Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
Clinical Biomechanics 20 (2005) 254–263
CLINICAL BIOMECHANICS
www.elsevier.com/locate/clinbiomech

Differentiating lifting technique between those who develop low back pain and those who do not

Allan T. Wrigley [a,*], Wayne J. Albert [a], Kevin J. Deluzio [b], Joan M. Stevenson [c]

[a] *Human Performance Laboratory, Faculty of Kinesiology, University of New Brunswick, P.O. Box 4400, Fredericton, NB, Canada E3B 5A3*
[b] *School of Biomedical Engineering, Dalhousie University, Halifax, NS, Canada*
[c] *School of Physical and Health Education, Queen's University, Kingston, ON, Canada*

Received 11 August 2004; accepted 15 November 2004

Abstract

Background. No research to date has been able to discriminate differences in lifting technique for healthy individuals who eventually develop low back pain compared to those that do not while employed in a manual materials handling industry. The purpose of this study was to demonstrate the ability of principal component analysis to identify differences in lifting technique.

Methods. Principal component analysis was applied to sixteen kinematic and kinetic waveforms describing the two-dimensional motion of the trunk and load. The principal component scores for each variable were used as the dependent measures in a one-way ANOVA to determine group differences.

Findings. Significant group differences ($P < 0.05$) were found for five of the principal component scores capturing associated kinematic waveform patterns related to the control and placement of the box on the shelf, and associated kinetic waveform patterns related to the relative timing of extension moment generation in the sacral and thoracic regions. A related waveform pattern for trunk compression was also found.

Interpretation. Due to the coordinated movements involved in tasks such as lifting, differences among clinical populations have been difficult to demonstrate empirically. We were able to identify different characteristics in lifting kinematics and kinetics prior to the development of low back pain. Principal component analysis was able to identify important biomechanical differences where traditional analyses failed. This is the first study to identify such lifting differences prior to the development of low back pain.

Keywords: Principal component analysis; Movement patterns; Low back pain

1. Introduction

In manual materials handling (MMH) industries, it has been shown that the majority of over-exertion injuries occur as a result of lifting tasks, which have also been identified as one of the leading causes of low back pain (LBP) (NIOSH, 1991). Considering the cost in man-hours, rehabilitation, and the chance of reoccurrence, prevention of LBP has been a major focus in workplace education and job design (Gundewall et al., 1993; Kim and Chung, 1995; Mooney et al., 1995; Potvin and Norman, 1993). From an occupational biomechanics perspective, the load, frequency, and duration of the lift are often assessed in relation to the method (technique) of lifting, raising a number of associated challenges. First, the term technique is synonymous in the literature with lift posture (stoop versus squat), strategy, pattern, and coordination (Kjellberg et al., 1998), providing obscurity in the definition. Secondly, since lifting involves a number of mechanisms

* Corresponding author.
E-mail address: allan.wrigley@unb.ca (A.T. Wrigley).

0268-0033/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2004.11.008

and is a very complex task (Hsiang et al., 1997), segment kinematics, kinetics, and electromyographic patterns are required to track the coordinated pattern and individual variations rather than simply characterizing the technique by the starting lift posture (Hamill and Knutzen, 1995; Khalaf et al., 1999; Kjellberg et al., 1998). Thirdly, the large amount of biomechanical data required to accurately describe and analyze lifting technique is particularly challenging for researchers.

Although lift posture, described by changes in knee and trunk position, has been used to illustrate both differences between novice and experienced lifters (Gagnon et al., 1996) and changes during fatiguing conditions (Sparto et al., 1997), it is limited as a descriptor. It has been clearly shown that lifting performance can vary considerably despite using similar lifting methods even when the lifting task is constrained (Albert et al., 1999; Garg et al., 1983; Hsiang and McGorry, 1997; Leskinen et al., 1983; Troup et al., 1983). Furthermore, parameter-based methods have been employed to explain biomechanical differences in lifting technique between controls and LBP with varied success. Larivière et al. (2002), for example found no differences in the lifting technique between a chronic low back pain group and control group using a parameter-based approach, but their study revealed that differences in muscle activation were present. This suggests the need for electromyography-driven models to explain the coordination of the lift pattern. Similarly, another study utilizing a parameter-based approach was unable to discriminate between the lifting techniques of healthy experienced lifters, over 50% of which developed LBP within a two-year period (Albert et al., 1998). In their award winning paper, Marras et al. (1993b) on the other hand, were able to classify the motion characteristics of over 500 subjects as either normal or belonging to one of ten low back disability groups with success rates ranging between 16% and 100% depending on the disorder. Their discrimination model used seven parameter-based variables associated with velocity and acceleration of trunk movement.

These results begin to explain the complexities of the lift, but have reduced the lifting data by extracting summary statistics or events (mean, maximum, range, time in the lifting cycle of these parameters) to describe the lift. The disadvantages of this approach are that the descriptive measures must be chosen a priori and the temporal characteristics of the trajectory may be lost, reducing the sensitivity of subsequent hypothesis testing (Khalaf et al., 1997, 1999; Rice and Silverman, 1991). The need to coordinate upper and lower extremities in a synergistic manner makes lifting a complex task requiring robust analysis techniques for assessment of the entire lifting profile. The coordination of movement implies proper timing; therefore, temporal information is needed in the analysis. Gait research has recognized the advantages of methodologies that assess the entire waveform, reducing the information needed to accurately describe normal and abnormal gait patterns (Deluzio et al., 1997; Wooten et al., 1990). In the lifting literature, Khalaf et al. (1999) have used principal component techniques to determine the variability in kinematic and kinetic lift characteristics such as: angular position, velocity, acceleration and net torque profiles for the ankle, knee, L5/S1, shoulder and elbow joints to describe different lift techniques, lift speeds, and lift loads. Furthermore, the concept of motion signatures characterized by trunk flexion/extension velocity and acceleration (Marras et al., 1993b; Marras et al., 1993a) and principal patterns of variation in electromyography (EMG) waveforms from specific muscles (Hubley-Kozey and Vezina, 2002; Larivière et al., 2000) have been advocated as a means of identifying lower back disorders in clinical populations.

However, no research to date using either a parameterization approach or waveform analysis techniques has been able to discriminate differences in lifting technique for healthy individuals who eventually develop LBP compared to those that do not while employed in a MMH industry.

Therefore the purposes of this study were: (1) to explore the use of a principal component analysis in discriminating lifting motion patterns of healthy experienced lifters who do and do not develop low back pain; and (2) to compare the principal component analysis (PCA) approach to a traditional parameter-based approach.

2. Methods

2.1. Sample data set

The analyses presented in this paper were conducted on data extracted from the Queen's DuPont Low Back Pain Research Study (QDLBPS) database (Stevenson et al., 2001). In 1995, 149 healthy employees (35 females, 114 males) from a nylon production plant volunteered to be monitored for LBP development during the proceeding two-year period. Health and LBP status were monitored every six months with the Health & Lifestyle questionnaire (Stevenson et al., 2001) and the Oswestry Low Back Disability Scale (Fairbanks et al., 1980). Employees were included in the study if they were considered healthy as operationally defined by them: (1) having no previous history of LBP; or (2) having had LBP in the last 2 years that did not require them to seek medical attention or to change their activities. Over 87% of the participants had Oswestry Low Back Disability scores less than 20, indicating minimal disability (Fairbanks et al., 1980).

Measures related to lifting technique, physical measures, and health and lifestyle variables were collected at the onset of the study. The battery of physical measures included erector spinae muscular endurance (Biering-Sørensen test), quadriceps strength (maximum voluntary contraction for seated knee extension), quadriceps endurance (endurance time for 50% maximum voluntary contraction in seated knee extension), abdominal muscle endurance (curl-ups), hamstring flexibility (straight leg raise angle) and trunk velocity (during a trunk flexion/extension test). To assess lifting technique, five freestyle sagittal plane lifts were performed at three separate box weights (5, 15 and 25 kg) through a lift envelope from the floor to shoulder height. A FASTRAK™ motion system (Polhemus Inc, Colchester, VT, USA) was used to monitor the lifting motion with electromagnetic sensors placed on the wrist, T1 and L1 spinous processes, and the L5/S1 intervertebral space. Each sensor provided 6 degrees of freedom (x, y, z displacement and yaw, pitch, and roll orientations). The sensor placement permitted the assessment of lumbar kinematics and kinetics using a previously developed dynamic 2D link segment (Albert et al., 1998). The sensors at each of the spinous processes provided information on the motion at the thoracic, lumbar, and sacral levels respectively. The wrist sensor was used to define the forearm and the location of the box. Segment determinations were a result of translations from the sensors. Moments at the L5/S1 level were calculated using standard rigid body mechanics using Winter (1990) anthropometric tables to calculate centre of mass and radius of gyration locations for each segment in the model.

The present investigation focused on the results of the 15 kg sagittal lifts in order to assess differences in lifts performed by healthy male workers ($n = 50$) who remained as such over the follow-up period versus those that developed mild LBP ($n = 58$). Sixteen kinematic and kinetic waveforms describing the two-dimensional motion of the trunk and box and 17 discrete measures describing the anthropometrics and strength characteristics of the sample were extracted from the database (Table 1) based on previous empirical evidence as to their relevance in discriminating between lifting techniques (Kjellberg et al., 1998). The waveforms, which represented the ensemble average of five lifting trials, were normalized to 51 time points from beginning to end of the lift, and are referenced to the proximal vertebrae about which vertebral joint interface the kinematic and kinetic measures were determined (i.e., L5/S1 = S1; T12/L1 = L1; C7/T1 = T1). The filtering and extraction of data resulted in the inclusion of 50 control and 58 LBP subjects. Visual inspection of all waveforms was utilized in order to determine the applicability of parameterization into peak, time to peak, minimum, time to minimum, and mean values. Forty-eight parameters commonly used for summarizing temporal data were created. The 48-waveform parameters along with the 17 discrete measures were entered into a one-way ANOVA in order to determine if there were any significant group differences ($P < 0.05$).

Table 1
Variables selected for analysis based upon criteria of males lifting 15 kg mass

Waveform variables	Discrete variables
Box vertical velocity	Leg raise left
Box vertical acceleration	Leg raise right
T1 extension displacement	Leg strength (mV)
T1 extension velocity	Leg strength (N)
T1 extension acceleration	Leg endurance
L1 extension displacement	Curl-ups
L1 extension velocity	Back endurance
L1 extension acceleration	Initial lumbar posture
S1 extension displacement	Initial thoracic posture
S1 extension velocity	Initial sacral posture
S1 extension acceleration	Lift time
T1 extension moment	Age
L1 extension moment	Height
S1 extension moment	Weight
Trunk compression	Mean vertical trajectory of box
Trunk shear	Maximum vertical trajectory of box
	Minimum vertical trajectory of box

2.2. Waveform analysis technique

Principal component analysis was applied to the 16-waveform variables from both groups. This allowed for the assessment of both amplitude and relative timing differences of waveform trajectories over the entire lift time. Briefly, a collection of matrices consisting of complete waveforms normalized to 51 time points were created. Each matrix was set-up such that every subject's waveform data was entered as a row vector with dimensions 1×51. The first 50 rows consisted of the control group's data, and the last 58 rows were the LBP group's data. The process yielded 16 matrices, each with the dimensions 108×51. All waveform data was transformed into principal components using an eigenvector analysis of the covariance matrix. Each eigenvector represented a principal component, and the associated eigenvalue the amount of variability captured. The set of eigenvalues were scaled to the percentage of total variation captured. The number of principal components retained for comparison (k) was determined using parallel analysis (Jackson, 1991). Parallel analysis involves the creation of a 108×51 matrix of normally distributed random values that are transformed into principal components using the same methodology outlined for the 16 waveform variables. A SCREE plot of the scaled eigenvalues obtained for a single variable was created with a line plotted representing the scaled eigenvalues from the random data set. Any eigenvalues that fell above the plotted line were retained as they represented principal components that captured a greater amount of variability than would be expected by chance. An example of

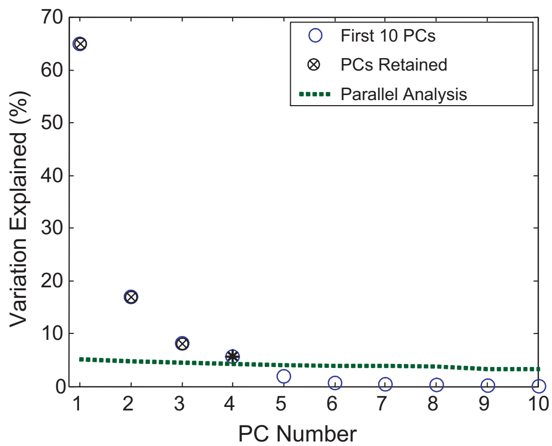

Fig. 1. Parallel analysis applied to the scaled eigenvalues of the first 10 principal components (PCs) for box vertical velocity (○). The broken line (■■■) represents the scaled eigenvalues of principal components from a data set of normally distributed random numbers. The associated principal component for each eigenvalue that lies above the line was retained for analysis as they represented principal components that captured a greater amount of variability than would be expected by chance.

parallel analysis applied to the box vertical velocity variable is shown in Fig. 1. In order to assess how well the retained principal components represented the original data, the sum of squares of the residuals comparing the predicted data set using the *k* principal component scores and *k* principal components with the original data was calculated and compared to the associated critical value (Jackson, 1991).

Of particular interest were the principal component scores for the two groups. Principal component scores provide a measure of distance indicating how closely each waveform conforms to the mode of variability captured by each principal component, and were calculated by projecting the original data points into the new coordinate space defined by the *k* principal components. A positive principal component score indicates that the associated waveform will deviate by adding to the average waveform when the principal component coefficient is positive, subtract when the principal component coefficient is negative, and vice versa. As indicated by Larivière et al. (2000), the most challenging task is to find the association between the results from PCA with the clinical status. For assessing the difference between the groups, the principal component scores represent the distance and direction whereas the principal components represent the location in the lift (Deluzio et al., 1997). It is also possible to determine where in the lifting cycle a particular principal component loads the greatest by scaling it to the proportion of variability accounted for. By examining the sign of the principal component scores and principal component coefficients along with the principal component scaled to the proportion of variability accounted for, it is possible to visually extract curves from the original dataset illustrating the mode of variation captured. The process involves selecting curves that correspond to a particular principal component score/principal component coefficient relationship within the portion of the lifting cycle where the principal component loads the greatest, and plotting them along with the mean curve. Two waveforms are selected to demonstrate the mode of variability clearly. All matrix calculations were performed using custom software written in MatLab (release 12.1, MathWorks Inc.).

A test of normality (Shapiro–Wilk) and of equality of covariance matrices (Box's Test of Equality of Covariance Matrices) revealed that the assumptions of multivariate normality and equality of variances for a MANOVA could not be met. Therefore, one-way ANOVA's with Bonferroni adjustment for multiple comparisons were utilized to analyze those principal component scores which were normally distributed with equal covariance matrices, while the Kruskal–Wallis Test was utilized to analyze those principal component scores which could not meet these assumptions in order to determine if there were any significant group differences ($P < 0.05$). All statistical tests were performed using SPSS for Windows (Release 10.0.5 SPSS Inc).

3. Results

3.1. Parameterization

No significant group differences ($P < 0.05$) were found with respect to the set of waveform parameters. Significant group differences ($P < 0.05$) were found for four of the discrete measures, with descriptive data presented in Table 2. Inspection of knee and trunk angular positions indicated that both groups used lift postures ranging between squat and stoop methods.

3.2. Waveform analysis

The number of principal components retained for each waveform variable ranged from two to six, and accounted for an average of 94.02% (range 87.08–98.46%) of the variance in the datasets. Residual analysis (Jackson, 1991) of the retained principal components and principal component scores revealed that the original dataset was adequately represented for an average of 94.44% of the participants, indicating that the principal components captured the key features within the waveforms. Significant group differences ($P < 0.05$) were found for five of the principal component scores. Descriptive data for the significant differences are presented in Table 2.

The mode of variation captured by box vertical velocity principal component four (Fig. 2a) represents

Table 2
Group descriptive data for variables found to be significantly different ($P < 0.05$)

Variable	Control		LBP		P^*
	Mean	SD	Mean	SD	
Discrete measures					
Age (years)	35.08	7.94	31.67	6.84	0.018
Lift time (s)	1.76	0.29	1.93	0.29	0.042
Mean box vertical trajectory (m)	0.70	0.06	0.72	0.04	0.011
Maximum box vertical trajectory (m)	1.18	0.07	1.22	0.07	0.029
Principal component scores					
Box vertical velocity PC4	−0.08	0.30	0.07	0.35	0.018
T1 extension acceleration PC6	−34.83	164.78	30.02	124.61	0.022
T1 extension moment PC3	7.67	34.66	−6.61	37.10	0.042
S1 extension moment PC2	−21.88	72.52	18.86	78.61	0.006
Trunk compression PC2	−6.04	29.05	5.20	28.34	0.018

Principal component labels have been abbreviated to PC#, where # denotes which principal component score had a significant group difference.
* Significance for all variables except T1 extension acceleration PC6 determined using one-way ANOVA with Bonferroni adjustment for multiple comparisons. A significant group difference for T1 extension acceleration PC6 was assessed with the Kruskal–Wallis test.

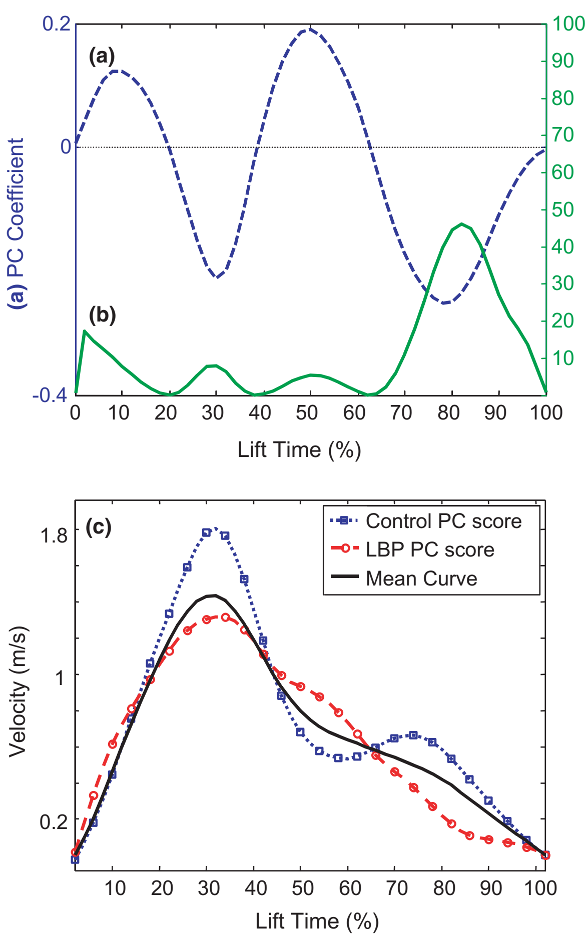

Fig. 2. Box vertical velocity principal component four plotted in the original form (a) and as the percentage of variation explained (b). Of particular interest is the region from approximately 65% to 100% of the lift time. To illustrate the mode of variability captured, the mean curve along with waveforms that corresponded to Control and LBP principal component scores (c) were plotted. Principal component labels have been abbreviated to PC.

a magnitude operator and accounts for 5.73% of the total variance. When plotted in this form, it is evident that the significantly different pattern of variability exists in four distinct regions. By comparing the sign of the principal component score (Table 2) and principal component coefficients (Fig. 2a), it appears that the control group will have a pattern of lower (0–20%), higher (20–38%), lower (38–62%), and higher (62–100%) box vertical velocity than the LBP group over the lift time. In order to assess the relative importance of principal component coefficients, box vertical velocity principal component four was scaled to the percentage of variation explained and plotted in Fig. 2b. As Fig. 2b shows, the majority of the variability captured by the principal component concentrates between 70% and 100% of the lift, with a little over 45% of the total variability accounted for at 83% of the total lift time. Therefore, box vertical velocity principal component four accounts for a magnitude difference near the end of the lift. In order to illustrate the mode of variability captured, representative curves for mean, control, and LBP principal component scores were extracted and plotted in Fig. 2c. Although the representative curves in Fig. 2c reveal an interchanging pattern in relative box vertical velocity between the groups, it is critical to reiterate that box vertical velocity principal component four concentrates on the region between 70% and 100% of the lift, where the control group increases the velocity of the box. The control group appears to perform a wrist change-over where the vertical velocity of the box was briefly increased in order to thrust the arms out to the shelf for placement, whereas the LBP group demonstrated a progressive decline in box vertical velocity from the peak value. The other discrepancies between the waveforms represent regions that account for less than 20% of variation at the start of the lift, and less than 10% of the variation at 30% and 50% of the lift time.

T1 extension acceleration principal component six accounts for 4.20% of the total variance and represents a difference operator. Fig. 3a reveals six fluctuations within the mode of variation, but is much clearer when plotted as the percentage of variation explained across the lift (Fig. 3b). The magnitude difference being captured exists in two distinct regions during the last half of the lift. Roughly 45% and almost 30% of the variation is explained around 65% and 88% of the lift respectively. Fig. 3c shows that the negative principal component score and negative principal component coefficient results in the control group having a higher T1 extension acceleration in the first region and a lower T1 extension acceleration in the second region where the principal component coefficient is positive. This difference operator quantifies the difference in the waveforms at specific periods of the task, and is likely related to the box vertical velocity patterns and a difference in motor control strategies employed to control and place the box on the shelf.

A phase shift is captured by T1 extension moment principal component three and accounts for 8.09% of the total variance. As Fig. 4a shows, the positive principal component score for the control group will cause their waveforms to add to the average waveform until around 25%, subtract from around 25–65%, and finally add again for the rest of the lift time causing a curve shift to the right. The shift in the waveforms will be noticeable between 25% and 65% of the lift time as shown in Fig. 4b. The representative curves plotted in Fig. 4c display the mode of variability quite clearly. The control group is able to delay the contribution of a thoracic extension moment which results in a decreased relative amount of time spent at peak loading.

Both S1 extension moment principal component two and trunk compression principal component two

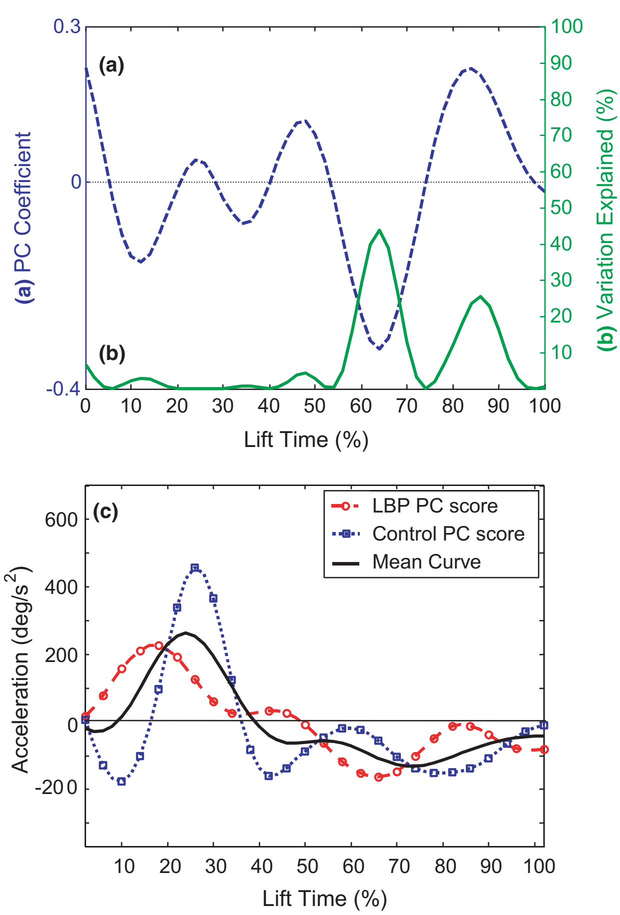

Fig. 3. T1 extension acceleration principal component six plotted in the original form (a) and as the percentage of variation explained (b). Two distinct regions from approximately 55% to 75% and from approximately 75% to 100% of the lift time are most important. To illustrate the mode of variability captured, the mean curve along with waveforms that corresponded to Control and LBP principal component scores (c) were plotted. Principal component labels have been abbreviated to PC.

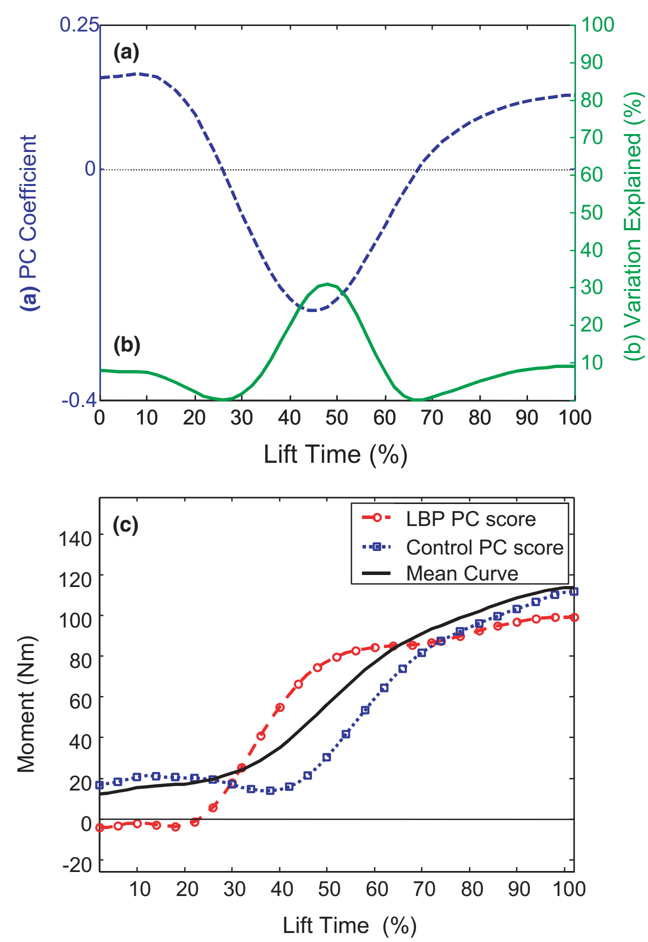

Fig. 4. T1 extension moment principal component three plotted in the original form (a) and as the percentage of variation explained (b). Of particular interest is the region from approximately 30% to 65% of the lift time. To illustrate the mode of variability captured, the mean curve along with waveforms that corresponded to Control and LBP principal component scores (c) were plotted. Principal component labels have been abbreviated to PC.

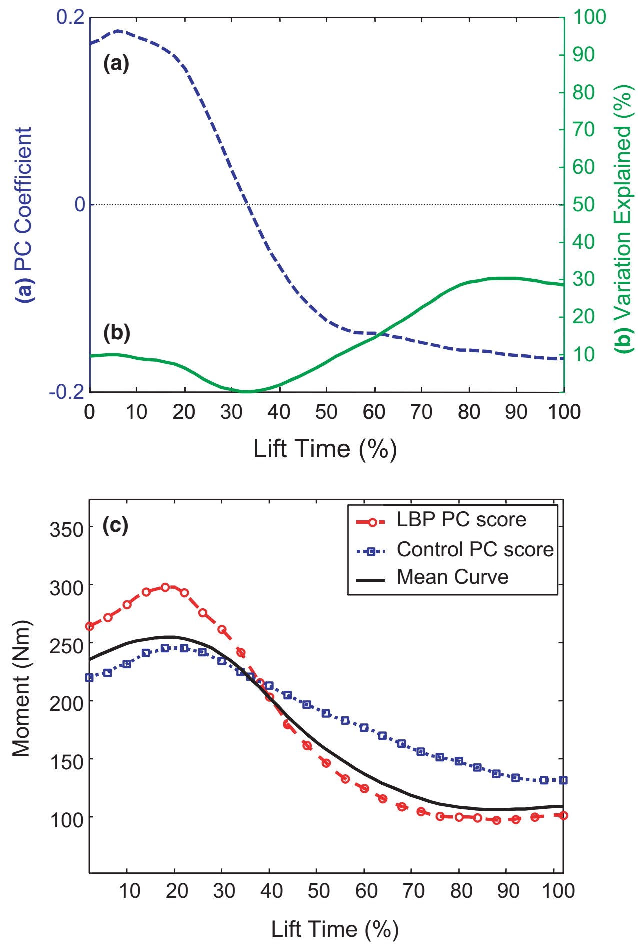

Fig. 5. S1 extension moment principal component two plotted in the original form (a) and as the percentage of variation explained (b). Of particular interest is the point around 35% of the lift time where the principal component coefficients change sign. The region from approximately 35% to 100% of the lift time captures the greatest amount of variability. To illustrate the mode of variability captured, the mean curve along with waveforms that corresponded to Control and LBP principal component scores (c) were plotted. Principal component labels have been abbreviated to PC.

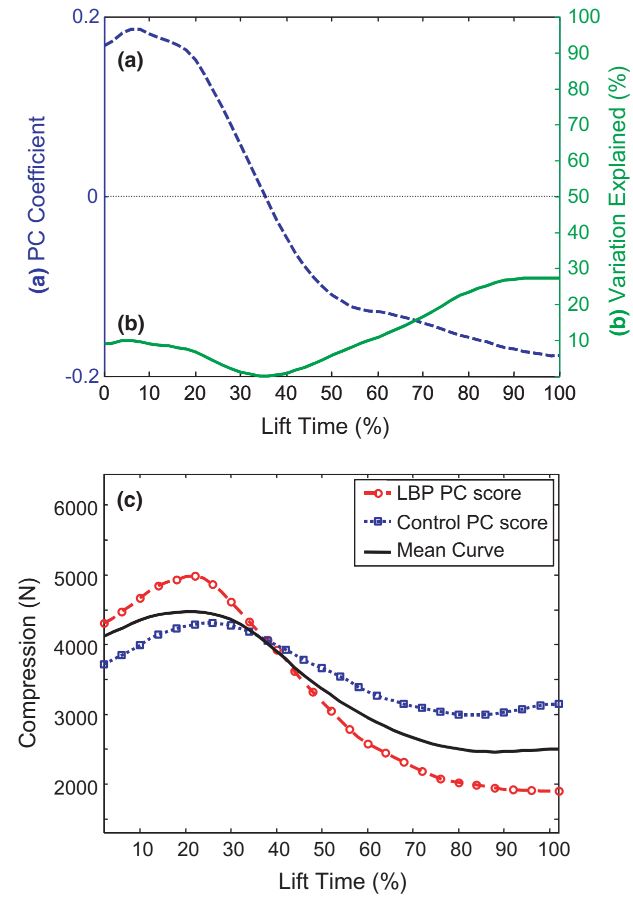

Fig. 6. Trunk compression principal component two plotted in the original form (a) and as the percentage of variation explained (b). Of particular interest is the point around 40% of the lift time where the principal component coefficients change sign. The region from approximately 40% to 100% of the lift time captures the greatest amount of variability. To illustrate the mode of variability captured, the mean curve along with waveforms that corresponded to Control and LBP principal component scores (c) were plotted. Principal component labels have been abbreviated to PC.

represent difference operators. Considering the similarities in waveform patterns between S1 extension moment and trunk compression, it is not surprising that Fig. 5a and b are nearly identical to Fig. 6a and b. For both principal components, the negative mean principal component score of the control group will cause the waveforms to be subtracted from the average waveform when the principal component coefficient is positive until approximately 35% of the lift time. After this point has been reached, the principal component coefficients change sign, which will cause the control group's waveforms to be added to the average waveform, thereby illustrating a difference operator. Figs. 5b and 6b both indicate that the difference in variability will be greatest during the second half of the lift time, with the most variation accounted for after 80% of the lift. Both Figs. 5c and 6c illustrate this pattern clearly. As expected the S1 extension moment and Trunk compression were highest at the start of the lift. The rapid decrease in S1 extension moment in the LBP group was inversely related to the development of the T1 extension moment. The differences in relative timing of S1 and T1 extension moments are mirrored in trunk compression patterns (Fig. 6c).

4. Discussion

The parameter-based analysis focused on summary variables like peak motions where non-significant findings suggest a similar technique. The lack of significant differences with respect to the 48 parameters extracted to characterize the lifting task indicated that the techniques used by the two groups were the same. For example, knee angle is often used as a kinematic marker for lifting technique. Subjects with similar maximum knee bend would imply a similar lift posture yet how the task was completed is not addressed. Although the two groups had statistically equivalent anthropometric characteristics, there was a significant difference for the two end effect variables of mean lift time and maximum height attained by the box. It stands to reason that within a constrained task different end effects would require different motions to achieve the results. However, as with previous research (Albert et al., 1998; Larivière et al., 2002), the parameters chosen to describe the kinematic waveform data were not able to discriminate lifting performance between the two groups in this study. Furthermore, in their discussion on the coordination of muscle activity as it relates to lumbar spine stability, McGill et al. (2003) indicate that similar motion patterns can be generated through different motor patterns, each with different characteristics with respect to joint loading and stability. Waveform analysis techniques such as PCA afford researchers the opportunity to explore movement patterns as they relate to both kinematic and kinetic variables.

When describing the retained principal components, there were three primary modes of variation captured; a magnitude operator, a difference operator, and a phase shift. A magnitude operator explained variability that existed between the amplitudes of waveforms and occurred within specific sections of the lift, but could also have occurred over the entire lift time. Difference operators described variation that changed in sign or direction, where a waveform will first be either added or subtracted from the average waveform, and then switched to the opposite operation. Changes in the relative timing of events within waveforms were captured by a phase shift, and were characterized by a waveform event either shifting to the right or left of the average waveform.

PCA was able to distinguish the two groups on patterns of variability associated with two kinematic and three kinetic properties of the lift. The patterns of variability captured by box vertical velocity principal component four and T1 extension acceleration principal component six represent magnitude operators and describe a movement strategy related to the placement and control of the load near the end of the lift. Both groups began the lift with rapid vertical movement of the box. However, once the peak trajectory was reached, the LBP group decreased the velocity until load placement whereas the CON group demonstrated an increase in vertical box movement just prior to shelf placement. A freestyle lifting technique from the floor to shoulder height can be broken down into three distinct stages consisting of the load being pulled up with leg and back extension, a wrist changeover where the hands are repositioned from above to below the target, and finally the load being pushed out to the target (Stevenson et al., 1990). In comparison, when the lifting trajectory was constrained with an incremental lifting machine, there was no wrist changeover resulting in a progressive decline in the vertical velocity of the load from the peak value (Stevenson et al., 1991). Interestingly, the pattern of box vertical velocity found in the present study for the LBP group resembles the lifting trajectory constrained task which was reported to be evident in only 8% of male subjects' natural lifting strategy (Stevenson et al., 1991). Correspondingly, the LBP group's T1 extension acceleration near the end of the lift reveals a pattern of trunk flexion deceleration when the vertical velocity of the box is also decreasing. At the same time this pattern occurs with the LBP group, the CON group increases their T1 flexion acceleration when the load experiences a rise in the vertical velocity, suggesting movement correction during the wrist change-over. However, the cause of such a pattern is difficult to determine without more information about arm movement, but the modes of variation captured by T1 extension moment principal component three and S1 extension moment principal component two may be related.

T1 extension moment principal component three and S1 extension moment principal component two capture a phase shift and difference operator respectively describing the relative timing of moment generation about T1 and S1. When compared to the CON group, the LBP group's pattern of generating a relatively higher S1 extension moment until around 35% of the lift then changing to relatively lower values coincides with the phase shift captured by T1 extension moment principal component three. It appears that the difference operator for S1 extension moment principal component two leads to the phase shift in T1 extension moment principal component three. As a result, the LBP group reached and remained at peak thoracic loading for 50% of the lift cycle whereas the CON group were at peak for only 30%. Similarly, Larivière et al. (2002) found that chronic LBP patients tended to reduce lumbar erector spinae activation in favor of increasing thoracic erector spinae activation during a lifting task. Their results suggested that the chronic LBP group might have been attempting to compensate for lumbar pain. The Queen's DuPont Low Back Pain Research Study did not track muscle activation and therefore electromyographic information about the trunk musculature was not available for analysis. However, the moment generation patterns found in the present study suggest that the contribution of muscle activation found by Larivière et al. (2002) may be a result of a motor control issue that was evident prior to the patients developing LBP, and not a means to protect lumbar tissues. Larivière et al. (2002) went further to indicate that their findings should have been reflected in trunk compression, which was not found. The researchers identify that methodological constraints imposed by the calculation of resultant moments and forces may have contributed to their lack of findings in this regard. Perhaps the researchers were further constrained by the parameterization approach utilized in the analysis as trunk compression principal component two captured a difference operator that reflected a similar pattern for trunk compressive unloading that was found by S1 extension moment principal component two. It appears that the group differences in the inferred motor pattern and identified timing of moment generation about S1 and T1 led to the differences in the control and placement of the box.

Surprisingly, the waveform analysis employed did not find any significant differences with respect to the modes of variation for any of the trunk angular velocities or accelerations. When Khalaf et al. (1997, 1999) performed similar waveform analyses on lifting curves, it was found that more modes of variation were required to represent velocity and acceleration data as compared to torques. Such results indicate that higher order kinematics have a greater amount of inherent variability and thus require more features to adequately represent them (Khalaf et al., 1997, 1999). Their results were attributed to the noise and error present in the process of differentiating the displacement. However, the researchers suggested that the inclusion of inertial components in the calculation of torques might have resulted in reduced overall variability for these variables. Similarly in the present study, up to four principal components were required to adequately describe the velocity data, six principal components for the acceleration data, but only three and two principal components for the moments and net forces (compression and shear) respectively. Therefore, the increased amount of variability present in the velocity and acceleration data has led to the inability to identify significant group differences with respect to scores on specific patterns of variation.

5. Summary

Two methods for discerning lifting technique of industrial manual material handlers prior to either developing LBP or not were explored. The parameter-based approach using 48 discrete kinematic and kinetic measures associated with the lifting activity (such as maximum and minimum joint angles and associated angular velocities) and 17 discrete measures describing the anthropometrics and strength characteristics of the sample was unable to identify group differences. The PCA approach, which determined the largest modes of variability for 16 waveforms, revealed differences on five different lifting variables.

The sensitivity of the PCA approach in identifying differences in the synergistic lifting patterns between workers who did and did not develop low back pain is encouraging. Despite the mild nature of the low back pain experienced by the workers, differences in lifting technique were found. The reasons for the differences in the chosen techniques are not understood but require further investigation into motor control pathways and strategies to link their association to low back pain development.

References

Albert, W.J., Stevenson, J.M., Costigan, P.A., 1999. Quantification of lifting technique in a manual materials handling plant. In: Lee, G.C.G. (Ed.), Advances in Occupational Ergonomics and Safety, vol. 3. IOS Press Inc., Virginia, pp. 73–79.

Albert, W.J., Stevenson, J.M., Smith, J.T., 1998. Queen's-Dupont Back Study: Prediction of mild low back pain using lifting technique. In: Proceedings of the Third North American Congress on Biomechanics, Waterloo, pp. 93–94.

Deluzio, K.J., Wyss, U.P., Zee, B., Costigan, P.A., Sorbie, C., 1997. Principal component models of knee kinematics and kinetics: normal vs. pathological gait patterns. J. Hum. Mov. Sci. 16, 201–217.

Fairbanks, J.C.T., Couper, J., Davies, J.B., O'Brien, J.P., 1980. The Oswestry low back pain disability questionnaire. Physiotherapy 66, 271–273.

Gagnon, M., Plamondon, A., Gravel, D., Lortie, M., 1996. Knee movement strategies differentiate expert from novice workers in asymmetrical manual materials handling. J. Biomech. 29, 1445–1453.

Garg, A., Sharma, D., Chaffin, D.B., Schmidler, J.M., 1983. Biomechanical stresses as related to motion trajectory of lifting. Hum. Factors 25 (5), 527–539.

Gundewall, B., Liljeqvist, M., Hansson, T., 1993. Primary prevention of back symptoms and absence from work: a prospective randomized study among hospital employees. Spine 18, 587–594.

Hamill, J., Knutzen, K.M., 1995. Biomechanical Basis of Human Movement. Wiliams & Wilkins, Baltimore.

Hsiang, S.M., Brogmus, G.E., Courtney, T.K., 1997. Low back pain (LBP) and lifting technique—a review. Int. J. Ind. Ergon. 19, 59–74.

Hsiang, S.M., McGorry, R.W., 1997. Three different lifting strategies for controlling the motion patterns of the external load. Ergonomics 40, 928–939.

Hubley-Kozey, C.L., Vezina, M.J., 2002. Differentiating temporal electromyographic waveforms between those with chronic low back pain and healthy controls. Clin. Biomech. 17, 621–629.

Jackson, J.E., 1991. A User's Guide to Principal Components. John Wiley & Sons Inc., New York.

Khalaf, K.A., Parnianpour, M., Wade, L., 1997. Feature extraction and modeling of the variability of performance in terms of biomechanical motion patterns during MMH. In: Proceedings of the Rocky Mountain Bioengineering Symposium, Dayton, OH, pp. 35–40.

Khalaf, K.A., Parnianpour, M., Sparto, P., Barin, K., 1999. Feature extraction and quantification of variability of dynamic performance profiles due to the different sagittal lift characteristics. IEEE Trans. Rehabil. Eng. 7, 278–288.

Kim, S.H., Chung, M.K., 1995. Effects of posture, weight and frequency on trunk muscular activity and fatigue during repetitive lifting tasks. Ergonomics 38, 853–863.

Kjellberg, K., Lindbeck, L., Hagberg, M., 1998. Method and performance: two elements of work technique. Ergonomics 41, 798–816.

Larivière, C., Gagnon, D., Loisel, P., 2000. An application of pattern recognition for the comparison of trunk muscles EMG waveforms between subjects with and without chronic low back pain during flexion–extension and lateral bending tasks. J. Electromyogr. Kinesiol. 10, 261–273.

Larivière, C., Gagnon, D., Loisel, P., 2002. A biomechanical comparison of lifting techniques between subjects with and without chronic low back pain during freestyle lifting and lowering tasks. Clin. Biomech. 17, 89–98.

Leskinen, T.P.J., Stålhammar, H.R., Kuorinka, I.A.A., Troup, J.D.G., 1983. A dynamic analysis of spinal compression with different lifting techniques. Ergonomics 26, 595–604.

Marras, W.S., Lavender, S.A., Leurgans, S.E., Rajulu, S.L., Allread, W.G., Fathallah, F.A., Ferguson, S.A., 1993a. The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. Spine 18, 617–628.

Marras, W.S., Parnianpour, M., Ferguson, S.A., Kim, J.Y., Crowell, R.R., Simon, S.R., 1993b. Quantification and classification of low back disorders based on trunk motion. Eur. J. Phys. Med. Rehabil. 3, 218–235.

McGill, S.M., Grenier, S., Kavcic, N., Cholewicki, J., 2003. Coordination of muscle activity to assure stability of the lumbar spine. J. Electromyogr. Kinesiol. 13, 353–359.

Mooney, V., Kron, M., Rummerfield, P., Holmes, B., 1995. The effect of workplace based strengthening on low back injury rates: a case study in the strip mining industry. J. Occup. Rehabil. 5, 157–167.

NIOSH, 1991. Scientific Support Documentation for the Revised 1991 NIOSH Lifting Equation. National Institute of Occupational Safety and health, PB91-2262274.

Potvin, J.R., Norman, R.W., 1993. Quantification of erector spinae muscle fatigue during prolonged, dynamic lifting tasks. Eur. J. Appl. Physiol. 67, 554–562.

Rice, J.A., Silverman, B.W., 1991. Estimating the mean and covariance structure nonparametrically when the data are curves. J. R. Statist. Soc. 53, 233–243.

Sparto, P.J., Parnianpour, M., Reinsel, T.E., Simon, S., 1997. The effect of fatigue on multi joint kinematics and load sharing during a repetitive lifting test. Spine 22, 2647–2654.

Stevenson, J.M., Bryant, J.T., French, S.L., Greenhorn, D.R., Andrew, G.M., Thomson, J.M., 1990. Dynamic analysis of isoinertial lifting technique. Ergonomics 33, 161–172.

Stevenson, J.M., Bryant, J.T., Andrew, G.M., Langley, L.L., Greenhorn, D.R., 1991. Self-determined lifting styles compared to constrained ILM lifting protocols. J. Hum. Mov. Stud. 21, 69–83.

Stevenson, J.M., Weber, C.L., Smith, J.T., Dumas, G.A., Albert, W.J., 2001. A longitudinal study of the development of low back pain in an industrial population. Spine 28, 1370–1377.

Troup, J.D.G., Leskinen, T.P.J., Stalhammer, H.R., Kourinka, I.A.A., 1983. A comparison of intraabdomial pressure increases, hip torque, and lumbar vertebral compression in different lifting techniques. Hum. Factors 25 (5), 517–525.

Winter, D.A., 1990. Biomechanics and Motor Control of Human Movement. John Wiley & Sons Inc., New York.

Wooten, M.E., Kadaba, M.P., Cochran, G.V.B., 1990. Dynamic electromyography I: Numerical representation using principal component analysis. J. Pineal. Res. 8, 247–258.