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Biomechanical Analysis of Manual Material Handling Tasks using IMU Sensors

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Abstract: Advancement in the field of ergonomics and biomechanics has curtailed rate of injuries, but still Work-related Musculoskeletal Disorders (WMSDs) are a leading cause of lost work days in the construction industry. Manual material handling (MMH) tasks such as lifting, carrying and pushing heavy material such as rebars, pipes, and tools in construction are significant causes of WMSDs. Several regulations and standards dictate the safe practice of construction activities onsite to make it safer for the construction workforce. There exist several workplace assessment tools based on visual observation, direct measurement, remote sensing, and vision-based techniques. The remote-sensing and vision-based techniques such as Microsoft Kinect and Inertial Measurement Units (IMUs) are sophisticated and acceptable due to their efficiency and accuracy in real-time settings. Previous research has investigated the use of vision-based motion capture approach for biomechanical analysis. Some of the limitations of vision-based tools are being time-consuming, errors in the output, and requires a controlled environment. This study proposes a method using IMU sensors and 3DSSPP for biomechanical analysis of MMH tasks. In addition, the data collected using this system is used to determine the effect of lifting the weight on compressive stress and shear stress for squat and stoop lifting postures. The result shows that the threshold limit of compression and shear force is achieved at 35 lbs. and 51 lbs. for squat lifting posture. Whereas for stoop lifting posture the threshold limit of compression and shear force is achieved at 20 lbs. and 35 lbs., respectively. The proposed method overcomes the errors affiliated with vision-based assessment system. The reliability and practicality of the proposed system can be used to mitigate injuries related to WMSDs and make the workplace safer for the construction workers.

Keywords: Manual Material Handling, IMU Sensors, Biomechanical Analysis

1. Introduction

Chronologically construction industry has modernized with the latest technology and instrument to change the lives of millions by improving built-environment with better infrastructure, residential building, and energy facilities. Automation is the future of every industry, the construction industry is different, which is one exception that will always require skillful and proficient workers to provide efficiency and productivity to complete any construction project in a large time frame. The construction industry is a labor-intensive industry; workers must perform a plethora of manual material handling that involved physical strength, repetitive work, and awkward postures. This kind of activities exposes labor to musculoskeletal injury risks. In the construction industry in the United States, occupational injuries accounted for 10.1% with the Work-related Musculoskeletal disorder (WMSD) accounting for 35% of occupational injury and illness leading to loss of work (Bureau of Labor Statistics 2016).

Research in the field of ergonomics and biomechanics has curtailed rate of fatalities and injuries, but still, WMSDs are a leading cause of lost work days (Meerding, IJzelenberg, Koopmanschap, Severens, & Burdorf, 2005). Temporary or permanent disability by WMSDs affects a worker’s livelihood and self-esteem (Abásolo et al., 2012). Manual material lifting in construction has been considered for the study as most of the construction task include significant lifting, carrying and pushing of heavy elements such as rebar, pipes, and tools by construction workers.

Several regulations and norms dictate the safe practice of construction activities on site to make it safer and more vigilant for the construction workforce. With regulation, several assessment tool and methods supplement quest to reduce any unsafe activity on the construction site. The assessment tools are categorized on the bases of its implementation. Rapid upper limb assessment (RULA), Rapid Entire Body Assessment (REBA) are some of direct observation assessment techniques that can be used in the field study, being cost-effective with the real setting assessment of workers are highlights of observational assessment tools. But at the same time results can be prone to error as they depend on evaluator expertise. Analysis of Manual Material Handling (MMH) has gained the attention of researchers as most of the musculoskeletal disorders injuries are resultants of MMH. There are various methods that used ergonomics and biomechanical principles to analyze body postures and categorize them depending on risk levels. Methods that use full body evaluation for posture and risk analysis are being used in the field widely. Some of these methods are REBA, ROTA, TRAC, and QEC. In general, the main concern in these methods is the postural risk in the workplace does not indicate relative stress and workload with respect to worker's capacity (Seo, Starbuck, Han, Lee, & Armstrong, 2014). Observation methods have added the advantage of being inexpensive and can be used in a wide range of workplaces. Disadvantages related to observational methods is they may be subjected to intra and inter-observer variability when selection is based on different categories of exposure level (van der Beek, Frings-Dresen, & medicine, 1998). The motion-sensing technique is an advanced technique in which motion data is captured by using a markerless biomechanical sensing technique. In this wide range of image/video sensors are used to trace and map human motion in three dimensions. More suitable for dynamic analysis, kinematic data extracted from it can be used in both risk-assessment tool and biomechanical model to interpret muscle and joint moments (Chang, Hsiang, Dempsey, & McGorry, 2003). Microsoft Kinect is an exclusive cost-effective tool which is widely used in capturing 3-D dynamic and complex motion of human motion by remote-sensing. Research has been conducted to see the feasibility of remote-sensing using video mapping to evaluate WMSD related assessment. There has been previous research on how a vision-based motion capture approach can be applied to the biomechanical analysis. RGB-D sensors such as Kinect was used to capture motion data in BVH (Biovision Hierarchy) format. The specific conversion was carried out to convert BVH format from the vision-based motion capture approach to the available file format in an existing static biomechanical analysis tool 3DSSPP (3D Static Strength Prediction Program). Results indicated the identification of body parts where excessive force was exerted while performing manual material lifting task (Seo et al., 2014). Although it has proven to be effective the application of remote-sensing has its own challenges, its short-range applicability (i.e., less than 4 m) is the biggest bottleneck, time-consuming, and errors in the output results. There is also a restriction on the range of motion and posture. Video capture in high illumination may severely reduce the accuracy of data collected (Corazza et al., 2006). Limitations like these demand future extensions in remote sensing and vision-based assessment techniques (Moeslund, Hilton, Krüger, & understanding, 2006).

The direct Measurement assessment tool is used to increase the accuracy of risk assessment as they can be used to measure external and internal factors. These tool help to overcome the disadvantages of other assessment tools. Instruments such as goniometer, accelerometer, and 3D force sensors are directly attached to the human body to calculate various biomechanical parameters like 3D coordinate of a human joint, joint angles, etc. In ergonomics most excessively used direct measurement tool is EMG (Electromyography) and IMU's (Inertial Measurement Units). Former is generally used to calculate muscle activities, fatigue level, and muscle tension, latter to compute human skeletal coordinate structure, joint angles, and awkward posture for ergonomic analysis. Direct Assessment tools are used to mitigate drawbacks and errors of its counterpart assessment tools. Use of direct assessment method is more reliable than visual observational methods; it helps in ceasing human error factor from data analysis and can be carried out in indoor and outdoor settings with similar accuracy so that data homogeneity is maintained. Among the sensors attached human body are combined data extracted is from the accelerometer, gyroscope and magnetometer fused are IMU. It is essential to develop a system using IMUs to perform an automated biomechanical analysis.

2. Objective

To overcome the challenges of vision-based workplace assessment tools, this study proposes a system to perform static biomechanical analysis of MMH tasks using IMUs that helps in assessing the risk of WMSDs during construction activities on job sites. The proposed system is evaluated by conducting a case study on manual material handling, especially lifting tasks. In addition, the data collected using the proposed system is used to determine the effect of lifting the weight on compressive and shear stress for squat and stoop lifting techniques.

3. Biomechanical Analysis using IMUs and 3DSSPP

The process of biomechanical analysis using IMUs and 3DSSPP (3D Static Strength Prediction Program) is broadly divided into three steps namely data collection, data processing, and biomechanical analysis (Figure 1). For the data collection, seventeen IMU sensors were placed at different nodes of the body as shown in Figure 2 to capture the motion data of all the body segments. The sensors are calibrated with respect to gyroscope and accelerometer using gradient descent and sphere calibration techniques. Once the sensors were calibrated, the accuracy of all the sensors was validated using the real-time data charts. Once the desired accuracy was achieved, the sensors were used for data collection. The data collected by IMU sensors was stored in BVH (Bio Vision Hierarchy) file format as shown in Figure 3. BVH is a structural representation of bones of the skeleton. The BVH file consists of two parts where the first part represents the hierarchy of the initial pose of skeleton structure and second section depicts the channel data for each frame (Meredith & Maddock, 2001). In hierarchy section root joint (hip) represents the starting point of new skeletal hierarchy, a joint is a sub-division in this hierarchy that gives a clear pattern for a particular root and completes the hierarchy. The BVH data motion data was transformed into body segment angles using the procedure shown in Figure 1. Firstly, using the transformation matrix (M) for all the joints, the vertices (V_0, V_1) of the body segments are calculated in the global coordinate system using Equation 1 and 2, where V is the offset of the joint. Secondly, vectors (V') of the body segments are calculated using the vertices as shown in Equation 3. Finally, the absolute angles of such as horizontal (H) and vertical (V) angles were determined as defined in 3DSSPP (Equation 4 and 5). The horizontal angles (Figure 4) were measured between body segments and x-axis looking from the top view, and vertical angles (Figure 5) were measured between segments/joints with respect to an individual projected horizontal x-y plane. It is to be noted that the definition of rotation angles and coordinate system in BVH data is different from 3DSSPP. Once the BVH motion data was transformed into body segment angles, the biomechanical analysis was performed in 3DSSPP using the anthropometry, load, and body segment angle information. The analysis provides compressive and shear forces on the lower back.

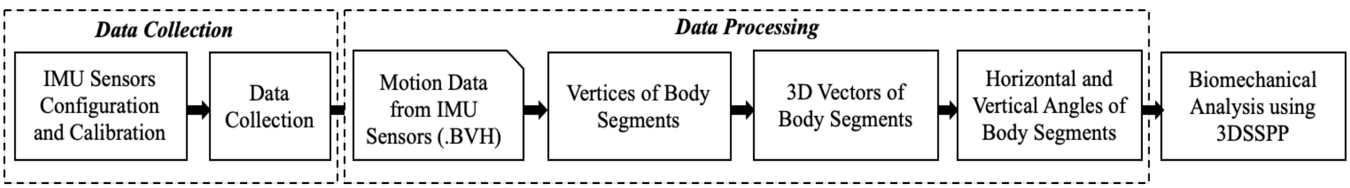


Figure 1. Methodology for Biomechanical Analysis using IMUs and 3DSSPP

$$V_0 = M_{Hips}*M_{LeftUp}*Leg M_{LeftLowLeg}*M_{LeftFoot}* [0, 0, 0, 1]^T \quad (1)$$

$$V_1 = M_{Hips}*M_{LeftUpLeg}*M_{LeftLowLeg}*M_{LeftFoot} * V \quad (2)$$

$$V' = V_1 - V_0 \quad (3)$$

$$H = \cos^{-1}[x/\sqrt{x^2 + y^2}] \quad (4)$$

$$V = \cos^{-1}[z/\sqrt{x^2 +} y^2 + z^2 \quad (5)$$

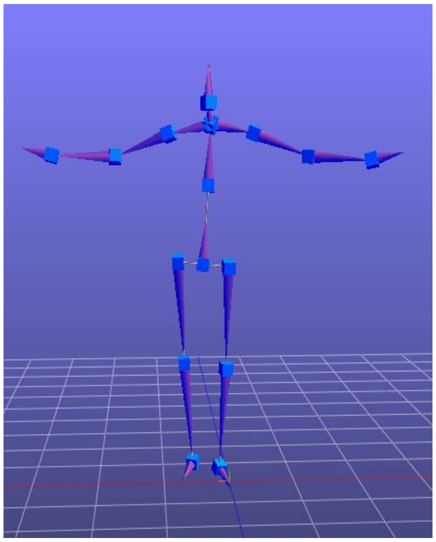
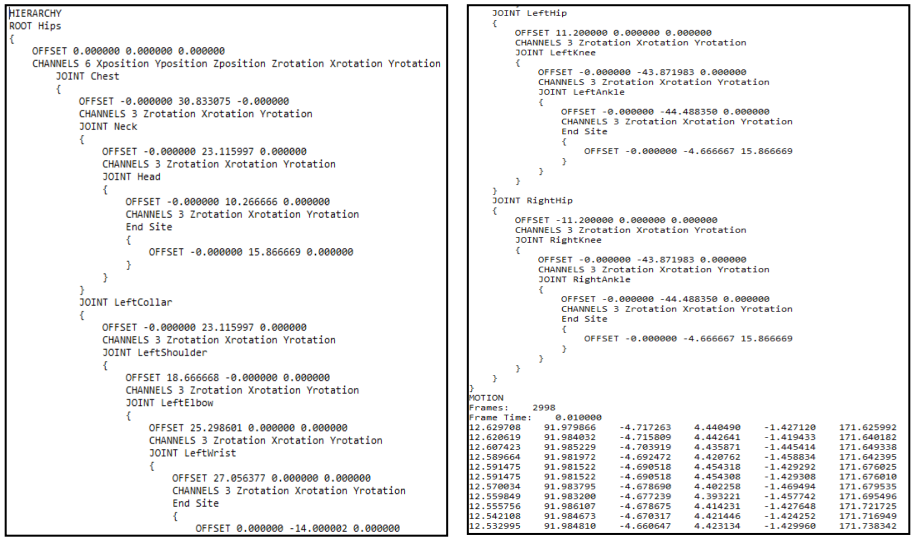


Figure 2. Position of IMUs



```
HIERARCHY
ROOT Hips
{
    OFFSET 0.000000 0.000000 0.000000
    CHANNELS 6 Xposition Yposition Zposition Zrotation Xrotation Yrotation
        JOINT Chest
        {
            OFFSET -0.000000 30.833075 -0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT Neck
            {
                OFFSET -0.000000 23.115997 0.000000
                CHANNELS 3 Zrotation Xrotation Yrotation
                JOINT Head
                {
                    OFFSET -0.000000 10.266666 0.000000
                    CHANNELS 3 Zrotation Xrotation Yrotation
                    End Site
                    {
                        OFFSET -0.000000 15.866669 0.000000
                    }
                }
            }
            JOINT LeftCollar
            {
                OFFSET -0.000000 23.115997 0.000000
                CHANNELS 3 Zrotation Xrotation Yrotation
                JOINT LeftShoulder
                {
                    OFFSET 18.666668 -0.000000 0.000000
                    CHANNELS 3 Zrotation Xrotation Yrotation
                    JOINT LeftElbow
                    {
                        OFFSET 25.298601 0.000000 0.000000
                        CHANNELS 3 Zrotation Xrotation Yrotation
                        JOINT LeftWrist
                        {
                            OFFSET 27.056377 0.000000 0.000000
                            CHANNELS 3 Zrotation Xrotation Yrotation
                            End Site
                            {
                                OFFSET 0.000000 -14.000002 0.000000
```

```
    JOINT LeftHip
    {
        OFFSET 11.200000 0.000000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT LeftKnee
        {
            OFFSET -0.000000 -43.871983 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT LeftAnkle
            {
                OFFSET -0.000000 -44.488350 0.000000
                CHANNELS 3 Zrotation Xrotation Yrotation
                End Site
                {
                    OFFSET -0.000000 -4.666667 15.866669
                }
            }
        }
    }
    JOINT RightHip
    {
        OFFSET -11.200000 0.000000 0.000000
        CHANNELS 3 Zrotation Xrotation Yrotation
        JOINT RightKnee
        {
            OFFSET -0.000000 -43.871983 0.000000
            CHANNELS 3 Zrotation Xrotation Yrotation
            JOINT RightAnkle
            {
                OFFSET -0.000000 -44.488350 0.000000
                CHANNELS 3 Zrotation Xrotation Yrotation
                End Site
                {
                    OFFSET -0.000000 -4.666667 15.866669
                }
            }
        }
    }
}
MOTION
Frames:    2998
Frame Time:    0.010000
12.629708    91.979866    -4.717263    4.440490    -1.427120    171.625992
12.620619    91.984032    -4.715809    4.442641    -1.419433    171.640182
12.607423    91.985229    -4.703919    4.435871    -1.445414    171.649338
12.589664    91.981972    -4.692472    4.420762    -1.458834    171.642395
12.591475    91.981522    -4.690518    4.454318    -1.429292    171.676025
12.591475    91.981522    -4.690518    4.454308    -1.429308    171.676010
12.570034    91.983795    -4.678690    4.402258    -1.469494    171.679535
12.559849    91.983200    -4.677239    4.393221    -1.457742    171.695496
12.555756    91.986107    -4.678675    4.414231    -1.427648    171.721725
12.542108    91.984673    -4.670317    4.421446    -1.424252    171.716949
12.532995    91.984810    -4.660647    4.423134    -1.429960    171.738342
```

Figure 3. BVH Data Structure

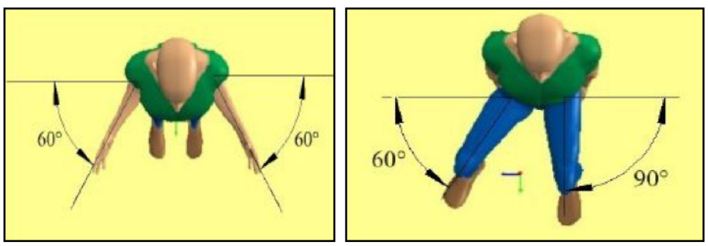


Figure 4. Horizontal Angle in 3DSSPP

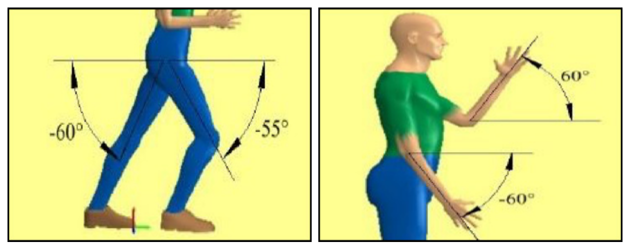
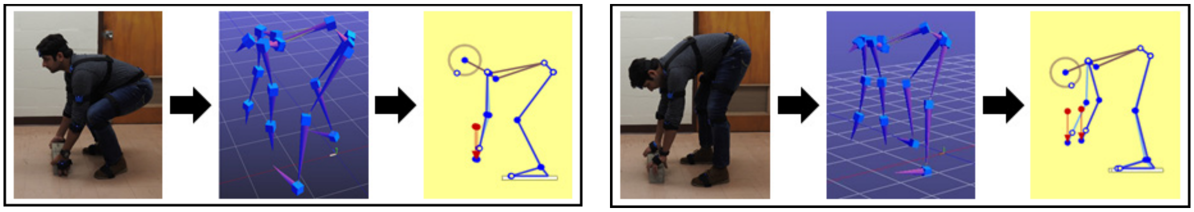


Figure 5. Vertical Angle in 3DSSPP

4. Case Study on Manual Material Handling

To evaluate the proposed system for performing static biomechanical analysis using IMUs and 3DSSPP, this research conducted a case study on manual material handling tasks, specifically lifting a weight from the floor to torso height. Lifting task was selected because the lower back will be at maximum risk during hip flexion and adduction. The MMH task includes squat and stoop lifting of twelve different weights (5 lbs. to 60 lbs. with an increment of 5 lbs.) with three iterations for each weight. The motion data while performing the lifting task was collected using IMUs. The experiment was performed by a male participant (175 cm, 78 kg) in a laboratory. The participant was equipped with all the 17 IMU sensors after they were configured and calibrated. The data for all the trials were stored in the BVH file format. The BVH data was transformed into horizontal and vertical angles for 3DSSPP using the procedure described in the previous section. Figure 6 shows the transformation of IMU data to 3DSSPP for squat (Figure 6(a)) and stoop (Figure 6(b)) lifting technique. Using anthropometric information (participant's height and weight), motion data from IMUs, and load characteristics, we conducted static biomechanical analysis using the proposed system. The 3DSSPP provides compression and shear forces at L4/L5. The results were further analyzed to determine the effect of lifting the weight on compressive stress and shear stress for squat and stoop lifting postures.



(a) Squat Lifting Technique (b) Stoop Lifting Technique

Figure 6. Transformation of Motion Data to 3DSSPP

5. Results and Discussion

The results of this experiment develop a clear understanding of how posture plays a vital role in exposing construction workers towards risk of WMSD. Investigation of results evaluated that compressive stress and shear generated in the low back (L4/L5) is a direct effect of body posture or explicitly say the impact of body segment angles while performing lifting task. According to the NIOSH tolerance limit for compressive stress in the low-back is 3400N for 95% of population 6400N for 25% (The Health Hazard Evaluation Program, NIOSH 2009). Similarly, acceptable shear loading limit was the threshold to 700 N because of the logarithmic nature of fatigue failure curve (Gallagher & Marras, 2012).

Low Back Compression Forces

From Figure 7, it can be observed that for the stoop lifting the threshold limit of 3400N for compressive stress has been reached at 20 lbs. whereas for the squat lifting, the threshold limit is attained after 35 lbs. consolidating the fact that lifting in stoop posture exerts excessive force on the low-back as the weight increases. A two-tail t-test between the compressive forces of squat and stoop lifting techniques show that the forces are significantly (p-value = 4.01E-08) different. Moreover, the compressive forces in case of stoop lifting are higher than squat lifting technique. In addition, it can be observed that there is a sudden increase in stress exerted on low-back after 20 lbs. in stoop lifting, whereas this sudden increase is observed after 35 lbs. The difference in forces concludes that performing a lifting task using squat technique will minimize the exposure towards WMSDs.

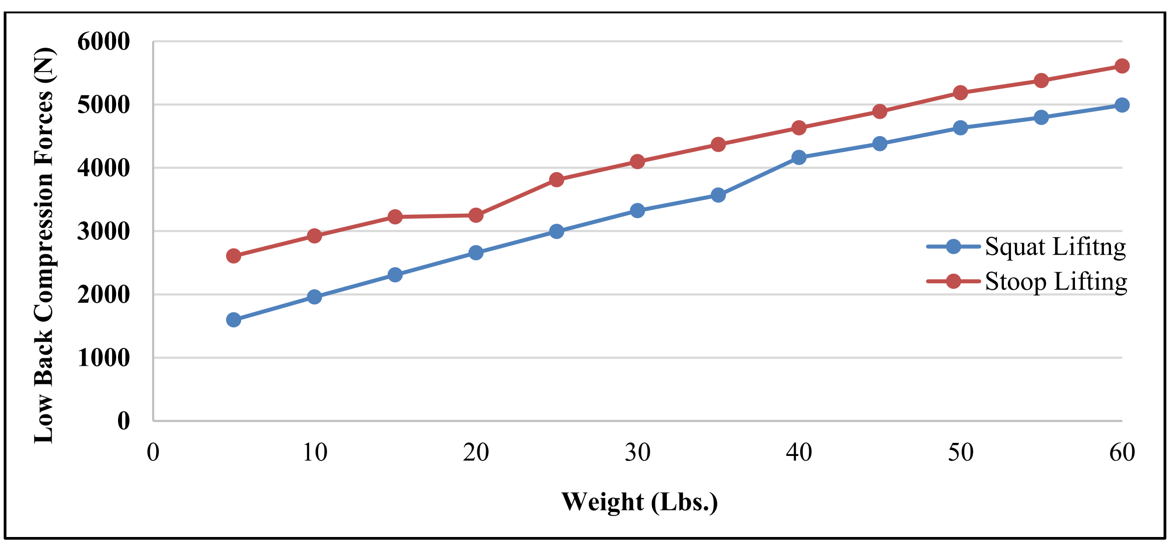


Figure 7. Low-Back Compressive Stresses versus Weight

Shear Forces

From Figure 8, it can be observed that for the stoop lifting the threshold of 700N for shear force has been reached at 35 lbs. whereas for squat lifting, the threshold of shear force is reached at 60 lbs. A two-tail t-test between shear forces of squat and stoop lifting show that the forces are significantly (p-value = 1.67E-10) different. Moreover, the shear forces in case of stoop lifting are higher compared to squat lifting. Further, the change in the threshold limiting value towards greater load in Figure 8 shows that performing lifting task in squat technique reduces the effect of shear force in the lower back. Compared to stoop technique, the shear threshold value in squat lifting arrives after 51 lbs. which is also recommended weight limit from NIOSH.

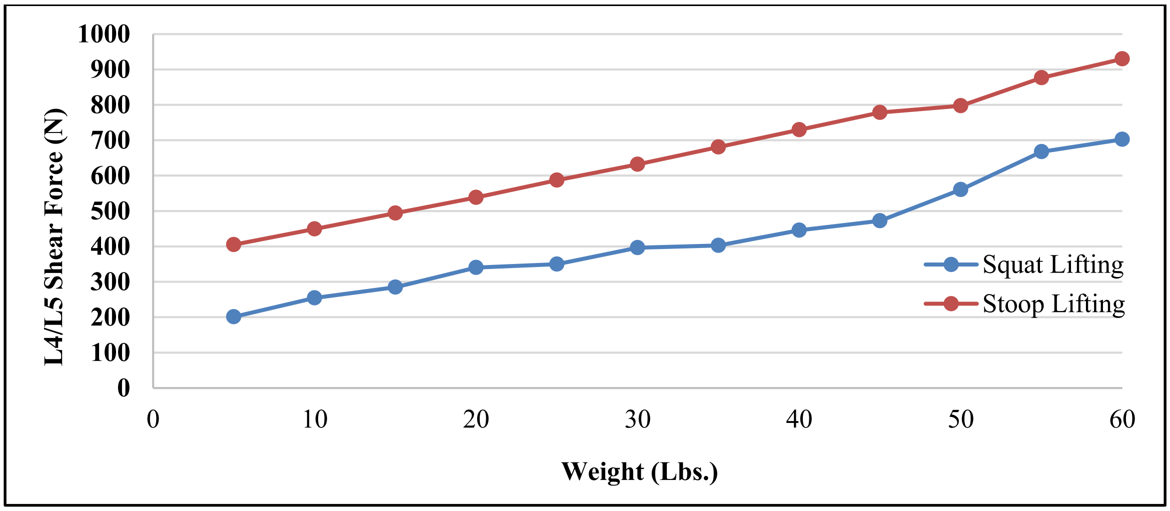


Figure 8. Shear Forces versus Weight

From the results of the case study, it was observed that compression forces and shear developed in low-back vary depending on posture and load exerted while performing the lifting task. In the construction industry workers must perform manual material lifting on a daily basis, exposing their body segment to substantial forces. Risk affiliated to WMSD is higher if the lifting task is performed with unsafe posture compared to safe posture.

This controlled environment pilot study has proved that IMU can be used as active equipment to collect construction worker's data in the field for biomechanical and ergonomic analysis. In this context, the automatic process of motion data capturing in the field provides ergonomists and safety department for evaluating potential risk towards WMSD.

The results indicate that IMU captured BVH file can be efficiently converted to specific horizontal and vertical angles that can be used in 3DSSPP software for biomechanical analysis. This procedure reduces biomechanical error affiliated to vision-based biomechanical assessment techniques such as Kinect. In nutshell reliability and practicality of the proposed process can be used to mitigate injuries related to WMSD and make the workplace safe for all construction workers.

6. Conclusion

In this paper, we have proposed a system to perform static biomechanical analysis using motion data obtained from IMUs. This study has widened the horizon for an in-depth understanding of different motion-based biomechanical data capturing techniques and computerized biomechanical model to be used for ergonomic assessment in the construction industry. Further research in automation of data transformation from the BVH file to the user-friendly platform can provide ease of individual body posture assessment.

Expanding data collection in actual field condition will provide validation for this process and deliver on-site biomechanical analysis for the construction industry. For dynamic assessment to be incorporated in this study, there should be special care taken to consider acceleration motion in the analysis. Identification of excessive musculoskeletal stresses in dynamic movement through biomechanical analysis will help to evaluate ergonomic arbitration to mitigate the risk affiliated to WMSD.

Eventually, continuous monitoring for compressive stresses and shear while performing construction task will narrow down the void between work demand and worker's capabilities. It will also deliver an affirmative improvement of workers' productivity and health in the construction industry.

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