Kinetic & Kinematic Evaluation of the Use of Stiff Form-Fitted Industrial Back Belts Using 3-D Motion Capturing System

Tamer ElAttar, Shihab Asfour, Mohamed Fahmy

Abstract—The objective of this study is to examine the effect of using a new stiff form-fitted industrial back belt on musculoskeletal stresses and movement restriction during manual material handling (MMH). The use of back belts to prevent musculoskeletal injuries has been controversial. Back-A-Line (BAL) introduced new stiff form-fitted industrial back belts that were proven to modify reaching postures during tasks requiring enhanced stability and that design was yet to be tested during tasked that required enhanced movement. A 3-D motion capturing system was used to capture trajectories and calculate dynamic properties of body joints and relative angles between body segments of participants lifting a 9kg box from floor to table. Lifting tasks had two conditions: box placed in front of participants or beside them (symmetric and asymmetric).Lifting techniques included stoop and squat lifting. Participants either wore a BAL stiff form-fitted belt, ProFlex elastic belt or no belt. Newtonian mechanics and force plates were used to calculate peak musculoskeletal stresses at body joints

Index Terms—Back injuries, Back support, Biomechanics, Lifting, Personal protective equipment, Motion Capturing.

1 Introduction

Musculoskeletal Disorders (MSDs), such as sprains or strains resulting from overexertion in lifting, accounted for 31% of the total 1.53 million cases of days-away-from-work in 2015 [43]. They are the most expensive healthcare problem for the 30-50 years old age group [53]. The lifetime prevalence of lower-back pain amongst the general population is estimated at 60–80% for industrialized countries [15]. One-fourth of all compensation indemnity claims involve back injuries, costing industry millions on top of the pain and suffering. National estimates of the direct costs of care for low back pain range from $25 to $33 billion annually [19].

Back belts were originally used in medical rehabilitation therapy and leather belts are used by athletes during weight lifting. Industrial back belts were introduced to the consumer in the 90s as a Personal Protective Equipment (PPE) to prevent back injuries. Back belts were used to stiffen the spine and improve the posture reducing the range of motion during lifting. Fifteen studies reported a reduction in trunk motion in at least one motion plane when using back belts [5], [10], [11], [12], [13], [23], [25], [26], [27], [30], [35], [37], [46], [54]. Three groups reported inconsistent results [29], [38], [44] while in two reported no effect of back belts [16], [32].

Back belts are believed to reduce the forces on the spine by increasing the intra abdominal pressure (IAP). IAP was measured in 12 studies. Eight studies reported an increase in IAP [8], [14], [22], [34], [40], [49], [60], two studies showed no effect [29], [57] and two studies reported inconsistent results [13], [42]. Seven research groups found no effect of using back belts on Electromyography EMG [3], [9], [14], [17], [22], [31], [34]. Seven studies reported a reduction in EMG [7], [12], [18], [22], [30], [56]. Four studies showed inconsistency [24], [25], [42], [55]. Physiological studies investigating back belts included heart rate (HR), respiratory frequency (RF), systolic blood pressure (SBP), diastolic blood pressure (DBP) and oxygen consumption (Vo2). Results indicate that there is no effect of belt use on HR [56], [4] [35], [32].In 1997, Soh et al [51] reported a significant effect of using belts on RF which is in disagreement with [32] and Bobick [4] who found no significant difference in both SBP and DBP. Marley [32] found no effect of belts use on Vo2, while Bobick [4] reported a significant reduction in Vo2 because subjects flexed hips more than torso.

Kraus et al. [20] reported that 36,000 employees who wore back belts had a 34% drop in injury rate. In 1998, Van poppel [45] concluded that neither belts nor education lead to a reduction in low back pain incidence for 312 workers observed. In 1994, Mitchell [39] administered a retrospective survey instrument to 1316 workers who perform lifting activities at an air force base and did not find back belts effective in preventing back injuries. Wassell [53] conducted a 2 years back belt use study for Walmart including 13,873 participants and found no evidence that back belts are a useful preventive measure. Five controlled studies found no effect of using belts as a preventive measure [1], [39], [48], [52],[57].The investigation of the effect of using back belts on total forces and moments at joints has rarely been tackled because of the complexity of the calculations and the absence of 3-D biomechanical models that efficiently calculates those forces and moments.

In summary, back belts showed contradicting effects on both IAP and EMG. Studies concluded that back belts had a little to no effect on Heart rate (HR), Respiratory frequency (RF), Systolic blood pressure (SBP), Diastolic blood pressure (DBP) and Oxygen consumption (Vo2). On the other hand, some research showed a decrease in the range of motion and improvement in the posture and thereby reduction in the range of motion during lifting. Posture is the relative position

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or attitude of the body at any one period of time. Correct posture is the position in which minimal stress is applied to body joints. Punnett et al. in 1991 [47] reported strong associations between MSDs and non-neutral postures of the back and shoulder. There is no clear reason to either accept or refute the effectiveness of back belts as a tool for injury prevention, reduction or elimination. The key is to continue investigating back belts especially new designs in the market.

Elastic, light-weight belts are the most common design on the market and in the research we reviewed. Other research of leather weight lifting belts or prescribed lumbar braces cannot compare to the industrial back belts due to design difference.

Back-A-Line Stiff form-fitted industrial back belts were introduced with a design that promises to coax the spine into better posture and providing better back support. In 2004, Smith [50] investigated the effect of Stiff form-fitted industrial back belts on reach actions. They concluded that they consistently modified reaching postures by limiting extreme ranges of motion during a task that required enhanced stability. They recommended investigating the potentialbenefits of Stiff form-fitted belts in industrial or other settings with natural work conditions and comparison against more traditional belts.

2 Methodology

The purpose of this study was to evaluate the use of two different kinds of back belts (ProFlex elastic belts and Back-A-Line stiff form-fitted belts) by a utility company crew as personal protective equipment during their daily tasks studying the effect of using the two kinds of belts on peak moments at major joints and movement restriction.

Eight adult males participated in a task that required lifting a 9kg balanced box with handles (35.6cm x 25.4cm x 35.6cm) from floor to table level (76.2cm). The stiff form-fitted belts used in the study were Back-A-Line non-stretch polyester belts with a 20 cm inner pad grooved to bridge spine and curved to promote correct posture. The elastic belts used in the study were ProFlex universal belts made of spandex elastic material with an adjustable two-stage closure system for added support and rubber-tracked webbing to keep belt in place (Figure 1). We observed the utility company's crew for 2 weeks and identified that loading /unloading of equipment on trucks is the most common repetitive daily task. We documented the main task parameters (height of back of trucks, weight of equipment, loading/unloading techniques and working conditions). The average weight of the equipment handled (transformers and tool boxes) was 12.8kg (SD=5.5).

The average height of the back of a truck was 75.4cm (SD=7.2). Based on that we determined that the task can be simulated indoors using a floor to table height (76.2cm) lifting a 9kg box with a combination of some common lifting task parameters measuring musculoskeletal stresses at shoulder, L5/S1 and knee joints and trunk movement restriction utilizing a 3-D motion capturing system to capture movement trajectories, calculate dynamic properties of body joints and relative angles between body segments during lifting tasks.

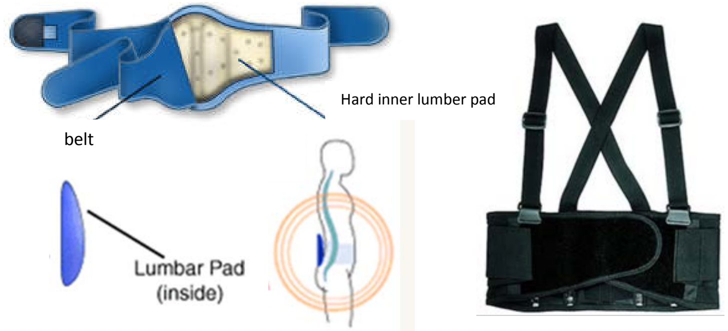

Fig. 1. Back-A-Line stiff belt (left) & ProFlex elastic belt (right)

A randomized block design was used in this study. The within-subject variables were belt (no belt, elastic belt, form-fitted belt), technique (symmetric: angle between shoulders line and pelvis is zero degrees, asymmetric: angle between shoulders line and pelvis is degrees) and posture (stoop: knees straight, back bent, squat: knees bent, back straight). The belt and lifting parameters created 12 different unique combinations (tasks). In a six hours session, each participant performed each task 5 times for a total of 60 lifts per participant with 4-5 minutes breaks between lifts and 15 minutes breaks every 15 lifts. The sequence of the tasks done by each participant was completely randomized using a random number generator spreadsheet. The resulting data matrix included 480 observations (8 participants * 3 belt conditions * 2 lifting techniques * 2 lifting postures * 5 tasks).

A three dimensional motion capturing system (Vicon) was used to capture the movement of participants. The instantaneous position of the markers placed on specific anatomical locations on the human participants were captured by 8 infra-red cameras capable of capturing up to 250 frames /sec with 1000x1000 pixels resolution used define the position of body segments and main body joints during lifting.

A generalized computerized 3 dimensional dynamic biomechanical model was used to calculate instantaneous forces and moments at body joints during lifting based on the trajectories captured by the 3-D motion capturing system and the floor force plates, all data collected was processed using Bodybuilder (data manipulation and modeling software). Participants' body dimensions, joint trajectories and force plates output were processed using Plug-in Gait program to calculate instantaneous body angles, forces and moments at joints.
Dependent variables measured where the normalized peak moments in frontal, sagittal and transverse planes recorded at body joints (Shoulders, elbows, Knees, and L5/S1), absolute peak values of trunk sagittal flexion (the angle between trunk and hip in the sagittal plan), trunk lateral angle (the angle between trunk and hip in the traverse plan) and knees angles in sagittal plan. To examine the extreme stress imposed on the seven body major joints, peak trunk sagittal flexion, trunk lateral angle and knees angles during lifts. The normalized peaks were used in the MANOVA as the dependent variable. ANOVA was then performed assessing significant effects from the MANOVA, followed by post-hoc tests (Tukey pair-wise comparisons) on significant effects from the ANOVA.

2.1 The Biomechanical Model

The human body was represented as ten segments and eleven joints in space (figure 2). The ten links and 2 dummy links (Pelvis [L3] and shoulders [L12] for programming purposes) were Left/Right lower leg, Left/Right upper leg, Left/Right lower arm and Left/Right upper arm. The eleven joints were the Left/Right ankles, Left/Right knees, Left/Right hips, L5/S1 disc, Left/Right shoulders and Left/Right elbows. The trunk was divided into two-link system separated by the L5/S1 disc (upper torso: above the L5/S1 disc and lower torso: below the L5/S1 disc).

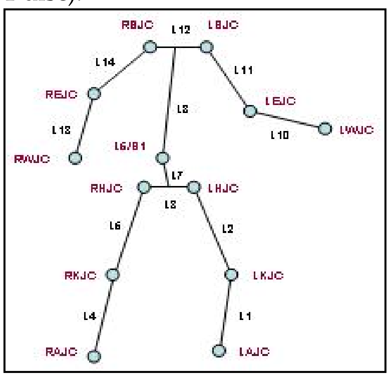

Fig. 2. The Linkage Representation used in the Model.

We used BodyBuilder (data manipulation and modeling software) to edit, modify, interpolate broken trajectories, filter and resample data, create a kinematics model from the static capture, generate kinematics angles, define joint centers using a CHORD function, capture segments and joint centers movements and calculate the linear velocity (m/s) and acceleration (m/s^2) of the i^{th} position vector in the k^{th} frame, using numerical differentiation [59].

Linked segments formed a chain containing Pelvis, Femur and Tibia, we described the movements of each segment relative to the more proximal segment. Each segment had an origin and three segment axes. The orientation of the segment was described by rotations about the origin, relative to the global frame of reference. We used Chaffin's *Static Biomechanical Modeling in Manual Lifting* (Chapter 52 in *The Occupational Ergonomics Handbook* [33] to calculate segment lengths, weights and center of gravity. Segment length were calculated as a percentage of the total body height based on standard proportions. The proportions of the two-link trunk lengths were also identified as shoulder joints to L5/S1 being 0.805 of trunk length and L5/S1 to hip joints being 0.195 of trunk length. Segment weight is defined as the effect of gravity on the mass of the body segment. The mass of the trunk links were estimated as 65.5% of the trunk mass above L5/S1 and 34.5% from L5/S1 to hip joints. Segment center of gravity was expressed as percentages of segment lengths. Radius of gyration was calculated as a percentage of a segment length about transverse axis for major joints [33]. For the location of the L5/S1 Center, we assumed all the external force and moment components were to act at or about the center of the L5/S1 disc surface "c" [6] thus it was important to identify its coordinates. Chen assumed that the transverse cutting plane is stiff and remains in the same shape throughout the trunk flexion and rotation. A reference point on the back at L5/S1 level was assumed and called "p". Point "c" was determined at a distance which was estimated as a ratio of trunk depth (about 0.4) from point "p" along the short axis of the ellipse formed by the cutting plane.

The global axes X, Y and Z, are established by the VICON calibration. Co-ordinates of global points are an ordered triplet of numbers, in the order X co-ordinate, Y co-ordinate, Z co-ordinate. Segment axes, to avoid confusion with global axes, are referred to as 1, 2 and 3, rather than X, Y and Z.

For every joint, the position, linear velocity and linear acceleration vectors were given by the Vicon motion analysis system with a sampling rate of 250 frames/second. The built-in macro calculates the linear velocity in m/s and the linear acceleration in m/s^2 of the i^{th} position vector in the k^{th} frame, using numerical differentiation based on the equation reported by Atkinson in 1989 [2], [21], [59].The angular acceleration for each segment about its proximal end was calculated by multiplying the unit vector in the direction of the segment by the linear acceleration vector perpendicular to the segment (tangential) divided by the length of the segment.

For any link i and joint j, the total reaction forces (F_j) and the total reaction moments M_j assuming dynamic equilibrium are: Total reaction forces (F_j) = Reaction forces from previous joint (F_{j-1}) + Static forces on segment i + Linear inertial forces at c.g. of segment i.

Total reaction moments (M_j) = Reaction moments from the previous joint (M_{j-1}) + Static moment of segment i + Moment due to linear acceleration effects + Moment yielded by reaction forces from joint (j-1) + Inertial moment due to rotation of link.

2.2 Procedures

Eight males from a major utility company with at least 5 years of field experience volunteered to participate in this study. Mean age was 41.5 years (SD = 2 years), the mean height was 179 cm (SD =2.54 cm) and the mean weight was 82.1 kg (SD = 2.7 kg). All Participants were informed about the experimental procedures and signed a consent form stating they were in good physical health with no history of back injuries, musculoskeletal injuries or other medical restrictions. The belts, lifting techniques and task details were explained to participants. The proper belt sizes were chosen for each participant and they were instructed on how to wear it according to the manufacturer's recommendations.

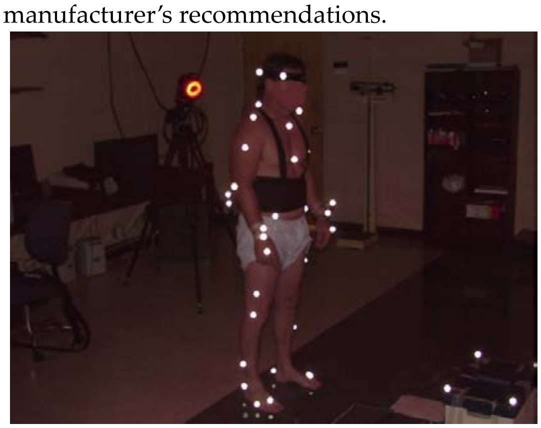

Fig. 3. Participant with markers ready to start a lifting task.

Sessions started by recording the anthropometric measurements for each participant (height, weight, leg length measured from the hip upper tip till the inner tip of the ankle), width of elbows, knees and ankles. Reflective markers with 25mm diameter were placed at specific anatomical locations recommended by Vicon systems (figure 3). The capturing volume was then defined making sure that each marker is continuously captured by at least two cameras throughout the task.

To correctly capture and measure the pelvis angle, two rear waist markers were to be positioned on the flat skin relative to the two small dimples at lower back. However, wearing a back belt made it difficult to place those markers. We designed a protruding back bracket (Figure 4), one side of the bracket was positioned relative to the two small dimples found in the bottom of the back and the other side had 3 markers defining a plane and reconstructing and incorporating a virtual marker in the position of the rear waist markers using the Vicon Bodybuilder program throughout the trials.

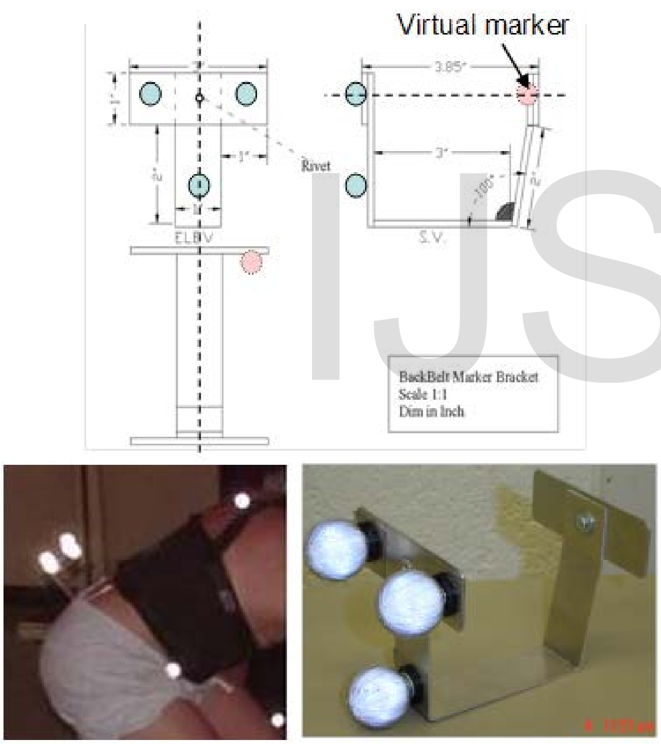

Fig. 4. The design and use of the back brackets to overcome the lower back markers problem

Static followed by dynamic calibration were done to define the origin coordinates of trials. Participants started the lift by stepping on the force plate with their right leg then moving left leg to be adjacent to the right leg, and then they performed the lift. Data reconstruction was done to derive the virtual 3D locations of the markers in each frame and to link these 3D positions between frames to form trajectories (figure 5).

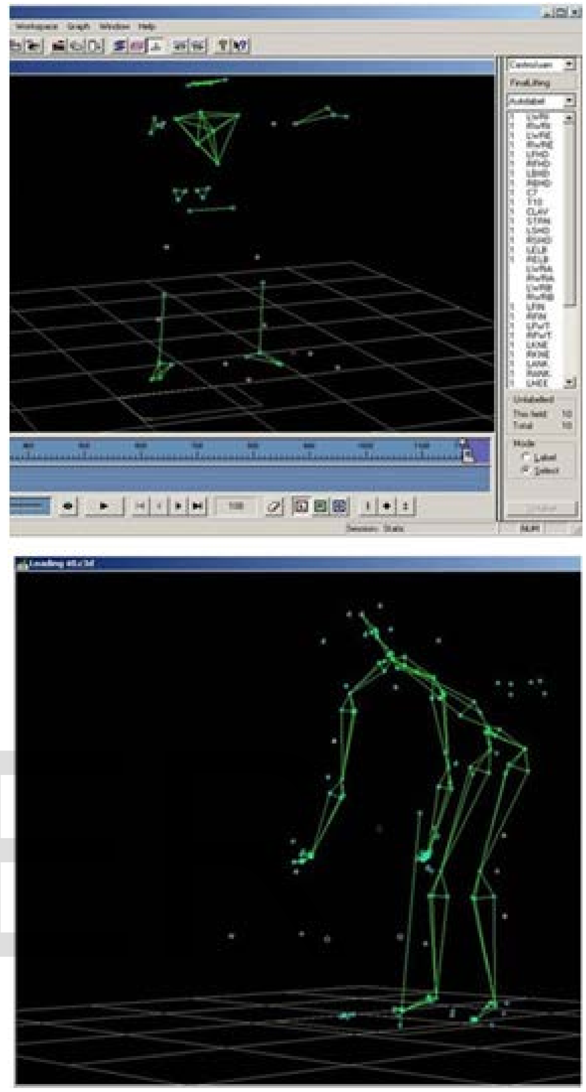

Fig. 5. Trajectories to construct 3-D Model (top). Defined segments during an actual participant lift task (bottom).

The instantaneous 3-D coordinates (X, Y, Z), linear velocity (m/s) and acceleration (m/s^2) for the body major joints during tasks were collected. The coordinates of the center of the L5/S1 disc were defined as reported by Chen in 1990 [6], the tilt angle and rotational angle were also calculated. The model calculations using plug-in gait program were done on each free body diagram using bottom-up approach starting from the ankles where the force platforms collected the reaction forces and moments, proceeding to the knees and up to the L5/Sl joint. The model then calculated instantaneous forces and moments at each major joint of the human body including the forces and moments in X, Y and Z directions.

3 Results

Examining the extreme stress imposed on the seven body major joints, MANOVA analysis showed significance of angle of twist and lifting technique. Asymmetric lifting showed significant higher peak moments at right shoulder (*M* = 45.2, *SD* = 9.3) ($F_{1,7}$=4.10, p=0.032), left shoulder (*M* = 37.4, *SD* = 7.5) ($F_{1,7}$ =11.93, p=0.017), L5/S1 (*M* = 364.2, *SD* = 24.2) ($F_{1,7}$ =5.43, p=0.020), right knee (*M* = 56.6, *SD* = 12.6) ($F_{1,7}$ =4.67, p=0.001)and left knee (*M* = 45.7, *SD* = 9.4) ($F_{1,7}$ =1.71, p=0.000) compared to symetric lifts. Stoop lifts showed significant higher peak moments at right shoulder (*M* = 34.3, *SD* = 7.6) ($F_{1,7}$=7.28, p=0.002), left shoulder (*M* = 41.1, *SD* = 8.8) ($F_{1,7}$=8.26, p=0.004), right elbow (*M* = 22.7, *SD* = 3.4) ($F_{1,7}$ =0.13, p=0.029)and right knee (*M* = 57.8, *SD* = 14.5) ($F_{1,7}$ =41.22, p=0.000) compared to squat lifts. The belts showed no significant effect on peak moments at any of the major joints.

We concluded that neither form-fitted nor elastic belts have any significant effect on the peak moments at the body joints during lifting. Asymmetric lifting showed significant higher peak moments compared to symetric lifts. Stoop lifts showed significant higher peak moments compared to squat lifts.

Trunk flexion angle is the angle of the pelvis with respect to the femur. The two dependent variables investigated were the absolute peak values of the trunk sagittal flexion and lateral angle. MANOVA results showed significance of belt ($F_{2,7}$ =28.63, p=0.000), twist angle ($F_{1,7}$ =143.08, p=0.000). ANOVA results showed significance of belt and twist angle for trunk sagittal flexion and lateral angle.

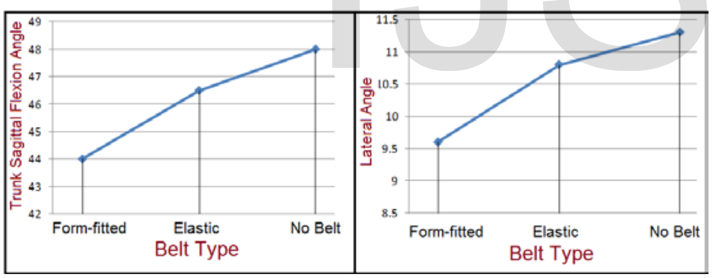

Fig. 6. The Main Effect Plots of Belt on Trunk Sagittal Flexion (left) and Lateral angle (right)

Participants wearing BAL belt bent forward the least (*M*= 44°, *SD* = 5.8°) compared to wearing elastic belt (*M*= 46.5°, *SD* = 4.3°) and no belt (*M*= 48.4°, *SD* = 6.8°). Participants wearing BAL belt bent to the side the least (*M*= 9.6°, *SD* = 1.1°), compared to wearing elastic belt (*M*=10.8°, *SD* = 2.4°) and wearing no belt (*M*= 11.3°, *SD* = 1.6°). Lifting technique analysis showed that participants bent forward more during asymmetric lifts (*M*= 49.5°, *SD* = 8.3°), compared to symmetric (*M*= 42.5°, *SD* = 7.4°). Participants bent to the side more during asymmetric lifts (*M*= 13°, *SD* = 1.7°) compared to symmetric lifts (*M* = 8°, *SD* = 1.2°).

Knee flexion is defined as the angle of the femur with respect to the tibia. We examined the absolute peak values of knees flexion in sagittal plane. MANOVA results showed that belts had no significant effect on knee flexion ($F_{2,7}$ =1.20, p=0.302). The angle of twist and had a significant on peak flexion of left knee ($F_{1,7}$ =69.76, p=0.000) and right knee ($F_{1,7}$ =4.80, p=0.029). ANOVA results showed that participants bent their right and left knee more during symmetric lifts (M_R =82.5°, *SD* = 5.9°), (M_L = 92°, *SD* = 5.5°) compared to asymmetric lifts (M_R =77.5°, *SD* = 6.7°), (M_L = 83°, *SD* = 9.5°). Type of belts had no significant effect on knee angles when performing controlled lifts. Participants bend both knees more when they are doing symmetric lifts compared to asymmetric lifts.

4 Discussion

In 1994, NIOSH [58] expressed doubts about the validity of some of the studies suggesting that back belts had a significant effect on limiting the trunk motion either because the participants that performed the experiments had limited variation in age (mostly students) and did not represent the actual population that the investigation should target; and because most of those studies were focusing on EMG and IAP measures. NIOSH criticized some of the studies because the postures and conditions were not randomized such as in McGill research in 1994 [35].Our experiments dealt with those concerns by focusing on trunk motion analysis, choosing participants that were professional MMH workers and by using an accurate 3-D motion capturing system to monitor trunk motion and to calculate accurate stresses at joins during tasks.

In 2004, Smith [50] investigated the effect of BAL back belts on reach actions and concluded that they consistently modified reaching postures by limiting extreme ranges of motion during a task that required enhanced stability. Our investigation of the effect of the use of BAL belts on trunk sagittal flexion and lateral angle showed that BAL belts led to statisticly significant restricting of both trunk sagittal flexion and lateral angle compared to elastic belts and no belts during lifting. However, this restriction; though significant; did not lead to any significant effect on the peak moments at major joints. We conclude that the motion restrictions imposed by BAL belts; although significant; are not enough to lead to any reduction in the stresses imposed on major body joints during various lifitng tasks.

Our analysis of peak moments at major joints during different combinations of symmetric/asymmetric and stoop/squat lifts supported the agreement among researchers that it is better to perform symmetric, squat lifts to yield less peak moments at body joints. Our results also showed that participants performing symmetric lifts used their legs rather than their backs (reflected in the significant increase in their knee flexion angles).

It should be noted that the use of back belts as personal protective equipment alone is not enough to protect users against injuries. The effect of belts depends dramatically on the exact type of task and its surrounding environment. Training on tasks, with or without back belts, remains a major component of back injury prevention. It must be accompanied by changes to the working conditions in order to minimize the actual number of back injuries. Most importantly, we need to evaluate and improve existing manual material handling tasks. Ergonomic risk factors, such as awkward postures and repetitive motions, should be taken into account more seriously through these evaluations.

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