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Feature Detection and Biomechanical Analysis to Objectively Identify High Exposure Movement Strategies When Performing the EPIC Lift Capacity test

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Abstract

Purpose The Epic Lift Capacity (ELC) test is used to determine a worker's maximum lifting capacity. In the ELC test, maximum lifting capacity is often determined as the maximum weight lifted without exhibiting a visually appraised "high-risk workstyle." However, the criteria for evaluating lifting mechanics have limited justification. This study applies feature detection and biomechanical analysis to motion capture data obtained while participants performed the ELC test to objectively identify aspects of movement that may help define "high-risk workstyle". *Method* In this cross-sectional study, 24 participants completed the ELC test. We applied Principal Component Analysis, as a feature detection approach, and biomechanical analysis to motion capture data to objectively identify movement features related to biomechanical exposure on the low back and shoulders. Principal component scores were compared between high and low exposure trials (relative to median exposure) to determine if features of movement differed. Features were interpreted using single component reconstructions of principal components. *Results* Statistical testing showed that low exposure lifts and lowers maintained the body closer to the load, exhibited squat-like movement (greater knee flexion, wider base of support), and remained closer to neutral posture at the low back (less forward flexion and axial twist) and shoulder (less flexion and abduction). *Conclusions* Use of feature detection and biomechanical analyses revealed movement features related to biomechanical exposure at the low back and shoulders. The objectively identified criteria could augment the existing scoring criteria for ELC test technique assessment. In the future, such features can inform the design of classifiers to objectively identify "high-risk workstyle" in real-time.

Keywords Automated pattern recognition · Lifting · Work capacity evaluation · Kinematics · Kinetics

Introduction

Workplace injuries, specifically overexertion-type musculoskeletal disorders (MSDs), are common in industries where lifting exceeding a worker's capacity is required, such as freight, stock and material movers [1]. To prevent overexertion-type MSDs, job matching [2, 3] can be used to ensure workers' capacities are well matched to job demands. As an essential element of job matching, functional capacity evaluations (FCEs) are frequently used by employers pre-hire, pre-placement, or following a work absence (i.e., a lost time injury) to quantify a worker's capacity. Matching workers to jobs based on their capacity can reduce the incidence of injury over the long term [4].

FCEs intend to measure workers' capacity. In the context of lifting, the Epic Lift Capacity (ELC) test is often used to establish a worker's maximum acceptable lift weight [5, 6]. Several criteria exist to determine the endpoint of common lift capacity tests, corresponding to the determination of the maximum acceptable lift weight. Endpoint criteria include psychophysically determined maximum acceptable weight (i.e., participant perceives the weight as their maximum) or when the participant reaches a pre-determined maximum acceptable weight (i.e., the job requires the ability to lift a specific weight and once the worker reaches that level the test is stopped). While endpoint criteria and FCE testing protocols are clearly defined, factors such as clinician fear

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of movement [7, 8], patient height [9], patient pain intensity [9] and country of FCE evaluation [8] have all been shown to influence FCE results. The influence of these reported factors on FCE performance further highlight potential pitfalls of current FCE assessment practice, where presence of bias has been identified as an important concern to address as outlined in the recently adopted FCE best practice guideline [10]. Another important concern that can influence FCE results is that the decision to stop a test is frequently dependent on a clinician observing a candidate adopting a "high-risk workstyle". Such "high-risk workstyles" could include high magnitudes of low back flexion, which has been associated with injury risk [11]. Among kinesiologists administering FCEs in Canada, the most common endpoint criteria (more than 40% of the time) is observation of body mechanics, or the detection of "high-risk workstyles" [12]. Using subjective appraisal of lifting movement strategies to determine maximum acceptable lift capacity has been reported to jeopardize the objectivity, validity and reliability of the FCE [3]. To reduce subjectivity in the visual appraisal of lifting in FCEs, guidelines for detecting "high-risk workstyles" have been recommended in the literature such as not maintaining a stable stance, not keeping the weight close to the body, twisting the thorax relative to the pelvis, and raising hips before shoulders as high-risk [13]. While guidelines for detecting "high-risk workstyles" have been suggested, they may not be sufficiently justified by advanced biomechanical analysis.

Surprisingly, very few studies have applied biomechanics to quantify exposures associated with participants' movement strategies during the performance of FCE tests, despite a heavy reliance on the qualitative evaluation of biomechanics during FCE performance. The WorkHab FCE battery is one example of an FCE where movement has been quantified in performance where upper body joint and trunk angles were influenced as participants lifted heavier weights when performing the overhead lift element [14] and bench to shoulder height lift elements [15]. While it is expected that one might adopt a compensatory movement strategy when lifting a heavier load, it is important to identify individuals that adopt maladaptive strategies, or strategies that increase the relative exposure (e.g., magnitude of reaction forces or moments on a joint), relative to those that adapt using more appropriate compensatory strategies. Where maladaptive strategies are detected, targeted motor learning and coaching can be prescribed to minimize reliance on maladaptive strategies. Additionally, Cole et al., [16] demonstrated that L4/L5 spine compressive force increased as participants lifted heavier weights during performance of the Work Capacity Assessment Test, where, in some cases, L4/L5 spine compressive forces exceed recommended threshold limits for safe lifting [17, 18]. This finding emphasizes the importance of considering biomechanical analysis within the FCE paradigm, where the ability to lift heavier loads, perhaps even using strategies that minimize relative exposure, can still result in absolute exposures that exceed population-based risk thresholds. The ability to link biomechanical exposures to lifting movements during the performance of FCEs can strengthen the ability to objectively detect those individuals who adapt to the increasing challenge of lifting heavier loads by adopting "high-risk workstyles," or who have reached the limits of their capacity such that they can no longer continue without adopting "high-risk workstyles."

Feature detection techniques, such as principal component analysis (PCA), provide the ability to detect underlying synergistic or functional patterns within the movement to support time-series-based biomechanical analysis [19]. Where approaches to study movement strategies have historically relied on a priori decisions of relevant variables (i.e. local maxima or minima of discrete measures), PCA can be applied to detect meaningful synergistic or functional patterns across entire waveforms, without the need for such a priori decisions. When applied in this way, PC represent synergistic or functional movement components, that when added together represent the whole movement [20] PCA has been used to identify how patterns in lifting joint angle waveforms were altered when lifting different weighted boxes [21–24]. PCA has also been used to characterize time series marker trajectory data, identifying primary features of gait [25] and uncovering movement features that explain differences in sport performance, expertise and age effects [20, 26–28]. A key benefit of identifying and extracting underlying synergistic or functional patterns is that those patterns can be further explored to reveal potential difference in movement control between individuals. Recently, we have used this PCA-based approach, in conjunction with a supervised machine learning model, to objectively detect synergistic or functional patterns of movement that identified how some paramedics controlled their movements in a manner that increased their relative exposure on the low back, where others controlled their movements in a manner that decreased the relative low back exposure when performing backboard lifts [29]. That data revealed which participants could likely be targeted for intervention, and also highlighted specific functional aspects of their movement control that should be addressed. Successful application of PCA to detect features of movement relevant to performance or risk in sport and workplace applications, combined with biomechanical analysis can support continued efforts to objectively determine which movement strategies might be best described as "high-risk workstyles" based on underlying biomechanical exposures within the FCE paradigm.

The purpose of this study was to objectively differentiate features of lifting and lowering movement strategies (considered separately) between individuals that experienced relatively higher biomechanical exposures at the low back and shoulder than those that experienced lower biomechanical exposures. Considering previous work [29], we hypothesized that using a PCA model we would detect a feature of movement related to the horizontal distance between the load and participant, and that PC scores on this movement feature would be different between those allocated into the "high" and "low" relative exposure groups. Additionally, we hypothesized that features described in the "high-risk workstyle" guidelines outlined in the ELC test protocol [5] would also be identified as related to resultant biomechanical exposure at the low back and shoulders. By identifying features of movement strategy that result in higher biomechanical exposure to the low back and/or shoulder joints, we can substantiate currently used or suggest novel criteria for assessing "high-risk workstyles" in the ELC test.

Methods

Participants

A convenience sample of 24 individuals (14 female; age 23.0 ± 5.6 years, height 1.71 ± 0.10 m, weight 71.4 ± 15.3 kg) participated in this study. Participants were excluded if they had more than 6 months manual materials handling experience, were a varsity athlete, had formal biomechanics and ergonomics training, or sustained a musculoskeletal injury preventing them from completing activities of daily living within 12 months prior to data collection. Such exclusions were required in an effort to test a population that would be new to manual materials handling work and as a result, a likely candidate for a pre-hire or pre-placement FCE. This study was approved by the University's Office of Research Ethics, and all participants read and signed the information and consent form prior to participation.

Instrumentation

Three-dimensional (3D) whole-body kinematic data were collected at 60 Hz using an eight-camera Vicon motion capture system (Vicon, Oxford, UK). Participants were instrumented with a whole-body marker set, including 35 individual anatomical markers to define anatomical coordinates (28 of which were removed following calibration) and 59 markers on rigid plastic clusters to track the upper arms, forearms, hands, trunk, pelvis, thighs, shanks, and feet segments. All markers were affixed to the participant with double-sided tape and/or Velcro straps.

Experimental Protocol

Experimental sessions began by obtaining informed consent. The participant was then instrumented with passive reflective markers to track their movement. A five second static calibration trial was collected, in which the participant stood stationary in the anatomical position so all markers were visible and all segments could be defined.

Epic Lift Capacity (ELC) Test

Following the calibration procedure, participants performed the ELC test, conducted according to standardized instructions [5]. The ELC test was selected based on its high frequency of use in the workplace [12] and availability of a relatively easy-to-use and detailed protocol [5, 6]. The test uses a psychophysical approach to assess a worker's ability to complete job demands considering aspects of lifting including frequency, vertical lift height, lift duration, and load [5, 6]. The ELC test includes six subtests: three progressive one-repetition maximum tests (subtests 1–3; representing middle, low, and high lifting heights respectively) and three progressive four-repetition maximum test (subtests 4–6; representing middle, low, and high lifting heights respectively). Subtests 1 and 4 (middle lifts) were performed between knuckle and shoulder heights; subtests 2 and 5 (low lifts) between floor and knuckle heights; and subtests 3 and 6 (high lifts) between floor and shoulder heights. All subtests were performed in the same order for all participants (1 through 6) replicating the standard administration of the test. The height of each respective shelf (at knuckle and shoulder height) was set 24 cm below the participant's measured knuckle and shoulder height to account for the height of the box.

Participants were required to complete each subtest within a one-minute window, followed by a mandatory one-minute rest period. After each subtest, the participant was asked for their Rating of Perceived Load (RPL), ranging from 1 ("Like nothing at all") to 10 ("Too heavy"). They were also asked two questions: "Do you think you could lift this load 8–10 times per day?" and "Can you lift heavier?" If the participant responded with an RPL of 7 ("Heavy") or lower, and answered "yes" to both questions, more weight was added to the box, and the subtest continued. If the participant responded with an RPL of 8 ("Very heavy") or higher, answered "no" to either of the questions, or exhibited dangerous lifting patterns (i.e. using body parts other than the hands to support the box during lifting/lowering), the subtest was concluded, and the current weight was recorded as the subtest maximum [5]. However, only two of the twenty-four participants had ELC subtests concluded based on dangerous lifting patterns where they used either their chest or knees to support the load when completing the lift.

Data Processing and Analysis

All kinematic data were labeled and gap-filled, consistent with best practice [30], using Vicon Nexus 2.5.1 (Vicon, Oxford, UK), and imported into Visual3D software (C-Motion, Germantown, MA, USA). Motion data were filtered using a zero-lag dual-pass Butterworth filter with an effective cutoff frequency of 6 Hz. A rigid-linked skeleton model was created for each participant using individual anthropometric data from their static calibration trial. Hand force vectors were applied to the model at the palm center of each hand, where the magnitude of the vector corresponded to the weight of the box in each trial and the orientation was coincident with gravity. The model was used to calculate joint flexion/extension angles at the shoulders and about the L4/L5 spine. The Visual3D model was also used in concert with a top-down modeling approach to calculate net joint flexion/extension moments at the shoulders (upper arm relative to trunk) and low back (trunk relative to pelvis) following ISB recommendations [31, 32]. A single muscle equivalent model was used to estimate bone-on-bone compression forces at the L4/L5 level of the low back with a moment arm of 5.0 cm from the long axis of the spine [33].

Lifts (lower to higher shelf) and lowers (higher to lower shelf) were considered as separate actions for this analysis. Start and end events for each action were defined using the hand position vertical maximum (lift end/lower start) and minimum (lift start/lower end) values and were confirmed through visual inspection in Visual3D. For subtests 1–3, one lift and one lower were identified and extracted, and for subtests 4–6, four lifts and four lowers were identified and extracted. All actions were exported and normalized to 101 frames, or 0–100% of the action cycle, in MATLAB R2017b (Mathworks Inc., Natick, MA, USA). Seventeen anatomical locations were exported for all actions in 3D (x, y, z) relative to the global coordinate system and imported into MATLAB. Anatomical locations included joint centers bilaterally at the shoulder, elbow, wrist, hip, knee, and ankle, as well as the trunk and pelvis center of gravity locations, the seventh cervical vertebrae, suprasternal notch, and xiphoid process.

Estimating High vs. Low Biomechanical Exposures

The shoulder exposure score was based on the peak right and left shoulder flexion/extension moments within a lift/lower, while low back biomechanical exposure score was based on the peak low back flexion angle, peak low back compression force and peak low back anteroposterior (AP) joint reaction force within a lift/lower. Shoulder moments were selected as a measure of joint demand as heavy workloads are a risk factor for shoulder injury [34]. For the low back, all of peak low back flexion angle [11], compression force [18, 35, 36] and AP shear force [35–37] have been associated with risk of injury. Moments and forces were normalized to the sum of the participant body weight and weight of the box lifted in each trial. Normalization allowed comparison of relative exposure, quantified as exposure per unit mass. To calculate an aggregate exposure at a joint, all normalized biomechanical outcomes were expressed as z-scores relative to the data set. In a given trial the z-scores related to either the shoulder or low back were summed to give an aggregate measure of exposure for each joint respectively. Lifts and lowers were dichotomized as high or low exposure at the low back and shoulder based on the aggregate z-score. Without evidence to relate magnitudes of low back exposures to injury risk, the median aggregate z-score was selected as a threshold to define high and low exposure lifts. While dichotomizing based on the median may be a limitation, it is still a suitable method to differentiate between lifters with relatively higher and lower resultant biomechanical exposures. When aggregate z-scores were above the median, that lift or lower action was defined as high exposure, while lifts and lowers where aggregate z-scores fell below the median were classified into the low exposure.

Principal Component Analysis (PCA)

PCA was used to detect features of movement in lifting and lowering motions where each principal component (PC) described a feature of movement (functional or synergistic component) explaining an independent source of variability in marker trajectory data. PCA was applied to analyze the whole-body motion data consistent with past approaches [25, 28, 29]. Briefly summarized, an n x p matrix was produced for each action type (lifts and lowers), where n represented the number of trials (inclusive of all participants), and p represented the time series anatomical location trajectory data. In this case, the total number of trials (n) was 1216, but the number for each participant was dependent on their capacity during the ELC test. The smallest number of trials for one participant was 31 and largest was 77. The number of columns (p) was 5151, representing 17 anatomical locations in x, y, z components across 101 time points each. All anatomical location data were normalized to the participant height to control for the role of inter-individual height in affecting variance in anatomical location trajectory data. A 90% trace criterion was used to determine the number of principal components (PCs) retained for statistical testing [38–41] where subsequent PCs were retained until a total of 90% of variance in the data set was explained.

Statistical Analysis

With an application goal of identifying objective criteria to evaluate movement strategy in the ELC test, statistical analyses aimed to identify features of movement (i.e., PCs), based on marker trajectory data, that significantly differed between high and low exposure lifts and lowers independently of shelf height to define movement assessment criteria generalizable across all ELC subtests. Four, two-way mixed ANOVAs (one for low back and one for shoulder for each of the lifts and lowers) were completed to determine how shelf height (floor to knuckle, floor to shoulder, knuckle to shoulder) and biomechanical exposure score (high or low) independently and interactively effected PC scores associated with lifting and lowering movements when performing the ELC test (SPSS Version 24.0, IBM Corporations, Armonk, NY). Significance was set at $p < 0.05$. We assumed that exposures at the shoulder and low back would occur independently from each other, but would both be influenced by shelf height, hence why they were tested separately.

Principal Component Interpretation

To maintain the focus of this work, only PC scores that were independently influenced by biomechanical exposure score, excluding any interactions with shelf height, were interpreted. To interpret individual PCs, single component reconstruction was used where 5th and 95th percentile PC scores were reconstructed [42]. As interpretation of the single component reconstructions is subjective, the loading vectors for each anatomical location (averaged across the x, y and z directions for each time point) were plotted (sample plot shown in Fig. 1) to aid with interpretation. The anatomical location loading vectors were used to generally identify where on the body, and when in the time domain, the greatest variance was explained during either a lift or lower. Greater variance explained at a given time point is indicated by waveform magnitudes deviating from zero. Two researchers performed interpretation of single component reconstructions independently to ensure consensus on variance explained in a PC.

To visualize general differences in high vs. low exposure movement strategy, a modified single component reconstruction [42] was used:

$$r = \mu + \sum \left(LV_{PCx} * \alpha \right)$$

where r is the reconstructed data, μ is the mean movement across all trials, LV is the loading vector of a retained PC and α is an integer to scale the contribution of the loading vector. The PC score scalar (α) was set to the mean of a high or low exposure lift in a PC for the high and low exposure reconstructions respectively.

By including all PCs that independently differed as a function of biomechanical exposure in the aggregate reconstruction, we were able to produce generalized figures to grossly represent differences in high vs. low exposure movement strategy for the low back and shoulder in both lifts and lowers.

Results

The first thirteen PCs accounted for 90.8% of the variance in lifting and were retained for statistical analysis. Twelve PCs accounted for 90.4% of the variance in lowering and

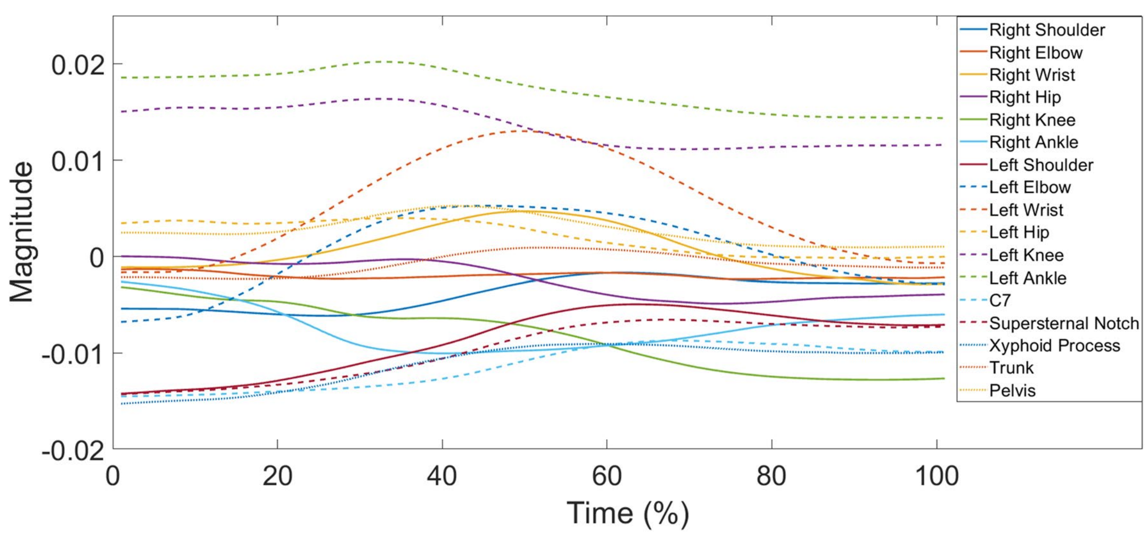

Fig. 1 Loading vectors plotted by anatomical location averaged across the x, y and z directions at each time point for PC5 during a lowering action

Table 1 Differences in lift PC scores between high and low shoulder and low back biomechanical exposure groups across lifting heights

PC lift	Percent variance explained	Low back biomechanical exposure			Shoulder biomechanical exposure		
		Sig. height (p-value)	Sig. low back (p-value)	Sig. height × low back (p-value)	Sig. height (p-value)	Sig. shoulder (p-value)	Sig. height × shoulder (p-value)
PC1	30.47	**< 0.001**	0.526	0.647	**< 0.001**	**0.015**	**< 0.001**
PC2	16.85	**< 0.001**	**< 0.001**	**0.036**	**< 0.001**	**0.003**	**0.004**
PC3[a]	10.22	***< 0.001***	***< 0.001***	*0.374*	**< 0.001**	**< 0.001**	**0.033**
PC4[a]	7.75	***< 0.001***	***0.004***	*0.156*	**< 0.001**	0.198	0.745
PC5[b]	6.23	**< 0.001**	0.137	0.313	***< 0.001***	***< 0.001***	*0.063*
PC6	4.74	**< 0.001**	0.091	0.219	**< 0.001**	**< 0.001**	**< 0.001**
PC7[b]	3.77	**< 0.001**	**< 0.001**	**< 0.001**	***< 0.001***	***< 0.001***	*0.074*
PC8	3.11	**< 0.001**	0.364	0.195	**< 0.001**	**0.009**	**< 0.001**
PC9	2.41	**< 0.001**	**< 0.001**	**0.001**	**< 0.001**	**< 0.001**	**0.017**
PC10	1.67	**< 0.001**	**0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
PC11[b]	1.52	**0.004**	**0.001**	**< 0.001**	***0.001***	***0.001***	*0.842*
PC12[b]	1.15	**< 0.001**	**< 0.001**	**0.023**	***< 0.001***	***0.016***	*0.066*
PC13[a,b]	0.93	***0.008***	***0.004***	*0.939*	***< 0.001***	***< 0.001***	*0.826*

Significant p-values ($p < 0.05$) are bolded to highlight where differences were detected

[a]Indicates a PC score with a significant ($p < 0.05$) effect of low back exposure score independent from height (no height × low back exposure interaction), which was retained for interpretation

[b]Indicates a PC score with a significant ($p < 0.05$) effect of shoulder exposure score independent from height (no height × shoulder exposure interaction), which was retained for interpretation. Italics represent a PC where a significant main effect of exposure score, but no significant interaction effect was observed

Table 2 Differences in lower PC scores between high and low shoulder and low back biomechanical exposure groups across lifting heights

PC lower	Percent variance explained	Low back biomechanical exposure			Shoulder biomechanical exposure		
		Sig. height (p-value)	Sig. low back (p-value)	Sig. height × low back (p-value)	Sig. height (p-value)	Sig. shoulder (p-value)	Sig. height × shoulder (p-value)
PC1	33.07	**< 0.001**	**< 0.001**	**0.025**	**< 0.001**	0.950	**< 0.001**
PC2[a]	17.16	***< 0.001***	***< 0.001***	*0.074*	**< 0.001**	**0.002**	**0.018**
PC3[b]	9.85	**0.001**	**< 0.001**	**0.027**	***0.001***	***< 0.001***	*0.231*
PC4[a,b]	7.34	***< 0.001***	***< 0.001***	*0.130*	***< 0.001***	***0.001***	*0.270*
PC5[b]	6.22	**< 0.001**	0.254	0.836	***< 0.001***	***< 0.001***	*0.560*
PC6[a]	5.07	***< 0.001***	***< 0.001***	*0.055*	**< 0.001**	0.908	0.101
PC7	3.15	**< 0.001**	0.626	**0.032**	**< 0.001**	0.717	**< 0.001**
PC8[a,b]	2.29	***< 0.001***	***0.030***	*0.809*	***< 0.001***	***< 0.001***	*0.544*
PC9[a,b]	1.84	***0.008***	***< 0.001***	*0.868*	***< 0.001***	***< 0.001***	*0.519*
PC10	1.69	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
PC11	1.51	**< 0.001**	0.125	**0.003**	**0.001**	0.808	0.603
PC12[a]	1.21	***< 0.001***	***0.002***	*0.181*	**< 0.001**	0.510	0.113

Significant p-values ($p < 0.05$) are bolded to highlight where differences were detected

[a]Indicates a PC score with a significant ($p < 0.05$) effect of low back exposure score independent from height (no height × low back exposure interaction), which was retained for interpretation

[b]Indicates a PC score with a significant ($p < 0.05$) effect of shoulder exposure score independent from height (no height × shoulder exposure interaction), which was retained for interpretation. Italics represent a PC where a significant main effect of exposure score, but no significant interaction effect was observed

were retained for statistical analysis. Shelf height significantly influenced PC scores across all retained PCs for lifts and lowers (Tables 1 and 2). Using the PCA model for lifting motions, biomechanical exposure classification significantly influenced PCs 3, 4 and 13 when considering low back exposure and PCs 5, 7, 11, 12 and 13 when considering shoulder exposure (Table 1). Using the PCA model for lowering motions, biomechanical exposure classification significantly influenced PCs 2, 4, 6, 8, 9 and 12 when considering low back exposure, and PCs 3, 4, 5, 8 and 9 when consider shoulder exposures (Table 2). Interpretation of single component reconstructions for PCs that had a significant effect of exposure independent of shelf height were consistent between researchers and are described in Tables 3 and 4. General visualization of the isolated effect of features of movement influenced by resultant biomechanical exposure were generated for the low back (Fig. 2) and shoulder (Fig. 3) using an aggregate reconstruction.

Discussion

This study aimed to objectively detect features of movement that explain differences between individuals experiencing higher relative biomechanical exposures at the low back and shoulder compared to those experiencing lower relative biomechanical exposures when performing the ELC test [5]. Objective identification of features of movement that differ between relatively high and low exposures lifts and lowers can help update, inform, and substantiate the criteria used for stopping an ELC test on the basis of "high-risk workstyles." Using PCA as a feature detection method, we were able to identify unique features of individual whole-body movement strategies that could differentiate between high and low exposure lifts and lowers, independent of shelf height. Supporting the hypotheses, high exposure lifting and lowering behaviors exhibited a greater reach distance, or horizontal distance to the box, and a narrower base of support. Additionally, greater deviations of low back and shoulder angles from neutral were also found to be related to resultant biomechanical exposure. These findings support that identification of "high-risk workstyles" in the ELC test

Table 3 Interpretation of variance explained by lifting PCs which had a significant main effect of either shoulder or low back biomechanical exposure

PC	Exposure location	Visual description
3	Low back	Variance is explained by whole-body posture at the beginning of the lift. High exposure lifters exhibited a stoop strategy (less knee flexion, greater forward trunk flexion) to reach the load. Low exposure lifters exhibited a squat posture (greater knee flexion, more neutral low back posture, wider foot stance and base of support) when beginning to lift the load
4	Low back	Variance is explained by lower body posture and low back flexion through the lift. High exposure lifters exhibited valgus knee collapse, shallower knee flexion and greater low back flexion at the beginning and throughout the lift. Low exposure lifters exhibited a squat lifting strategy, resulting in a lift driven by lower body motion (greater knee flexion), and a more neutral low back posture when completing the lift
5	Shoulder	Variance is explained by upper body posture at the end of the lift. High exposure lifters exhibited a greater shoulder flexion angle and low back extension when finishing the lift. Low exposure lifters maintain a more neutral shoulder flexion angle and low back posture through the duration of the lift
7	Shoulder	Variance is explained by the horizontal reach distance when beginning the lift. High exposure lifters exhibited a greater distance between the load and the lifter when starting the lift, as well as a greater shoulder flexion angle and greater back extension when completing the lift. Low exposure lifters exhibited a smaller horizontal reach distance through the duration of the lift, resulting in less shoulder flexion and a more neutral low back
11	Shoulder	Variance is explained by differences in shoulder movement and axial twist through the lift. High exposure lifters exhibited greater shoulder flexion and abduction during the lift, and maintained a large sagittal plane shoulder angle finishing the lift. Low exposure lifters exhibited more neutral shoulder posture and close to 90° elbow flexion through the duration of the lift. Both exposures exhibited trunk axial twist to assist the lift, but in opposite directions, and the low exposure lifters kept the load closer to their body
12	Shoulder	Variance is explained by initial posture, as well as co-ordination patterns through the lift. High exposure lifters exhibited a greater reach distance with the elbows away from the body when beginning the lift, and finished the lift with greater shoulder flexion. The high exposure lift was driven by upper body motion, while the low exposure lift was driven by lower body motion. The low exposure lifters exhibited greater knee flexion and less trunk flexion when beginning the lift, and finished the lift with a more neutral shoulder and trunk posture
13	Low back, shoulder	Variance is explained by upper body movement and horizontal distance to the load. High exposure lifters exhibited greater shoulder flexion and abduction, and less elbow flexion, while their trunk remained more upright through the duration of the lift. Low exposure lifters experienced greater forward trunk flexion, but less shoulder flexion, and elbow flexion close to 90° through the lift

Table 4 Interpretation of variance explained by lowering PCs which had a significant main effect of either shoulder or low back biomechanical exposure

PC	Exposure location	Visual description
2	Low back	Variance is explained by the difference in whole-body movement through the duration of the lower, or descent strategy. High exposure lowers experienced a stoop-like descent (greater forward trunk angle, less knee flexion, narrower stance width), where low exposure lowers experienced a squat-like descent (more upright trunk, greater knee flexion, wider stance)
3	Shoulder	Variance is explained by differences in posture at the end of the lower. High exposure lowers experienced greater forward trunk angle, greater shoulder flexion, and a larger distance of the load from the body at the end of the lower. Low exposure lowers experienced a more neutral low back posture through the lower, and ended the action with the load distance closer to the body
4	Low back, shoulder	Variance is explained by the range of motion about the shoulder joint and low back. High exposure lowers experienced a greater range of motion about the shoulder and low back, as well as greater horizontal distance between the body and load when beginning and ending the lower. Low exposure lowers experienced less range of motion about the shoulder and low back, maintaining more neutral postures through the lower
5	Shoulder	Variance is explained by posture at the beginning of the lower. High exposure lowers experienced trunk extension and subsequently greater shoulder flexion when beginning the lower. Low exposure lowers experienced a neutral low back and shoulder posture through the duration of the lower
6	Low back	Variance is explained by differences in trunk angle. High exposure lowers experienced trunk extension when beginning the lift, and underwent a greater range of motion about the low back through the lower. Low exposure lowers experienced a smaller range of motion and more neutral low back posture through the lower
8	Low back, shoulder	Variance is explained by distance of the body to the shelves. High exposure lowers experienced a greater range of motion about the upper body joints, and the stance placement is relatively stationary such that the reach when beginning and ending the lower is greater. Low exposure lowers experienced a greater range of motion about the lower body joints, and stance placement is more dynamic such that the body is close to the shelves when beginning and ending the lower, but takes a step away from the shelves during the lower
9	Low back, shoulder	Variance is explained by trunk and upper body joint coordination. High exposure lowers were driven by upper body motion followed by greater trunk flexion mid-way through the lower. Low exposure lowers experienced simultaneous shoulder and low back motion
12	Low back	Variance is explained by trunk flexion and axial twist. High exposure lowers experienced trunk extension at the beginning of the lower, followed by greater trunk flexion, axial twist and greater shoulder flexion and abduction through the lower. Low exposure lowers experienced a more upright trunk and greater knee flexion during the lower

should consider proximity of the body to the load, maintaining a wide base of support, using a knee-driven lifting strategy, maintaining a neutral low back angle and minimizing shoulder flexion and abduction angles. The results of this study highlight the benefit of performing biomechanical analyses in concert with subjective evaluation, which would improve the efficacy of FCE testing in the workplace.

Our findings are consistent with and extend current criteria for detecting "high-risk workstyles" in the ELC test [5]. First, our study demonstrated that greater horizontal distance from the body to the load throughout the entirety of a lift or lower had implications on biomechanical exposures at both the low back and shoulder. This finding adds support for the current guidelines (Table 5), stating, "minimize the horizontal distance" as an important criterion. The importance of minimizing the horizontal distance to the load is also reiterated in previous literature as a determinant of low back loading [43], strengthening support for the continued inclusion of this feature in ELC test technique assessment. Second, we also identified a wide base of support as an important feature of movement related to biomechanical exposures. Current ELC test guidelines specifically encourage lifters to have a broad and stable foot placement (Table 5), where our data support that criterion. The agreement of our findings to the current "high-risk workstyle" guidelines support that they should continue to be considered in technique assessment in the ELC test.

In addition to confirming that features of movement currently considered "high-risk workstyles" are objectively related to resultant biomechanical exposure, we also identified additional features of movement not previously considered. Specifically, using a knee-driven strategy, maintaining neutral low back posture and minimizing shoulder flexion and abduction angles were all identified as features of movement related to biomechanical exposures at either the low back or shoulder (Table 5). While using a knee-driven, or more squat-like, strategy has not been conclusively linked minimizing low back loading [44], this strategy is more conducive to generating more work from the lower body relative to the low back, which has been shown to reduce low back loading [45]. Maintaining a neutral low back to minimize biomechanical exposure is also supported by previous literature as greater low back flexion angles have been associated with higher risk of MSDs [11] and axial twist

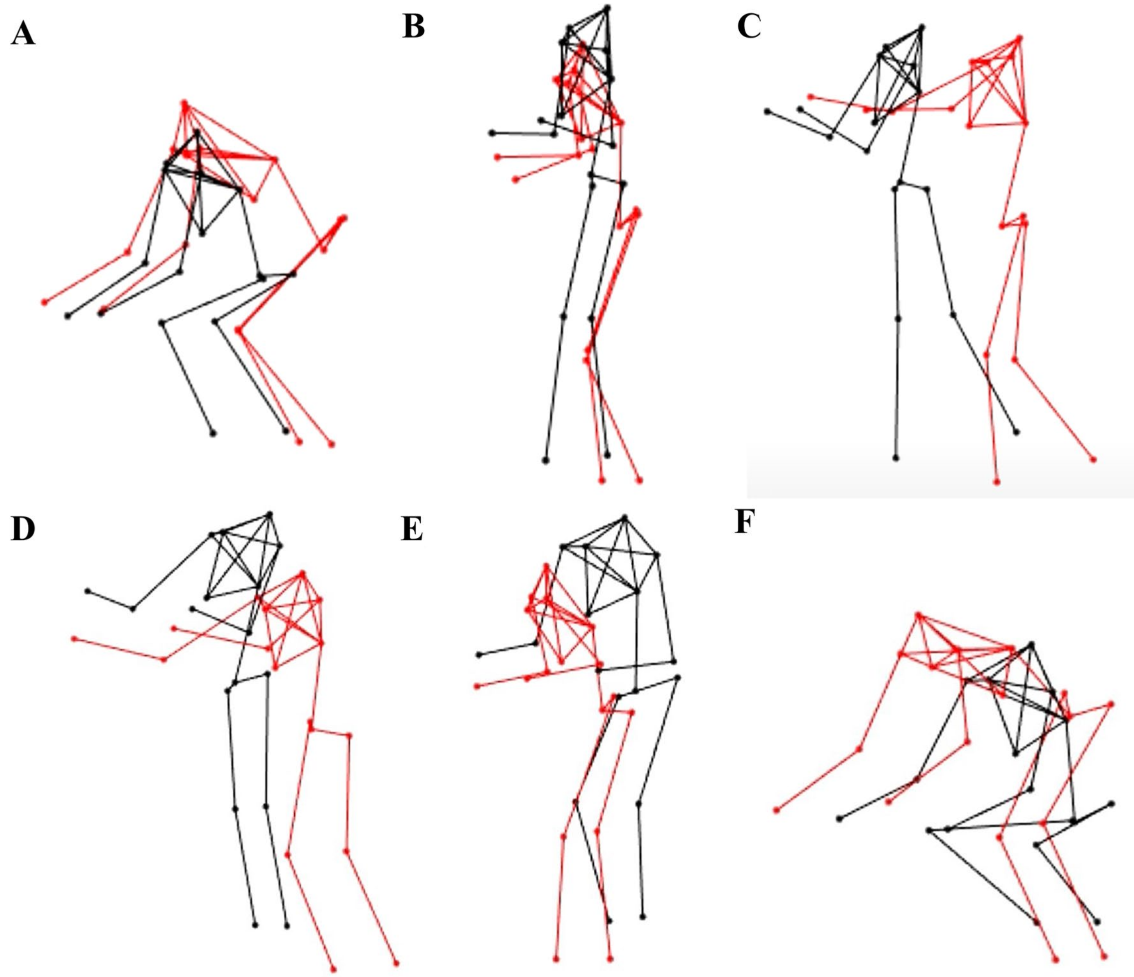

Fig. 2 Visual representations of high (red) and low (black) low back exposure movement strategies in the ELC test. **a**–**c** represent 0%, 50% and 100% of the lift, respectively, and **d**–**f** represent 0%, 50% and 100% of the lower, respectively (Color figure online)

has been shown to accelerate and increase injury susceptibility of the intervertebral joint complex in repetitive flexion–extension motions [46]. For the shoulder joint, reducing postural angles has also been associated with reducing the shoulder joint load [47]. Agreement between our findings and the literature describing features of movement related to biomechanical exposures strengthens the need to include these additional criteria into biomechanical assessments of maximum acceptable weight when using the ELC test.

The novel features of movement related to biomechanical exposure we have identified should augment current "high-risk workstyle" guidelines [5] for technique assessment in the ELC test. A reliance on subjectivity has been noted as a major drawback of FCEs [3], and so assessing movement based on objectively identified criteria offers a first step to reduce subjectivity in assessment. An additional consideration in implementing these findings in ELC test technique assessment is the need to consider whole body movement strategy over time. Currently, the ELC test criteria only considers the end effectors (hand and foot placement) within the lift/lower at discrete time points in technique assessment. However, different postures were evident at different times through the lifting cycle, dependent on PC and exposure score, indicating that the entire movement strategy, or pattern of movement, should be considered when assessing for biomechanical exposure. This information provides clinicians with guiding movement principles, which allow for more holistic technique assessment that can better relate to biomechanical exposures in the ELC test.

This study provides objectively identified features of movement strategy to inform ELC test technique assessment, but future work should focus on automating movement assessment in FCEs. Specifically, a future opportunity is to explore the ability to quantify movement strategy and then use this data to classify workers based on movement strategy in real time in the ELC test. Such a method may be able to use advances in lower fidelity or marker-less motion capture systems [48, 49] to reliably collect kinematic data outside of

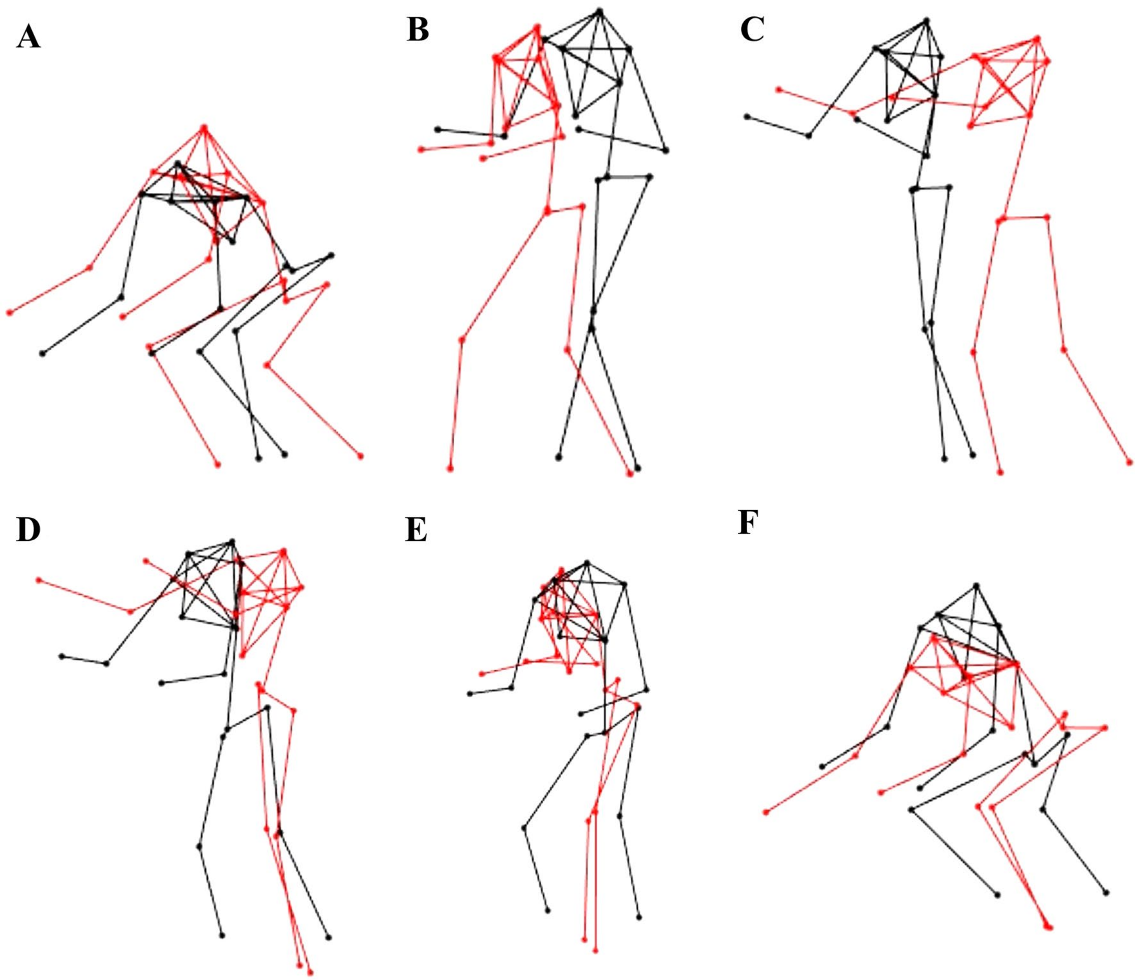

Fig. 3 Visual representations of high (red) and low (black) shoulder exposure movement strategies in the ELC test. **a**–**c** represent 0%, 50% and 100% of the lift, respectively, and d–**f** represent 0%, 50% and 100% of the lower, respectively (Color figure online)

Table 5 Epic lift capacity test "high-risk workstyle" guidelines compared to recommended technique assessment guidelines based on objectively identified high exposure movement strategy at the low back and shoulder joints

Epic lift capacity high-risk guidelines [5]	Recommended technique assessment guidelines
Minimize the horizontal distance between the load and sacrum at the end of the lift	Minimize the horizontal distance between the load and sacrum throughout lifts and lowers
Maintain feet placement in a broad and stable stance during work tasks	Maintain a wide stance width in lifts and lowers
	Lift and lower by flexing about the knee joints opposed to the low back
	Limit low back flexion, extension and axial twist in lifts and lowers
	Minimize shoulder flexion and abduction angles in lifts and lowers

a lab environment. If there is success in reliably quantifying kinematics in practice, then the PCA methodology described in the study can be paired with classification models, such as a linear discriminant function [28, 29], to classify performance on the ELC test based on resultant biomechanical exposure. This proposed future approach would also remove the need to conduct detailed biomechanical analysis in a clinical setting, such as collecting force plate data and calculating low back loads using an inverse dynamics modelling approach. Instead, movement could be classified based on resultant biomechanical exposure using only kinematic data. By implementing this proposed automation approach the subjectivity in movement assessment during the ELC test would decrease and would potentially reduce the influence of factors such as practitioner kinesiophobia [7, 8], participant height [9], participant pain intensity [9] and country of FCE evaluation [8] on measured FCE performance. The potential reduction of subjectivity in FCE assessment would therefore improve their efficacy.

Although this study shows promise to improve technique assessment in the ELC test, it is not without limitation. For instance, a certain level of biomechanical expertise is required to interpret each PC. Although the explanation of PCs relies on subjective interpretation based on reconstruction and loading vector information, the individual PCs represent independent modes of variation that were derived objectively. Secondly, the findings in this study do not necessarily capture all features of movement that are related to biomechanical exposure at the shoulder and low back joints in the ELC test. While we retained PCs that explained greater than 90% of variance in movement strategy, there is a chance that there are some features of movement that expose workers to high biomechanical exposures, but only explain a small percentage of variance in the dataset that were missed in analysis. Additionally, the methodology used in the study only assessed biomechanical exposure at the low back where utilizing different lifting strategies may increase biomechanical exposure, and therefore injury risk, at other joints of the body. The influence of strategy on loading other joints in the body can be explored in future work. Finally, by not considering inertial properties of the load [50], and using a single muscle equivalent model [51] the low back moments calculated were likely underestimated. However, since moments were expressed as a z-score across the data set, the under estimation of moments does not influence our ability to identify high exposure lifts as moments are only compared within the data set, not to injury threshold limits.

Conclusion

This study objectively identified features of movement strategy related to high and low biomechanical exposure during lifting and lowering loads in the ELC test. Overall, low exposure lifters displayed a squat-like movement, minimized the distance between the body and load, and reduced the range of motion used about the shoulder and low back joints. These findings demonstrate that when performing technique assessment in the ELC test, observers should focus on the features of movement identified to be related to biomechanical exposure, where our data support existing “high-risk workstyle” assessment guidelines, and further extend those guidelines to include additional features of importance. In the longer term, this approach shows promise to supplement FCE testing criteria to provide clinicians with a tool to objectively evaluate technique and risk, according to biomechanical outcomes.

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Compliance with ethical standards

Conflict of interest Daniel P. Armstrong, Aleksandra R. Budarick, Claragh E.E. Pegg, Ryan B. Graham, and Steven L. Fischer declare that they have no conflict of interest.

Informed Consent All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000 (5). Informed consent was obtained from all patients for being included in the study.

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