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A Biomechanical Analysis of Manual Lifting Tasks Performed in Restricted Workspaces

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This paper describes the results of an experimental study aimed at evaluating the biomechanical effects of working in a spatially restricted environment on manual lifting tasks. The main objective of the study is to estimate the biomechanical loading (in terms of peak compression and shear forces) on the lumbar spine for the selected combinations of limited headroom heights and twisting angles. A three-dimensional dynamic biomechanical model was utilized to assess peak compression and shear forces at the L5/S1 lumbosacral joint. The results indicated that by reducing the headroom height, the participants were forced to stand with their trunks fully flexed forward which, by increasing the mechanical disadvantage at the lumbosacral disc, increased the compression forces. Both compression and shear forces were affected by the increase in twisting angle. The greater the twisting angle, the higher the compression and shear forces. Regression models were developed and validated, which demonstrated high accuracy of predicting the psychophysical and biomechanical lifting capacities.

manual lifting tasks restricted workspaces compression and shear forces
regression modeling

1. INTRODUCTION

Despite the growing advancement in mechanization and automation, Manual Materials Handling (MMH) activities still play an important role in the industrial and service sectors of any economy. A significant problem associated with such activities is the fact that they are the primary cause of

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overexertion injuries. The moral and economic consequences that result from pain and injury made it necessary to study and, therefore, attempt to solve such a problem. To prevent pain and injuries, the MMH tasks should be designed to take into account several risk factors related to the task being handled. One very important risk factor that contributes to injury is the workspace where the task is performed. Recent studies indicated that in many real-world industrial settings the workspace available to perform MMH activities is restricted by many factors such as space limitation, workspace geometry, and so forth.

Earlier studies of the biomechanics of manual lifting tasks have mainly considered situations where the lifting tasks were performed in unrestricted workspace. Among the different work postures, restricted (awkward) postures were found to be associated with an increased risk for injury (Punnett & Keyserling, 1987). Restricted (awkward) postures occur when there is a mismatch between a worker's body size and the job requirements. Lifting practices that involve the factors of asymmetry, limited headroom height, and restriction to access are not uncommon. Such stresses are commonly encountered in industries such as underground coal mines, warehousing, shipping and receiving, mining, moving, maintenance, department stores, and others (Kumar, Mital, Garand, & Persad, 1993). Epidemiological and biomechanical studies have found that a combination of high external load and "poor" movement patterns cause a high internal load on the spinal structure and increases the risk of pain and injury. Poor movement patterns consist primarily of bending or twisting of the trunk, or both. Bending occurs during reaching and lifting of an object from a low to a high surface. Twisting of the trunk is mostly the result of inadequate workspace. Excessive bending and twisting of the trunk have been related to higher biomechanical and physiological costs and musculoskeletal injuries (Bigos & Battie, 1991; Chaffin & Andersson, 1984). The involvement of back and abdominal muscles in lifting activity has long been established (Kumar & Mital, 1996). However, low back pain and injury problems in industry have necessitated the discovery of any lead that may enable one to control the problem somewhat.

2. METHODS

A total of six combinations of three twisting angles (30, 60, and 90° to the left) and two heights of headroom (1.2 and 1.4 m) were studied. Thirteen male participants, all are university graduate students, volunteered to participate in this study. For describing the participant's physical condition, strength tests and anthropometric measurements were collected. These data are given in Table 1.

TABLE 1. Summary of Participants' Anthropometric Data (*n* = 13)

Anthropometric measurements (cm)	*M*	*SD*
Age (years)	31.7	4.6
Weight (kg)	74.3	8.3
Stature	173.0	3.8
Shoulder height	143.1	3.0
Elbow height	106.1	3.1
L5/S1 height	96.9	3.3
Knuckle height	76.5	3.3
Knee height	50.9	2.1
Chest depth	23.6	2.0
Chest breadth	31.5	2.4
Chest circumference	92.3	4.6
Abdominal depth	22.3	2.4
Waist breadth	32.8	2.3
Shoulder breadth	44.3	2.1
Arm reach	215.4	6.0
Wrist circumference	16.6	1.0

The participants lifted the average weight they had individually selected during a psychophysical experiment (Elfeituri, 2000). They were asked to lift a tote box (38 × 38 × 25 cm) filled with sand bags from floor level to

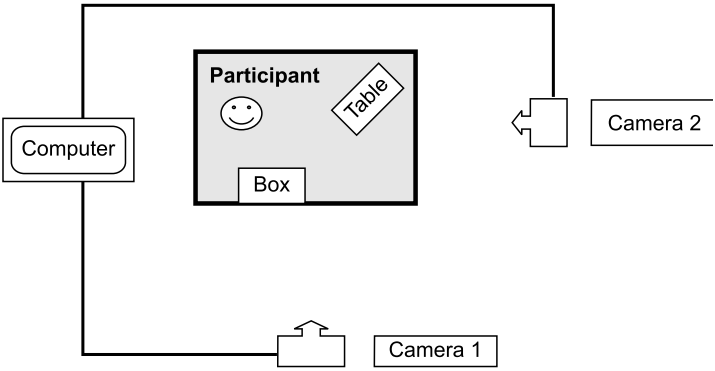

Figure 1. Experimental setup.

table 76 cm high for each of the six lifting conditions (three twisting angles × two headroom heights). Figure 1 illustrates the experimental setup. The order of the lifts for each participant was randomized. Participants were asked to wear elastic straps around selected body joints to help identify these joints during the digitizing process.

2.1. Videotaping

The Ariel Performance Analysis System (APAS; Ariel Dynamics, 1994) was used in this study. This system allowed for high precision freeze-frame video imaging with accurate single frame advance and reverse. Two video cameras placed about 90° apart were used to record the lifting tasks in order to develop a three-dimensional dynamic biomechanical model. Each participant was filmed from two different views, front view and side view, for the purpose of determining the biomechanical responses. A special photoflash, which can be viewed from both cameras, was used to generate a pulse signal to mark the beginning of the lifting action. Points of the body joints in each frame, from the beginning to the end of each lifting task, were digitized by the researcher utilizing the Ariel APAS software (Ariel Dynamics, 1994). The front and side views of each frame for each lifting task were digitized from the videotape using a high-resolution video frame grabber operating within the APAS hardware (Ariel Dynamics, USA). The positions of 16 critical joints from each view were obtained from the digitized module of APAS software. The stick figures developed from both front and side views were then combined to form a three-dimensional biomechanical model. To calculate the compression and shear forces, this model was then transformed, smoothed and fed to the A-Delta module, which was based on the formula used by Chaffin and Andersson (1984), along with the participant height, weight, number of hands lifting the load, and the weight of the box.

Klein and DeHaven (1995) have tested the accuracy of linear and angular estimates obtained from the APAS software. They found a high average reliability coefficient between the data obtained from A-Delta module and the data obtained from manual calculations. They concluded that the APAS software was shown to be valid and reliable for the required computation for the study of lifting.

2.2. Experimental Design

A randomized complete block factorial design, with blocking on participants, was used with the headroom height and twisting angle as the independent variables. The response variables were peak compression force (PCF) and peak shear force (PSF). The control variables for this part of study were the test environment (lighting, temperature, humidity, etc.), lifting box size and configuration (handles), lift distance and range, task duration, gender of participants (males only), and the weight of the load in the box. A ($2 \times 3 \times 13$) randomized block factorial design was used for the analysis of both the PCF and PSF. The Duncan Multiple Range Test (DMRT) was conducted on all significant results.

3. RESULTS

The overall mean and standard deviation of peak compression and shear forces for all six task conditions along with the results of the Duncan test are shown in Table 2. The results of analysis of variance for peak compression and shear forces are given in Table 3. These results indicated that the change in the headroom heights from 1.2 to 1.4 m had no significant effects on peak compression forces at the L5/S1 disc. The overall average of peak compression forces for both heights were 3716.8 and 3654.0 N respectively. Examining Figure 2 reveals that the beginning and the end of the lift were the points at which compression is greatest. Of these two points, the beginning of the lift exhibits the greatest compression load on the spine in both heights. This occurs because at the take-off stage, the posture would not be affected by headroom height due to deep forward flexion in preparation for lifting. However, the height of the headroom affects the participant at later stages when he raises his body to complete the lifting action. The reason for the high compression force at the take-off stage, when working under limited headroom, is that the load will be farthest from the body at that stage. As the lifting action progresses the participant held the load closer to his body until he reached for the table to place the box.

The results of this study support the findings reported by Farfan (1970) and Mirka (1988), regarding the effects of twisting angle on compression forces. They have indicated that twisting of the spine both reduces tolerance to compression and increases compression and shear forces. It was found that changing the twisting angles affects significantly the peak compression

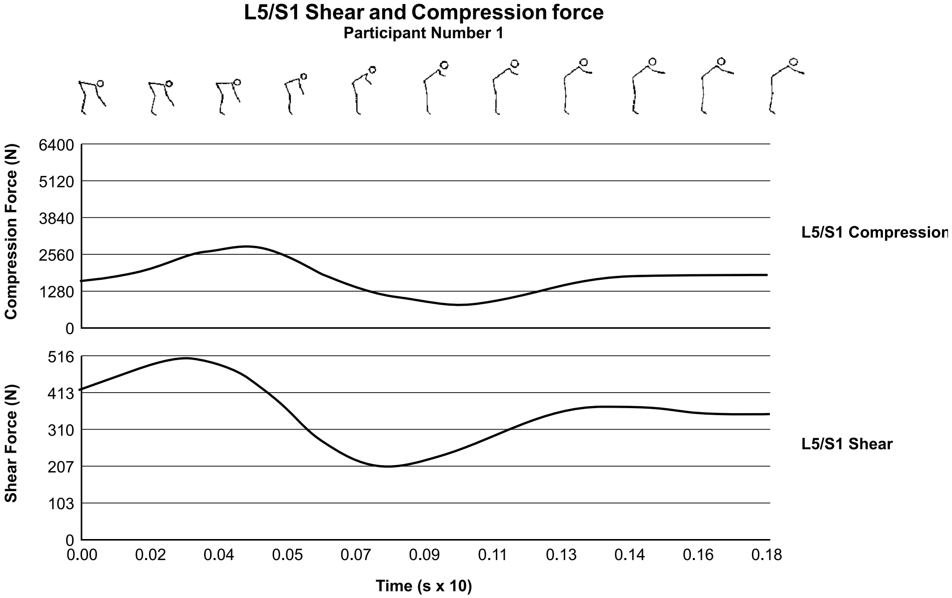

Figure 2. Curves for compression and shear forces.

TABLE 2. Overall Mean, Standard Deviation, and Duncan Test Results for Peak Compression Force (PCF) and Peak Shear Force (PSF)

	Compression Force (N)		Shear Force (N)	
Factors	***M* (*SD*)**	**Duncan Test**	***M* (*SD*)**	**Duncan Test**
Headroom height (m)				
1.2	3716.7 (605)	A	591.9 (119)	A
1.4	3654.0 (830)	A	585.3 (135)	A
Twisting angle (^{o})				
30	3530.0 (713)	A	557.6 (128)	A
60	3649.0 (685)	B	578.5 (123)	A
90	3877.2 (754)	C	629.7 (131)	B

force ($p < .01$). As the twisting angle changed from 30 to 60^{o}, the compression force increased by 3.4% (from 3530 to 3649 N), another increase of 6.3% in compression force was recorded when the twisting angle increased from 60 to 90^{o} (from 3649 to 3877.2 N). The results of the DMRT indicated that the three angles significantly differ from each other. Figure 3 shows the effects of changes in twisting angle on compression force. The compression value that has been considered to be safe for 75%

TABLE 3. Summary of ANOVA Results for Peak Compression Force (PCF) and Peak Shear Force (PSF)

	Peak Compression Force		Peak Shear Force	
Source of Variation	***F*-Value**	**Significance Level**	***F*-Value**	**Significance Level**
Main Effects:				
A: Headroom height	0.84	—	0.27	—
B: Twisting angle	8.86	**	11.55	**
C: Participants	90.11	**	100.90	**
Interaction:				
A × B	0.08	—	0.04	—

Notes. **—significant at 1%.

of female workers and 99% of male workers is a compression force of 3400 N (Waters, Putz-Anderson, Garg, & Fine, 1993). In the present study, the compression force in 45 of the 78 total test conditions (57.7%) exceeded this suggested criterion. Only 5 of the 13 participants had overall average of peak compression forces that are less than the 3400 N criterion.

Compared to compression, shear loading on vertebral structures has received little recognition as a potential mechanism for low back injury or pain. However, there are a few studies that provide hints to the contrary. McGill, Norman, Yingling, Wells, and Neumann (1998) suggested a maximum permissible limit (MPL) of 1000 N of lumbar spine shear force and an

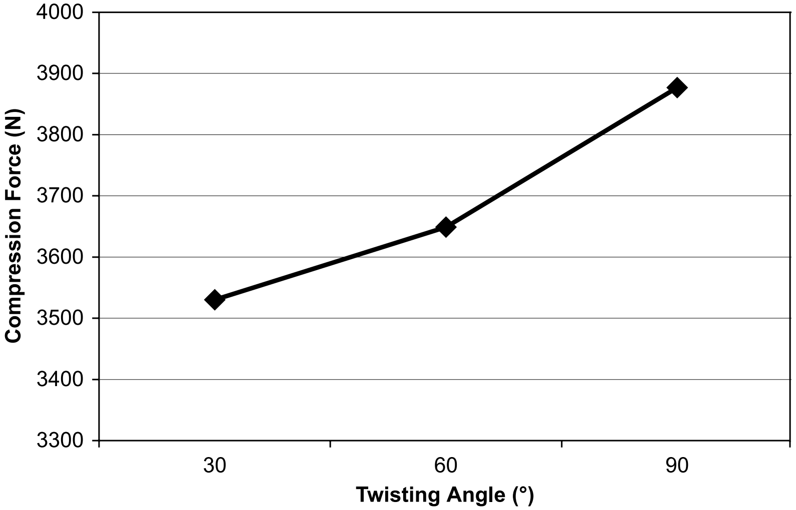

Figure 3. Effects of twisting angle on compression force.

action limit of 500 N. Even though no standards have been agreed upon for the shear force, the aforementioned estimate reported by McGill et al. (1998) will be used for the purpose of comparison with the results of this study. Among the shear force data in this study, 47 of the 78 total test conditions (60.3%) exceeded the suggested 500 N action limit and 3 values (approximately 4%) exceed the 1000 N maximum permissible limit. As in the compression force case, only 5 of the 13 participants had an overall average of peak shear forces that are less than the 500 N criterion.

As with the compression forces, the change in the height of headroom did not significantly affect peak shear forces at the L5/S1 disc ($p < .05$). The overall means of peak shear forces were 592 and 585.3 N at headroom heights of 1.2 m and 1.4 m respectively. Figure 2 shows that the greatest peak shear force on the spine occurs at the beginning of the lift where the participant is in a deep bending posture (the take-off stage). The headroom height did not affect the movement of the participants at this early stage, as enough room is available for the participant to move their backs while starting the lifting action. The load at this early stage of the lift is farthest from the body and hence resulted in the greatest shear forces.

It was found that the change in twisting angle significantly affected peak shear forces ($p < .01$). A change in twisting angle from 30 to 90° resulted in an increase in the shear force by 12.9% (from 557.7 to 629.7 N), whereas a change from 60 to 90° in twisting angle resulted in an 8.8% increase in

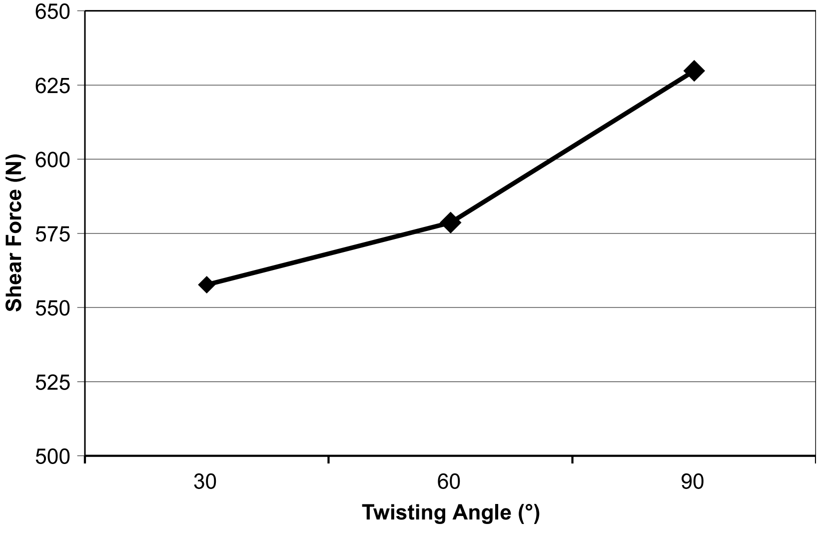

Figure 4. Effects of twisting angle on shear force.

shear force (from 578.6 to 629.7 N). However, no significant difference was found between shear forces for a change in twisting angle from 30 to 60°. The effects of changing the twisting angle on the shear forces are depicted graphically in Figure 4.

Comparing the compression and shear forces reported in this study to the aforementioned criteria (3400 N for compression and 500 N for shear forces), it is clear that working in restricted workspaces, where the participants have to bend deeply and twist their trunks, puts a greater stress on the worker in terms of the substantially high compression and shear loads on the low back.

4. REGRESSION MODELS

4.1. Overview

Statistical models were developed to predict the compression and shear forces of male workers using strength variables, anthropometric data, and task characteristics (headroom height and twisting angles). The SPSS package (SPSS, 1993), especially the stepwise procedure was used to develop regression models and residual plots.

For developing the models, determination of final models was made according to the principles of Simplicity, Representation of variables, and Goodness in statistical characteristics.

As the total number of the candidate variables is large, scatter diagrams showing possible relationships between the dependent variables and each of the candidate independent variable were utilized as a primary tool for choosing potential variables that appear to have a certain degree of relationship.

4.2. Prediction Models of Compression and Shear Forces

Regression models for peak compression and shear forces developed from the data of the biomechanical experiment. The stepwise procedure was utilized including only the main effects of the experiment: twisting angles, which were found to be statistically significant from ANOVA results, as a predictor along with selected participants' anthropometric and strength variables chosen previously in the modeling of lifting capacity using 10 of the 13 participants who were involved in the experiment.

The following two models were developed to predict peak compression and shear forces:

$$\text{PCF} = -8891.6 + 162.7 * \text{BW} + 57.9 * \text{TW} + 56.7 * \text{STAT} + 28.87 * \text{BS} \quad (R^2 = .92)$$

$$\text{PSF} = -2331.2 + 31.6 * \text{BW} + 12.0 * \text{TW} + 12.64 * \text{STAT} + 3.1 * \text{BS} \quad (R^2 = .89)$$

where PCF—peak compression force (N), PSF—peak shear force (N), BW—body weight (kg), TW—twisting angle ($^{\circ}$), STAT—stature (cm), BS—back strength (kg).

The resulting models showed that BW, TW, STAT, and BS were good predictors of both peak compression and shear forces.

4.3. Validation and Testing of the Models

Because of the lack of past references for lifting tasks under restricted workspaces, all the models developed were tested using the residual plots as well as data from the remaining 3 participants. No general trend was found in any of the residual plots; therefore, these models were judged as appropriate. No special pattern or trend was found in the residual plot of all the regression models. Data from the remaining 3 participants were used to validate the regression models. A paired *t* test was conducted to examine the difference of the predicted and observed values. The results showed that there is no significant difference between the predicted and the observed values for all the models developed in this study. The predicted versus the observed values for data obtained from the 3 participants that were used to validate the aforementioned models for peak compression force and peak shear force are shown in Figures 5 and 6 respectively. It is clear from these figures that strong correlations do exist between the predicted and the observed values. Also, no indication of unusual observations or outliers can be detected from these figures. Therefore, these models can be used reliably to predict peak compression and shear forces for lifting tasks performed under similar task conditions. The models for peak compression and shear forces also show a good predictability. R^2 values showed a good fit to the data set and could provide a good predictive model. One disadvantage common to the aforementioned models is the fact that a small sample size

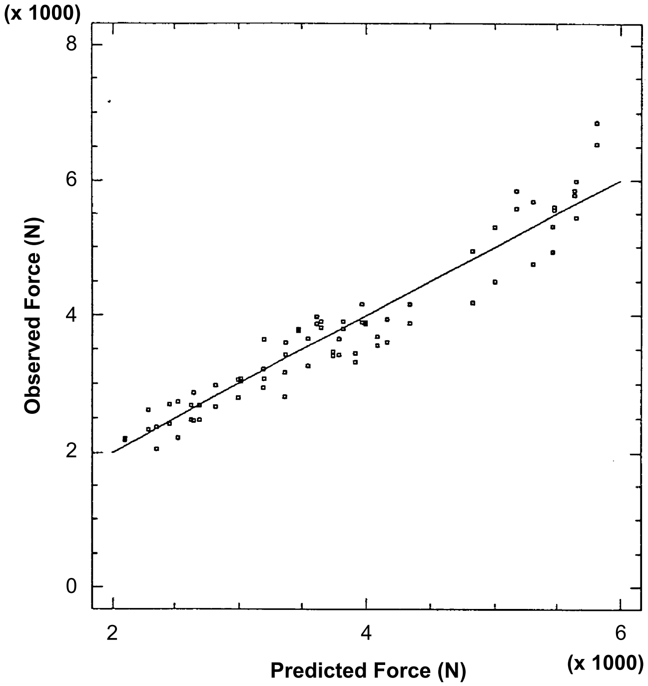

Figure 5. Predicted versus observed values for compression forces.

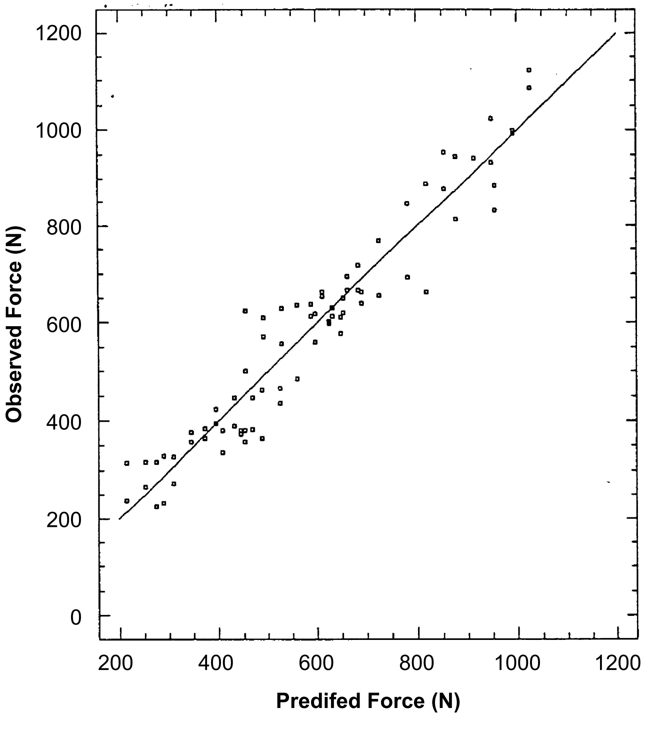

Figure 6. Predicted versus observed values for shear forces.

(10 participants) was used for model development in this study. Therefore, for the best-predicted results, these models should be applied within the range of the independent variables of this study. In another words, as a small sample size was used for developing the two models, the application of these models should be used with caution outside the range of the variables used for model development.

5. DISCUSSION

Both headroom heights used for this study would appear to have considerable biomechanical disadvantages. Clearly by reducing the headroom height, the participants stood with forward flexion that, by increasing the mechanical disadvantage at the lumbosacral disc, increased the compressive and the shear forces. The overall average peak compression forces at the two roof heights were 3717 and 3654 N respectively. Such forces are considered high when compared to the existing criterion of 3400 N. The same conclusion applies to peak shear forces, which averaged 592 and 585.3 N for the two roof heights. However, neither the compression nor shear forces were significantly affected by the change in headroom heights.

The results have revealed that both compression and shear forces are significantly affected by twisting angle. A change in twisting angle from 30 to 90^o caused a 9.8% greater disc compression with peak shear forces changed by as much as 12.9%. The increase in compression and shear forces while twisting was due to the increased lateral bending moments (Kumar, 1999) It would seem fairly consistent for individuals to exhibit lower lifting capacities in postures purported to have substantially greater biomechanical stresses.

The effect of twisting on peak compression forces seems to be a controversial issue in the literature. Kromodihardjo and Mital (1987) have reported a decreased compression force for tasks performed at a twisting angle of 90^o (asymmetric lifting) as compared to tasks performed in the saggital plane (symmetric lifting). Gallagher and Hamrick (1994) concluded that no significant differences in peak compression forces were found between symmetrical and asymmetrical lifting tasks. On the other hand, Mirka (1988) and Kumar (1999) have reported greater disc compression forces for asymmetric lifting than for symmetric tasks. One possible reason of this controversy is that different biomechanical models were developed for particular task settings, which may not give accurate results for all task conditions. It can be argued that twisting the spine led to higher stresses on the low back and, therefore, increased the biomechanical stresses. It had been indicated by Farfan (1970) and Mirka (1988) that twisting the spine both reduces tolerance to compression and increases compression and shear forces.

The regression models for peak compression and shear forces required inputs including body weight, stature, twisting angle, and back strength. The models explained 91.5 and 89% of peak compression and shear forces variances respectively. Previous models for predicting compression forces (e.g., Potvin, Norman, Eckenrath, McGill, & Bennett, 1992) included, in addition to body weight, the weight of the load. In this study, the weight of the load was controlled, for each participant, over all task conditions.

Back strength, rather than other strength variables, was included in both models as a predictor for peak compression and shear forces. This is expected as back strength was found to be highly correlated to compression and shear forces. Moreover, body weight and stature were the limiting factors among all anthropometric variables. This is anticipated as the weight of both the load and the body as well as the moment arm from the load to the L5/S1 affect compression and shear forces.

Both of the models developed in this study have a very important advantage over previously developed models in that all the variables required to construct these models are very easy to obtain. Body anthropometry and static strength measurements require simple weight scale, a tape measure, and a force readout unit. Moreover, the models developed comply with the principle of model simplicity both in construction and applicability.

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