pallet was not controlled. Lift strategy could vary with a keg's horizontal location on the pallet, but only vertical orientation was considered in the present study.

Magnetic immunity due to the IMU algorithm enabled data to be collected in an industrial setting (Roetenberg et al. 2013). Since the completion of this study, updated algorithms have been released with greater levels of magnetic immunity. While operating the kegging line operators occasionally had to check tank pressure (located across the brewery). When the worker walked to the tanks, they would exceed the range of the antennae. The hoses and tanks presented additional magnetitic interference that compromised the accuracy of the IMU system. Due to these circumstances, recording was paused and resumed when the worker returned to the kegging line. Future data collection under these conditions, with the updated algorithm, would be able to follow the worker throughout the brewery. The IMU system and sensor fusion algorithm approximate body segment kinematic data based on sensor data and a biomechanical model. While validation studies have been conducted and established

the accuracy of the IMU system, there are inherent limitations in the sensors and biomechanical models (Banos et al. 2014; Schall et al. 2016; Schall et al. 2015). Despite these limitations, the portability and small design of IMUs enables researchers to conduct studies during operational hours in the field, thus increasing ecologic validity (Allread et al. 2000).

Although the present study had limitations, the results provided valuable 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.

4.3 Future Directions

Results of the present study introduced baseline information on the trunk motion calculated from IMU sensor data for the sternum and pelvis during keg handling tasks. The data generated during this study can be used for multiple studies, from trunk kinematics as a function of lift weight to a characterization of other brewery tasks to other anatomical biomechanics studies.

Other studies of trunk motion in industries quantify the amount of time spent in 'extreme' (at or greater than 45° of flexion) postures. A study on hand planters in reforestation projects observed sagittal trunk motion and calculated percent time extreme flexion (Granzow et al. 2018). While the mean maximum sagittal flexion of brewery workers conducting kegging tasks was less than 45°, the values of the upper confidence intervals could be considered 'extreme'. This lack of 'extreme' forward flexion could be due to the design of kegs (the handle is 59.0 cm high which enables workers to grasp the keg without reaching all the way to the floor). Other tasks in breweries (from transporting pallets to handling raw ingredients) might require greater levels of trunk flexion. Future studies could investigate trunk posture across a variety of brewing-related tasks.

Future studies could also address additional factors related to occupational LBP other than trunk posture. Characteristics of the load (such as weight) influence the magnitude of compressive and shear forces generated about the low back. Compressive and shear forces at the lumbosacral joint have been correlated to LBP, and NIOSH has recommended action limits to reduce the risk of developing LBP (Marras 1993; Marras and Granata 1995; Waters et al. 1993). Keg weight was assumed to be constant at 13.6 kg (empty keg weight) for the present study. Lifting kegs with residual beer were up to the worker's discretion. If they determined that they could safely complete the lift with some amount of beer residue, the data were included in the analysis. Because of this, the true weight of the keg could have exceeded the assumption of 13.6 kg and workers' trunk motions could have changed to accommodate heavier loads. Lifting unexpectedly heavy loads has been suggested to be associated with LBP, but research is ongoing (Van Der Burg et al. 2000; Van der Burg and Van Dieën 2001). Future studies could consider how different keg weights impact the torso joint angles and peak loading.

Previous studies have estimated compressive and shear resulting forces during occupational task simulations in lab settings. Portable force plates (van Dieën et al. 2010) and in-shoe pressure sensors (Khurelbaatar et al. 2015) have been used to achieve this. Recently, an inverse dynamics model was developed that combines IMU

kinematic data and ground reaction force and moment model to predict internal resulting forces (Faber et al. 2016; Karatsidis et al. 2018). The ability to estimate trunk and spinal kinetics in the field will increase our understanding of how work factors can contribute to occupational LBP.

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 et al. 2017; Schall et al. 2015). Future studies should investigate reliability of simplified multiple IMU systems to measure specific body regions (Kim and Nussbaum 2013; van Dieën et al. 2010; 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.

The scope of this project was to use IMUs to measure trunk motion in the sagittal plane. Given the available developing technology, the continuation of measuring worker exposures in the natural work environment is hopeful.

5 Conclusions

The craft brewery used in the present study is in the process of redesigning the kegging line to reduce the musculoskeletal demands. Results from this study were shared to assist in that design process. Since completion of this study, the brewery installed additional safety mirrors above the pallet delivery area and increased the forklift traffic for delivering pallets of used kegs.

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 trunk motion when workers handled kegs from different pallet heights. While the overall duration of the handling task is low compared to a complete eight-hour shift, the workers are exposed to angular displacements and estimated forces associated with a risk of developing LBP. Due to the portability and simplicity of the IMU system, investigators will be able to return and measure the impact of the intervention in the future. Body and joint kinematic information can be used to improve workplace design in craft breweries, reduce risk, and create safer work.

Many risk factors associated with occupational LBP exist in MMH jobs. Effectively quantifying trunk postures during task performance helps researchers understand how work design influences worker movement. 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 but the 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 trunk flexion, many other approaches and levels of analysis are possible.

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