Visual perception of fatigued lifting actions

Steven L. Fischer a,*, Wayne J. Albert b, Tim McGarry b

a School of Kinesiology and Health Studies, Queen’s University, Kingston, Ontario, Canada
b Faculty of Kinesiology, University of New Brunswick, Fredericton, New Brunswick, Canada

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Fatigue-related changes in lifting kinematics may expose workers to undue injury risks. Early detection of accumulating fatigue offers the prospect of intervention strategies to mitigate such fatigue-related risks. In a first step towards this objective, this study investigated whether fatigue detection was accessible to visual perception and, if so, what was the key visual information required for successful fatigue discrimination. Eighteen participants were tasked with identifying fatigued lifts when viewing 24 trials presented using both video and point-light representations. Each trial comprised a pair of lifting actions containing a fresh and a fatigued lift from the same individual presented in counter-balanced sequence. Confidence intervals demonstrated that the frequency of correct responses for both sexes exceeded chance expectations (50%) for both video (68% ± 12%) and point-light representations (67% ± 10%), demonstrating that fatigued lifting kinematics are open to visual perception. There were no significant differences between sexes or viewing condition, the latter result indicating kinematic dynamics as providing sufficient information for successful fatigue discrimination. Moreover, results from single viewer investigation reported fatigue detection (75%) from point-light information describing only the kinematics of the box lifted. These preliminary findings may have important workplace applications if fatigue discrimination rates can be improved upon through future research.

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* Corresponding author. Address: 28 Division Street, Kingston, Ontario, Canada K7L 3N6. Tel.: +1 613 533 6000x75210; fax: +1 613 533 2009.
E-mail address: steve.fischer@queensu.ca (S.L. Fischer).

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1. Introduction

Lifting tasks are common to many workers in numerous industries. Unfortunately, lifting is also linked to the development of low back pathology (Chaffin & Park, 1973; Frymoyer, Pope, & Clements, 1983; Marras et al., 1993, 1995; Hoogendoorn et al., 2000; Wai, Roffey, Bishop, Kwon, & Dagenais, 2010). Attempting to uncover causal mechanisms for these pathologies, researchers have investigated the complex interactions between lifting techniques, loadings and the motor coordination required to perform these tasks (Burgess-Limerick, Abernethy, & Neal, 1993; Chaffin, 1969; de Looze, Kingma, Bussmann, & Toussaint, 1992; Freivals, Chaffin, Garg, & Lee, 1984; Granata & Marras, 1995; Marras & Sommerich, 1991a, 1991b; McGill & Norman, 1985, 1986; van Dieën, Hoozemans, & Toussaint, 1999; van Dieën, Kingma, & van der Burg, 2003). As research in this regard has increased, another line of inquiry has emerged examining how these complex interactions might be altered over time as a lifter fatigues, including how fatigue induced changes might affect developing pathologies.

Fatigue can influence lifting strategies and the underlying biomechanics. In terms of general lifting strategies, some lifters have shown complete transition from a squat strategy to a stoop strategy as a result of fatigue (Resnick, 1996). Others have trended towards this transition by decreasing the range of motion used at both hip and knee (Sparto, Parnianpour, Reinsel, & Simon, 1997) as well as increasing the flexion range of motion at the trunk (Dolan & Adams, 1998; van Dieën, Toussaint, Maurice, & Mientjes, 1996; van Dieën, van der Burg, Raaijmakers, & Toussaint, 1998). Temporal changes in the relative timing patterns between the knee and hip joint angles are also altered with fatigue (Sparto et al., 1997; van Dieën et al., 1996), in addition to reported increases in peak box acceleration (Bonato, Bossy, Della Croce, & Roy, 2002). However, other research has suggested that fatigue related changes may not be systematic; rather the changes depend on the individual lifter and his (her) lifting strategies (Bank & Aghazadeh, 2009). This contrast notwithstanding, lifting kinematics is affected by fatigue in terms of the timing, the ranges and the coordination of movements produced.

Kinematic related changes due to fatigue are important to consider when evaluating the demands of a work task, job performance and/or estimating the associated levels of injury risk. In the laboratory, small motion related changes may be detected given the wide range of motion capture equipment and the availability of corresponding analysis software. However, in the field these measurement tools are not readily available and practitioners and ergonomists routinely make use of video camera for kinematic analysis of work performance (Dempsey, McGorry, & Maynard, 2005). As a result, the facility to assess movement kinematics from video images depends on the perceptual abilities of the observer. This consideration begs the question whether visual perception can serve as a measurement instrument for fatigue detection based on fatigue induced changes in movement kinematics. If visual perception can be used to detect fatigue, as supposed, and if the sensitivity (or resolution) of fatigue discrimination by the observer is sufficient then the potential exists for developing a fatigue index based on visual assessment. For example, a fatigue index could be used to compare work performances early in a shift versus late in a shift offering a simple viable method for monitoring fatigue development and its consequent related risks. This report presents a first step on the path towards this objective.

The video-based derivative point-light method introduced by Johansson (1973) helps understand the perception of biological motions on a fundamental level. The point-light method presents the observer with a static (still) or dynamic (moving) representation of a human or animal using a series of point-lights (dots) often depicting joint center locations. In this way the degree of information on view is reduced from that obtained from video. When shown as a static body, the pattern of point-lights is often unrecognizable; however, when shown as a moving body the viewer instantly forms a coherent percept affording immediate recognition (Troje, 2008), a result attributed to the dynamic relations among joint markers. In this study we used the point-light method to examine visual perception for identifying lifting fatigue.

In the context of lifting, previous research using a point-light approach has identified that viewers can perceive differences in the weight of a box being lifted based on underlying kinematics. Viewers perceive the weight lifted by considering velocity (Bingham, 1987; Hamilton, Joyce, Flanagan, Frith, & Wolpert, 2007; Shim & Carlton, 1997), the time the lifter takes to prepare to lift (Shim & Carlton,
1997), the duration of the lifting event (Hamilton et al., 2007) and the kinematics of lifters (Bingham, 1987). The success viewers have had in identifying load weight between different lifts based on underlying kinematic changes lends additional support to the experimental hypothesis that viewers will discriminate between fresh and fatigued lifts based on the corresponding kinematic dynamics.

The purpose of this study then was to investigate if visual perception could be used to differentiate between fresh and fatigued lifts, and if so, to begin to inquire on the information basis necessary for these distinctions. Specifically, we hypothesized that observers would differentiate between fatigued and fresh lifts in binary forced choice representations with a success rate greater than chance (50%), and that the kinematic information reflected in point-light displays of joint landmarks would be sufficient to inform these decisions as compared with additional information available from video representation.

2. Methods

This experiment was conducted in accord with the guidelines specified in the Tri-Council (of Canada) Policy Statement on Ethical Conduct for Research Involving Humans.

2.1. The lifting task

Sagittal plane video data for 12 lifters (seven males, five females) collected in previous research (Wrigley, 2006) provided the representative dataset for this investigation. In the lifting study of Wrigley (2006), lifters performed a repetitive lifting task at a rate of six lifts per minute for 120 min (or until the lifter selected to stop before 120 min). The task required the lifters to move a handled box from floor to a shelf placed at shoulder height and then return the box to floor to complete the entire lift cycle. The box weight was scaled at 20% of maximum lift strength of each lifter. Fatigue was measured using a reported rate of perceived exertion (RPE) on a 10-point Borg scale (Borg, 1990) with all lifters reporting significant increase in RPE from beginning (2.3 ± 0.82; M ± SD) to completion (7.85 ± 0.82) of the lifting task. From these video data, a representative lift was extracted at random for each lifter from the first five minutes of lifting and taken as representing a fresh (non-fatigued) lift. Similarly, a representative lift was extracted at random for each lifter from the final five minutes of lifting and these data used to represent lifting in a fatigued state, although the level of fatigue sustained may well be different among lifters. In total, 12 pairs (one fresh and one fatigued lift per lifter) of kinematic profiles were extracted for use in the current study.

2.2. Point-light representation

The extracted video data were digitized using HUman Movement ANalysis (HUMAN) software (HMA Technology, Guelph, Ontario). Eight data points were digitized for each frame of the video to represent the following landmarks: the head (1), left wrist (2), left elbow (3), left shoulder (4), left hip (5), left knee (6), left ankle (7), and the left heel (8). The resulting digitized points were then presented in point-light format as white dots on a black screen. The coordinate data were scaled in software to represent the lifter within the same reference frame as other lifters to reduce individual differences between lifters in terms of viewing size. Fig. 1A provides a static example of the point-light display representation for a lifter (dots 1–8) preparing to move the box (dots 9–12) from the floor. Given the earlier noted difficulty in forming coherent percepts from static point-light displays, the same image with connection lines between markers demonstrating posture of the lifter and box is presented in Fig. 1B for purposes of comprehension.

2.3. The lifting trials

Using a forced binary choice (or paired comparison) approach, viewers were presented with a pair of lifting actions comprising a fresh and fatigued lift and tasked with discriminating between them. For the video condition, each pair of dynamic lifting trials was placed in sequence in a power-point
application for presentation as a trial. Trials were arranged with a fresh lift followed by a fatigued lift (early-late) and in reverse sequence with the fatigued lift following the fresh lift (late-early). This decision doubled the 12 trials to 24 by expressing each lifting pair in a given trial as being either early-late or late-early. The 24 trials were presented to participants in random order without replacement while excluding the possibility of back-to-back displays of the same lifter (i.e., it was not possible to view an early-late trial followed by a late-early trial from the same lifter and vice versa). Since 24 trials were presented using both video and point-light representation, each participant was presented with a total of 48 trials for decision making.

2.4. Experimental protocol

Nine males and nine females (university students) volunteered to participate in this study. Participants completed two viewing sessions separated by a ten minute break. Half of the participants viewed the video trials in the first session and the point-light trials (dots 1–8, Fig. 1B) in the second session, while the other half viewed the trials in reverse sequence. In all viewing sessions and trials, participants were presented with each lifting pair in succession and allowed to view each trial repeatedly for as long as required before passing judgment on which lift from the pair represented the fatigued lift. Feedback regarding response accuracy (correct or incorrect) was provided to the viewer immediately following each decision. Each participant received on completion of the study a performance-based financial payment of $0.25 per correct response.

2.5. Statistical analysis

To determine if viewers discriminated successfully between fresh and fatigued lifts at a rate greater than chance, the lower bound of the 95th percentile confidence interval for the mean of both sexes was used and compared against the chance score (12 from 24). Two-way mixed analysis of variance (ANOVA) was used to detect for differences in the number of correct responses with the type of visual information (video, point-light) treated as a within-participant factor and sex (male, female) as a between-participant factor. Shapiro–Wilk statistics were used to test for normality and a Box’s test was
used to confirm homogeneity of the variance-covariance matrices. Statistical processing was completed using SPSS software (SPSS INC., Chicago, IL, USA) using raw scores however the results are presented as percentage of correct scores to aid interpretation and facilitate comparison across other studies.

3. Results

The lower bound of the 95% confidence interval for the mean scores of males and females ranged from 56–64% (see Table 1), demonstrating in both instances that viewers could differentiate between fresh and fatigued lifts with a success rate greater than chance (50%). Type of visual information (within factor) or sex (between factor) did not significantly affect the number of correct responses (Table 2). Participants responded correctly on 68% ± 12% of trials when presented with video and 67% ± 10% when presented with the point-light images. This finding demonstrates that kinematic information reflected in point-light display representations was sufficient to inform decisions without more detailed video information, as predicted.

Sex differences were not a primary focus for this study; however they were included in the statistical model as a possible factor that may affect the interpretation of the results. Noted above, there were no significant differences in rates of correct responses between the sexes (72% ± 10% for males, 63% ± 10% for females). Pending additional research, the non-significant 9% mean difference in frequency of correct responses between sexes may nonetheless constitute a meaningful difference. This possibility notwithstanding, hereafter we interpret the results from the sexes combined given the non-significant result reported.

On determining that fatigued lifting actions could be identified with a success rate greater than chance, a follow-up was conducted to determine which aspects of the lifting action portrayed the information content required to perceive differences between fresh and fatigued lifting. Given that visual perception constitutes the measurement instrument in this study, a single viewer who performed well in the first part of the study was invited back for additional investigation. This time the viewer was shown reduced point light display images (containing subsets of dots 1–8, Fig. 1B) including a

<table>
<thead>
<tr>
<th>Type of visual information</th>
<th>Sex</th>
<th>Mean (% correct)</th>
<th>Standard deviation (%)</th>
<th>95% Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lower bound</td>
</tr>
<tr>
<td>Video</td>
<td>Male</td>
<td>72</td>
<td>13</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>63</td>
<td>9</td>
<td>64</td>
</tr>
<tr>
<td>Point light</td>
<td>Male</td>
<td>71</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>63</td>
<td>11</td>
<td>57</td>
</tr>
</tbody>
</table>

Table 2
Summary table of the results from the two-way mixed ANOVA contrasting sex (between factor) and type of visual information (within factor).

<table>
<thead>
<tr>
<th>Source</th>
<th>Degrees of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Between participants</td>
<td>17</td>
<td>34.03</td>
<td>34.03</td>
<td>4.422</td>
<td>.052</td>
</tr>
<tr>
<td>Sex</td>
<td>1</td>
<td>34.03</td>
<td>34.03</td>
<td>4.422</td>
<td>.052</td>
</tr>
<tr>
<td>Error (between)</td>
<td>16</td>
<td>123.11</td>
<td>7.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Within participants</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type of visual information</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
<td>0.57</td>
<td>.814</td>
</tr>
<tr>
<td>Sex x type of visual information</td>
<td>1</td>
<td>0.25</td>
<td>0.25</td>
<td>0.57</td>
<td>.814</td>
</tr>
<tr>
<td>Error (within)</td>
<td>16</td>
<td>70</td>
<td>40375</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
condition containing only the box (dots 9–12, Fig. 1B). This latter condition was conducted to determine if box trajectory information alone would permit fatigue detection. Since the viewer had only seen previous various information representing the lifter (dots 1–8, Fig. 1B), the box coordinate information was new and the results cannot have been influenced by prior knowledge gained from past viewing exposure. The viewer nevertheless identified fatigued lifts on 75% (18 of 24) of trials using point-light information from the four corners of the box. (Binomial theorem indicates a 1.13% chance of discriminating 18 of 24 trials as correct on an equal-chance basis per trial.) This important finding provides strong indication that visual perception can be used to detect between fresh and fatigued lifts given only information contained in the box kinematics.

4. Discussion

The results demonstrate that visual perception can be used successfully as a measurement instrument for detecting differences between fresh and fatigued lifts beyond chance expectations, albeit in an idealized type of presentation format using a forced binary-choice paradigm. While fatigue discrimination success rate may not be high enough for practical application at present, observational abilities for recognizing fatigue would nonetheless be expected to improve with dedicated practice. In view of informing practice however, further investigation regarding the information basis for discriminating fatigued lifting is required. Equipped with preliminary knowledge obtained from this study that fatigue can be detected using visual perception, future research undertakings should begin to assess the resolution (sensitivity) of this measure for identifying different levels of fatigue if the potential usefulness for ergonomic applications is to be realized.

The ability to detect equally well between fresh and fatigued lifts using both video and point-light representation provided insight about what information viewers used in perceiving fatigue. That fatigued lifts were detected with equal success rates independent of the mode of presentation supports the interpretation of kinematic information from joint center trajectories underpinning fatigue discrimination common to both presentation formats. This result is consistent with previous research suggesting that viewers are sensitive to changes in kinematic trajectories (Muchisky & Bingham, 2002; Wickelgren & Bingham, 2004). In the context of fresh and fatigued lifting, specific information from various joint trajectories likely change temporally and/or spatially (Bank & Aghazadeh, 2009; Bonato et al., 2002; Dolan & Adams, 1998; Resnick, 1996; Sparto et al., 1997; van Dieën et al., 1996, 1998) and these joint landmarks therefore provide important information cues for viewer judgments.

Understanding what information a viewer uses to recognize fatigued lifting actions may help guide observational training approaches in future. Viewing performances exceeded chance expectations but the frequency of correct identifications are not high enough at present for use in the workplace. However, knowing that joint trajectory information underpins fatigue discrimination identifies a key approach for guiding observational training with the aim of determining whether perception ability can be improved sufficiently for practical use in future workplace settings. For example, viewers could be provided with dedicated practice by reinforcing behaviors promoted at focusing attention on joint trajectories and their dynamic inter-related associations (Dolan & Adams, 1998; Resnick, 1996; Sparto et al., 1997; van Dieën et al., 1996, 1998). This suggestion must remain a long term focus for the time being but the results presented here support its pursuit.

The follow-up analysis revealed that visual perception could differentiate between fresh and fatigued lifting given point light information from only the four corners of the lifted box. This finding may be important for three reasons. First, it provides evidence that visual information of the item lifted and not the lifter is sufficient to inform decision making. Second, as with the previous findings from joint landmarks, the result demonstrates that much of the context rich information available from common video representations is unnecessary for purposes of fatigue discrimination. Instead, key information is embedded in the dynamic relations of discrete markers (points or dots) that sketch some meaningful outline of the object under investigation, namely the item lifted and/or the lifter. Results from the single viewer indicated a 75% fatigue discrimination success using box coordinate information only, a finding that stands regardless of the attributes of the lifter, their movements expressed in joint kinematics, and other varied contextual information possibly indicating fatigue such as facial expressions.

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(e.g., grimacing), verbal reports (e.g., commentary) or other signs of accumulated work load (e.g., labored breathing, sweating). Third, if sufficient information for detecting lifting fatigue is available only from the item lifted, as these results indicate, and if this information basis can be identified by future research advances then the possibility exists for future development of automated fatigue detection algorithms using conventional motion tracking methods. In this future workplace scenario note that it could be the item (box) that gets instrumented and not the worker. This unique finding, based on data from a single-subject, encourages further research to explore how visual perception of the lifted box may vary across a wider range of viewers.

Overall the results provided evidence to support the hypothesis that visual perception can be used to differentiate between fresh and fatigued lifts with a success rate greater than chance. Additionally, the results support the hypothesis that the kinematic information reflected in a point-light display representation is sufficient to inform decisions over more detailed video information. As industries continue to move away from traditional high force moderate pace work to low force high pace tasks (Marras, Cutlip, Burt, & Waters, 2009), the onset and impact of accumulated fatigue is likely to emerge as a dominating factor in the development of chronic pathologies. Therefore, it will become increasingly important for ergonomists and other workplace safety professionals to be able to perceive, identify and index fatigue related changes during work to help inform appropriate rest-break strategies. From a practical standpoint, these data provide preliminary indication that fatigue related changes in lifting can be perceived by untrained observers.

The findings from this study call for further research on using visual perception as a means of fatigue discrimination. By design, this investigation used a forced binary choice task (i.e., a 50% chance of success) to maximize the possibility of identifying fatigue, if present, and the results demonstrated that fatigued lifts can indeed be discriminated using visual perception. The next step in future research would be to ascertain the resolution of visual perception to fatigued actions, perhaps by presenting a number of trials from the same lifter in different fatigued states. Another step would be to introduce multiple trials from different lifters to examine whether fatigue perception extends from within-subject comparisons to between-subjects. In both suggestions, the common purpose is to advance understanding of the information basis that supports visual discrimination of lifting fatigue. If this underlying information can be identified then recognizing fatigue onset in the workplace by visual perception becomes a viable proposition. Given the availability and limited resolution of motion capture tools suitable for field applications at present, it would be useful if trained observers could detect between fresh and fatigued workers using paired comparisons of short video clips taken over the work shift.

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