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Using real-time feedback of L5/S1 compression force based on markerless optical motion capture to improve the lifting technique in manual materials handling

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ABSTRACT

Challenges in manual materials handling (MMH) are posed in particular by the requirements for continuous repetition and individual feedback. Low effort in MMH instructions is accordingly a relevant factor. The combination of a markerless motion capture system with a biomechanical model providing visual MMH instructions by individual real-time feedback of the compression force of the intervertebral disc in L5/S1 (CF) could tackle these challenges. However, this raises the question of whether this approach provides appropriate MMH instructions to improve the lifting technique in MMH. Results of an experiment with 22 young male participants indicate that visual MMH instructions with such individual real-time feedback have significant advantages in improving the lifting technique by reducing those factors associated with lower back pain compared to instructions with a reference paper-based tutorial or a baseline without instructions. Thus, peak and mean CF and peak trunk flexion, for example, were significantly lower when lifting with individual real-time feedback of CF compared to other conditions tested. Hence, the results suggest that it may be sensible to improve the lifting technique by such an approach of MMH instructions and integrate it in MMH training programs or on-the-job training in order to reduce or prevent lower back pain.

Relevance to industry: Using real-time feedback of the compression force of the intervertebral disc of L5/S1 based on markerless optical motion capture can improve the lifting technique in manual materials handling. This may be integrated into MMH training programs or on-the-job training to reduce or prevent low back pain.

1. Introduction

Manual materials handling (MMH) is known to be a major risk factor for work-related musculoskeletal disorders especially in the lower back (Anwer et al., 2021; Widanarko et al., 2012). Therefore, applying appropriate measures for avoiding MMH or reducing the risk involved in MMH, the European Union Directive 90/269/EEC states the obligation that workers should receive "proper training and information on how to handle loads correctly and the risks they might be open to particularly if these tasks are not performed correctly" (art. 6, cl. 2). There is still limited evidence about the effectiveness of MMH training in preventing lower back pain (LBP) (Clemes et al., 2010; Denys Denis et al., 2020; Hogan et al., 2014; Linton and van Tulder, 2001; Martimo et al., 2008; Sedgwick and Gormley, 1998; Verbeek et al., 2011; Verbeek et al., 2012). For example, a large-scale randomized controlled trial of an educational program designed to prevent low back injury that included knowledge teaching, exercises for strength training and workplace inspections found no long-term effects between the intervention and control group of 3597 postal workers over 5.5 years of follow-up (Daltroy et al., 1997). Similarly, a repeated behavioral oriented training that included direct biomechanical feedback and individual coaching was associated with similar low back injury as training by a single viewing of a video (Lavender et al., 2007).

A variety of interventions is used to prevent LBP. Systematic reviews conclude that exercise for strength training, rather than MMH training or other interventions, have the potential to be effective in the

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prevention of LBP (Maher, 2000; Steffens et al., 2016; van Poppel et al., 1997, 2004). However, practitioners responsible for occupational safety and health believe that MMH training is more effective if it is tailored to specific industry and task demands and includes practical elements (McDermott et al., 2012). The ineffectiveness of MMH training in preventing LBP could be also explained by the phenomenon that people do not necessarily apply their knowledge to practice (Overton et al., 2016). Continuous repetition seems to be a crucial factor for successful MMH training and behavioral chances. Accordingly, the effectiveness of MMH training seems to be more a question of how rather than if.

The literature suggests that an effective MMH training requires active exercise in combination with continuous repetitions and individual feedback, which should be adapted to the demands of the workplace. While the implementation of these requirements might be most effective in MMH training, it would likely require disproportionate effort and costs and thus would be rather unattractive as a prevention measure or program of LBP for many companies. These challenges may be mitigated by integrating continuous and immediate feedback into MMH training. Using real-time feedback could be a suitable approach in challenging that. For example, the application of visual real-time feedback based on data of an inertial measurement unit could significantly reduce the score of the Rapid Upper Limb Assessment (Vignais et al., 2013) and visual feedback of electromyography data can decrease muscle activity (Faucett et al., 2002). Furthermore, vibrotactile feedback based on data of an inertial measurement unit might significantly reduce the time spent in awkward working postures (Lind et al., 2020). Tactile feedback from an athletic strapping tape placed bilaterally along the lumbar extensor muscles could significantly reduce lumbar spine flexion (Pinto et al., 2018). Other studies suggest that individualized real-time auditory biofeedback on postural stabilities improves performance (Chan et al., 2022; Mullineaux et al., 2012). Approaches by Kamachi et al. (2021), Owlia et al. (2020), Punt et al. (2020), and Kernozek et al. (2006) revealed that audio real-time feedback based on thresholds of biomechanical calculations or lumbar spine flexion could reduce the risk factors of LBP in lifting and lowering tasks. Oppici et al. (2021) also concludes that auditory and tactile feedback conditions promoted a reduction of lumbar spine flexion and tactile was more effective than auditory.

Approaches that use markerless motion capture in combination with visual instructions might be more advantageous in addressing the above-mentioned challenges for MMH training in companies as it could provide real-time feedback in an effective, efficient and minimally invasive manner, even in the workplace. Markerless motion capture offers the opportunity to provide proper assistance for a wide range of applications in ergonomics and other fields (Clark et al., 2012; Ray and Teizer, 2012; Sarsfield et al., 2019). Such approaches focus almost exclusively on improving the ergonomic analysis of manual work using existing observational methods (Diego-Mas and Alcaide-Marzal, 2014; L. Li et al., 2020; Manghisi et al., 2017; Patrizi et al., 2016; Plantard et al., 2017; Spector et al., 2014). Many of the observational methods have been developed as easy-to-use screening tools for practical applications in the industry with well-known drawbacks (David, 2005; D. Denis et al., 2000; G. Li and Buckle, 1999; Roman-Liu, 2014; Takala et al., 2010). They can easily distinguish workplaces with a high risk of LBP from those with a low risk of LBP. However, even if an individual sampling strategy is used instead of a collective sampling strategy (Brandl et al., 2017), intra- and inter-differences in the biomechanical parameters of participants might be small when performing different executions of the MMH task (Kingma et al., 2006; Potvin et al., 1991; van Dieën et al., 1999). Hence, a clear distinction between low and high risk cannot always be made by observational methods. For a practical application of MMH instructions, the simplifications that are inherent to observational methods used for workload assessment might be insufficient for accurate LBP risk estimation (Beach et al., 2014).

Sufficient sensitivity might be achieved by using biomechanical analyses. A main parameter in the evaluation biomechanical load during MMH tasks is the compression force of intervertebral disc in L5/S1 (Jäger, 2018; Straker, 2002). In addition, it is known that if using verbal instructions to discourage spine flexion when lifting, the instructions should be spine-rather than leg-focused (Beach et al., 2018). A suitable approach to achieve practical requirements and sufficient data quality might be the combination of markerless motion capture and biomechanical analyses, which is widely used in the assessment of MMH (Gagnon et al., 2016; Mehrizi et al., 2017), but rarely in the applications of MMH instructions. This would also encourage people to choose their own lifting style by improving the biomechanical parameters.

Indeed, the focus on lifting techniques in MMH training could even be counterproductive, because the focus might be more on the supposedly correct execution of the presented lifting technique than on improving the underlying parameters of the lifting technique. The results of Gagnon et al. (2016) indicate that differences in biomechanical loads between experts and novices exist when participants are allowed to select their own lifting technique. Furthermore, the myoelectric silencing of the low back extensor musculature during a standing to full trunk flexion maneuver may indicate an increase in load sharing on passive structures (Colloca and Hinrichs, 2005) and emphasizes the importance of underlying parameters, such as spine load and trunk flexion over the specific lifting technique. Even if the visual display of static images of the spinal motion already influence the lifting technique (Chan et al., 2019), it still remains unclear which manual lifting technique should be taught in MMH training. However, the research focuses in particular on stoop, squat lifting, semi-squat lifting technique, whilst neglecting others, such as straddle and kneeling lifting techniques (Kingma et al., 2006). Squat lifting seems to be widely accepted as the "correct" way of lifting (Abdoli-Eramaki et al., 2019). However, there is no consistent evidence of the effectiveness of a particular lifting technique and it is known that no single lifting technique can be advised for all lifting conditions (Burgess-Limerick, 2003; Kingma et al., 2006; Straker, 2003; van Dieën et al., 1999; Washmuth et al., 2022). Such studies may show that the actual lifting technique may be less important than the lifting conditions, such as load placement, time pressure and experience, or small measures like shifting or tilting the load (Faber et al., 2011; Gagnon et al., 2016; Marras et al., 2006; Riley et al., 2015; van Dieën et al., 1999).

This raises the question of whether real-time visual feedback of L5/S1 compression forces based on markerless optical motion capture provides appropriate MMH instructions to improve the lifting technique in MMH. To answer this question, an experimental study was conducted to investigate two hypotheses. It was first, hypothesized that visual MMH instructions result in significantly reduced factors associated with LBP risk compared to a control condition in which no instructions were provided. Furthermore, it was hypothesized that MMH instructions with real-time visual feedback of L5/S1 compression force decrease significantly those factors associated with LBP risk compared to the MMH instructions with a paper-based tutorial.

2. Materials and methods

2.1. Population sample and task

An opportunity sample of 22 male university students without work experience with MMH participated in the study. Musculoskeletal pain and injury history of the last year were asked for the back, neck, shoulder and knee, and selected as criterion of exclusion prior to participating in this study. The participants had a mean (SD) age of 25 years (2), a height of 1.82 m (0.07) and a body mass of 81.8 kg (14.1). An informed written consent was obtained prior to participating in the experiment, which was performed in accordance with the ethical guidelines of the RWTH Aachen University and the approval form of the Ethics Committee of the RWTH Aachen University (EK 236/16).

The experimental task to be performed by the participants was to walk 3 m to a chain saw (STIHL MS 231 with a weight of 5.8 kg), lift it up from the ground and walk 2 m farther for the execution of a simulated sawing task and put the saw down on the ground in reverse. During walking, the chainsaw was held at about hip level. The chain saw was used because it could be embedded in a realistic use case in which the participants did not concentrate exclusively on the MMH task. The focus is the analysis of changes in the execution of the MMH task during the lifting phase with a chain saw. The application of different MMH techniques can also lead to changes before the actual lifting, which is why human movements are analyzed to be between a distance of 1 m before and 1 m after the chain saw.

2.2. Experimental design

A mixed-subject design was used. Each participant was tested in a baseline condition without prior lifting instructions to investigate the individual lifting technique. Afterwards, two independent randomly selected samples of 11 participants out of the population sample were selected to test the lifting technique in two intervention conditions. In intervention condition 1, visual instructions by individual real-time visual feedback of the compression force of the intervertebral disc in L5/S1 (CF) were given on a screen in a CF-time diagram during the execution of the lifting task (Fig. 1). The required data were obtained by a real-time markerless motion capture system. In the intervention condition 2, visual instructions were presented by a static paper-based tutorial, consisting of a textual description of “10 golden rules for correct lifting and carrying” and photographs of recommended and awkward lifting postures. The tutorial used was published by the Institution for the Woodworking and Metalworking Industries (BGHM) of the German Social Accident Insurance (DGUV), which is legally responsible for the prevention of accidents at work, occupational diseases and work-related health hazards. The paper-based tutorial was chosen as reference instruction because it is widely used in Germany’s occupational practice.

Investigated variables were selected with respect to the review by Straker (2002). The associated LBP risk of the MMH task was primarily investigated based on of the biomechanical criteria compression force (peak CF) and cumulative loading (mean CF and duration). Cumulative loading was investigated with the two main factors of commonly used models, which provided an opportunity to estimate model results since no model appears to be superior to the others (Johnen et al., 2021a, 2021b). Variables of psychophysical, physiological, psychological and epidemiological criteria were not included with respect to the study design, i.e. low number of repetitions, low total lifting duration, self-selected lifting technique and high accuracy requirements. Furthermore, various indicators of posture were reported as secondary variables, so changes in the primary variables could be interpreted. These investigated secondary variables were peak and mean flexion of trunk and knees as well as electrical activity of primarily associated muscles for trunk and knee flexion, i.e. right and left m. erector spinae longissimus (RES/LES) and right and left m. rectus femoris (RRF/LRF).

Fig. 1. Experimental setup for intervention condition 1 (real-time feedback of CF).

2.3. Procedure

The experimental procedure involved a sequence of preparation phase, baseline phase, intervention phase and post-processing phase. During the preparation phase, participants were prepared for the sampling of surface electromyography (sEMG) signals by a sensor and placement procedure in accordance with the European Recommendations for sEMG for Non-Invasive Assessment of Muscles (SENIAM) as defined by Hermens et al. (1999, 2000). To ensure good signal quality, the skin of the participants was prepared by hair removal and cleaning of the skin using an abrasive paste. Prior to the second phase, peak maximal voluntary contraction was obtained for each muscle as reference contraction obtained prior to the intervention phase in accordance with SENIAM (Hermens et al., 1999). During the baseline phase, the participants executed the experimental task five times without prior instructions on lifting techniques after a short familiarization. During the intervention phase, the participants were randomly assigned to one of the two intervention conditions. After a short familiarization, the experimental task was executed five times. In the intervention condition 1, the participants were informed that CF is individually calculated in real time and displayed as CF-time diagram on a screen in front of the chain saw. Based on a standardized experimental guide, the participants were informed about the location of the intervertebral disc in L5/S1 and that in occupational safety and health guidelines conditions with low CF are associated with an ergonomic and healthy lifting technique. In the intervention condition 2, the participants were shown a visual paper-based tutorial once prior to the execution of the experimental task. During the post-processing phase, the electrodes were removed and a short post-interview was conducted.

2.4. Data recording, processing and analysis

Biomechanical and performance parameters were recorded at a rate of 30 Hz using a Kinect V2 range sensor (Microsoft, USA), because it is widely used for markerless motion capture and has technological advantages over the Kinect V1 range sensor (Yang et al., 2015). Validation studies of the data obtained by the Kinect range sensor concluded that the accuracy is sufficient for several applications, such as anthropometric measurements (Bonnechère et al., 2014), postural control (Clark et al., 2012), measuring gait parameters (Clark et al., 2013; Xu et al., 2015), measuring workload parameters of observational methods (Diego-Mas and Alcaide-Marzal, 2014; Dutta, 2012; Manghisi et al., 2017; Patrizi et al., 2016; Plantard et al., 2017; Spector et al., 2014), pose estimation (Plantard et al., 2015; Xu and McGorry, 2015), and body angles (Brunner et al., 2022; Tarabini et al., 2018; Xu et al., 2017).

The CF was calculated for each frame using a dynamic biomechanical model (Jäger, 1987; Jäger et al., 1991, 2013; Jäger and Luttmann, 1989). The transfer phase of the load was identified by manual observation and pressing a button by an operator. Furthermore, the individual real-time CF for intervention condition 1 was displayed on a screen as CF-time diagram. The trunk and knee flexions were calculated based on ISO 11226 and EN 1005-4. The joint coordinates of the Kinect V2 range sensor were used as input for calculations, without applying any further filtering to kinematics.

The execution time (ET) was calculated based on the number of frames captured by the Kinect V2 range sensor while the participant's head point was within a distance of 1 m before and 1 m after the chainsaw.

The muscular parameters were recorded using the sEMG device Desktop DTS Receiver (Noraxon, USA). Ag/AgCl self-adhesive 8-shaped dual electrodes (dimensions of adhesive: 4 × 2.2 cm; diameter of the two circular adhesives: 1 cm; inter-electrode distance: 1.75 cm) were used. The signals were amplified with a gain of 1000 V/V, an input impedance of 100 MΩ and a common mode rejection ratio of 100 dB. The signals were sampled with a sampling frequency of 1500 Hz and digitally band-pass filtered (10–500 Hz) with a first-order high-pass filter. The signals were recorded using the analysis software MyoResearch 3.8 (Noraxon, US). The root mean square (RMS) amplitude was calculated with an overlapping moving window of 100 ms (Hermens et al., 1999). In order to compare sEMG data for different conditions, mean RMS values were normalized to percent muscle activation by using the peak of the corresponding maximum voluntary reference contraction.

The values of the dependent variables were derived by averaging over the five repetitions in baseline condition and intervention conditions each. All statistical analyses were conducted using SPSS version 27.0. The first hypothesis investigated the effect of MMH instructions on the lifting technique with repeated measures analysis of variance (ANOVA). Therefore, the baseline condition was compared to the intervention conditions regardless of whether they were based on individual real-time feedback of compression force of the intervertebral disc in L5/S1 or on a paper-based tutorial. The second hypothesis investigated the type of visual MMH instructions. Therefore, analyses of covariance (ANCOVA) were performed between intervention condition 1 (real-time feedback of CF) and intervention condition 2 (paper-based tutorial) with the covariate baseline condition. Type one error probabilities were accepted at an α-level of $p = .0038$, which is adjusted by the Bonferroni correction due to multiple comparisons of $n = 13$.

3. Results

Per participant, the results are based on five repetitions of the experimental task in the baseline condition and five repetitions in the intervention condition. A typical progression of CF is shown in Fig. 2 for one repetition of the same participant.

3.1. Effect of visual MMH instructions

Repeated-measures ANOVA revealed that all primary variables are significantly lower in intervention conditions with MMH instructions compared to the baseline condition without MMH instructions and the first hypothesis can be accepted. In secondary parameters, a significant effect could be observed in peak and mean trunk flexion, whereas the other parameters are not significantly affected by intervention conditions. Mean values, standard deviations and ANOVA values of the variables are shown in Table 1 and Fig. 3.

Table 1
Mean values (standard deviations) of measured variables in baseline condition and both intervention conditions (***p < .0038, adjusted by the Bonferroni correction***). (CF = compression force of the intervertebral disc in L5/S1, ET = Execution time, RES/LES = right and left m. erector spinae longissimus, RRF/LRF = right and left m. rectus femoris).

Primary variables	Baseline condition	Intervention conditions	F	p	η_p
Peak CF	**3.82 kN (0.5)**	**3.35 kN (0.5)**	**$F(1,21) = 33.744$**	**< .001**	**.616**
Mean CF	**3.02 kN (0.5)**	**2.53 kN (0.4)**	**$F(1,21) = 65.117$**	**< .001**	**.756**
ET of the manual lifting task	**2.61 s (0.8)**	**4.37 s (1.5)**	**$F(1,21) = 50.291$**	**< .001**	**.705**
Secondary variables	**Baseline condition**	**Intervention conditions**	**F**	**p**	**η_p**
Peak trunk flexion	**75.25 ° (12.9)**	**54.22 ° (14.8)**	**$F(1,21) = 34.920$**	**< .001**	**.624**
Mean trunk flexion	**45.09 ° (10.4)**	**31.38 ° (9.0)**	**$F(1,21) = 45.164$**	**< .001**	**.683**
Mean muscle activity of RES	22.61 % MVC (7.7)	20.89 %MVC (7.0)	$F(1,21) = 1.427$	.246	.064
Mean muscle activity of LES	28.8 %MVC (12.5)	23.0 %MVC (9.8)	$F(1,21) = 3.044$	.096	.127
Peak right knee flexion	33.87 ° (16.6)	35.93 ° (16.3)	$F(1,21) = 0.313$	.582	.015
Mean right knee flexion	104.61 ° (9.5)	104.14 ° (10.3)	$F(1,21) = 0.028$	.869	.001
Mean muscle activity of RRF	15.74 % MVC (8,6)	13.31 %MVC (8.2)	$F(1,21) = 2.637$	.119	.112
Peak left knee flexion	23.79 ° (9.9)	26.76 ° (11.9)	$F(1,21) = 1.826$	.191	.080
Mean right knee flexion	70.40 ° (8.3)	66.43 ° (10.3)	$F(1,21) = 4.056$	.057	.162
Mean muscle activity of LRF	17.81 % MVC (11.2)	20.12 %MVC (24.3)	$F(1,21) = 0.189$	.668	.009

3.2. Comparison of the type of visual MMH instructions

ANCOVA revealed that peak and mean CF are significantly lower in intervention condition 1 (instructions given by individual real-time feedback of CF) compared to intervention condition 2 (instructions given by a paper-based tutorial). However, there was no significant effect for ET. In general, primary variables support the second hypothesis. Apart from peak trunk flexion, no significant effect could be found for the other secondary variables. Mean values, standard deviations and ANCOVA values of the variables are shown in Table 2 and Fig. 4.

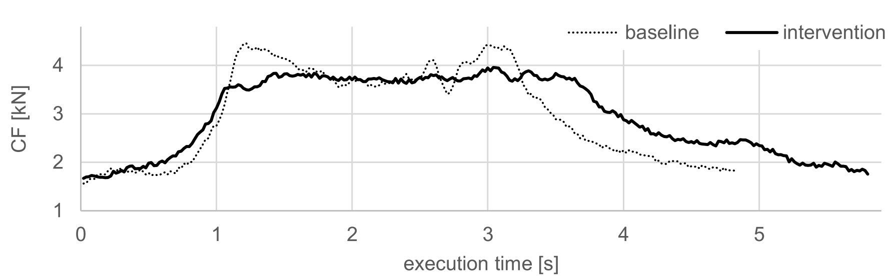

Fig. 2. Compression force of the intervertebral disc in L5/S1 (CF) over execution time comparing baseline and intervention condition for a typical example of one repetition of the manual materials handling task.

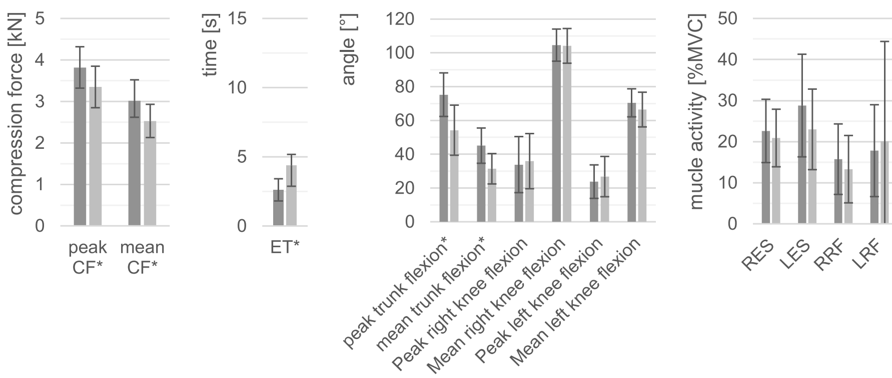

Fig. 3. Mean values of measured variables in baseline condition (dark gray) and both intervention conditions (light gray) (*p < .0038, adjusted by the Bonferroni correction). Error bars indicated standard deviations. (CF = compression force of the intervertebral disc in L5/S1, ET = Execution time, RES/LES = right and left m. erector spinae longissimus, RRF/LRF = right and left m. rectus femoris).

Table 2
Mean values (standard deviations) and ANVOVA values of measured variables in both intervention conditions (***p < .0038, adjusted by the Bonferroni correction***). (condition 1 = instructions given by individual real-time feedback of CF, condition 2 = instructions given by a paper-based tutorial, CF = compression force of the intervertebral disc in L5/S1, ET = Execution time, RES/LES = right and left m. erector spinae longissimus, RRF/LRF = right and left m. rectus femoris).

Primary variables	Condition 1	Condition 2	F	p	η_p	Covariate
Peak CF	3.11 kN (0.5)	3.60 kN (0.4)	F(1,19) = 18.414	<.001	.492	sign.
Mean CF	2.39 kN (0.4)	2.67 kN (0.4)	F(1,19) = 12.804	.002	.403	sign.
ET of the manual lifting task	4.75 s (1.8)	4.0 s (1.1)	F(1,19) = 2.675	.118	.123	sign.
Secondary variables	**Condition 1**	**Condition 2**	**F**	**p**	**η_p**	**Covariate**
Peak trunk flexion	**45.67 ° (14.8)**	**62.77 ° (9.0)**	**F(1,19) = 11.121**	**.003**	**.369**	**n. sign.**
Mean trunk flexion	27.32 ° (10.2)	35.43 ° (5.5)	F(1,19) = 6.386	.021	.252	n. sign.
Mean muscle activity of RES	21.19 %MVC (6.4)	20.59 %MVC (7.0)	F(1,19) = 0.038	.848	.002	n. sign.
Mean muscle activity of LES	21.51 %MVC (6.0)	24.58 %MVC (12.7)	F(1,19) = 0.506	.486	.026	n. sign.
Peak right knee flexion	36.31 ° (17.7)	35.54 ° (15.5)	F(1,19) = 0.332	.571	.017	n. sign.
Mean right knee flexion	101.86 ° (7.3)	106.41 ° (12.6)	F(1,19) = 0.882	.360	.044	n. sign.
Mean muscle activity of RRF	10.35 %MVC (6.5)	16.27 %MVC (8.9)	F(1,19) = 1.472	.240	.072	sign.
Peak left knee flexion	26.64 ° (13.1)	25.51 ° (11.1)	F(1,19) = 0.505	.486	.026	sign.
Mean right knee flexion	68.24 ° (9.2)	64.61 ° (11.3)	F(1,19) = 0.042	.840	.002	n. sign.
Mean muscle activity of LRF	12.61 %MVC (10.1)	27.63 %MVC (31.8)	F(1,19) = 1.630	.217	.079	n. sign.

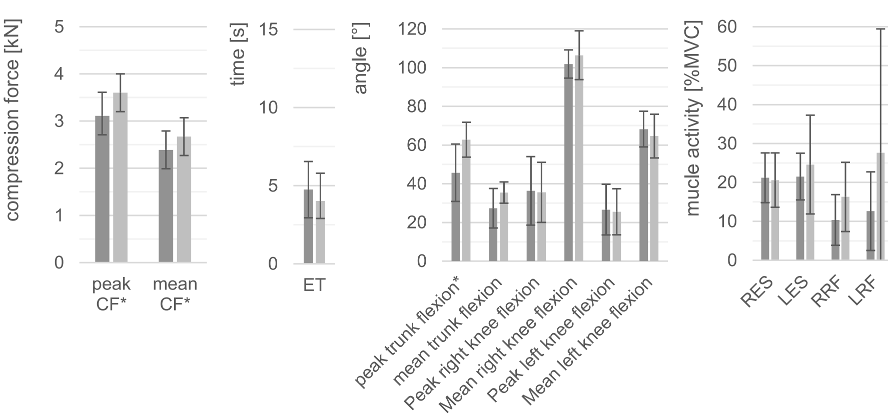

Fig. 4. Mean values of the measured variables in intervention condition 1 with instruction given by individual real-time feedback of CF (dark gray) and intervention condition 2 with instructions given by a paper-based tutorial (light gray) (*p < .0038, adjusted by the Bonferroni correction). Error bars indicated standard deviations. (CF = compression force of the intervertebral disc in L5/S1, ET = Execution time, RES/LES = right and left m. erector spinae longissimus, RRF/LRF = right and left m. rectus femoris).

4. Discussion

This study aimed to answer the question of whether real-time visual feedback of L5/S1 compression forces based on markerless optical motion capture provides appropriate MMH instructions to improve the lifting technique in MMH. For this purpose, it was first examined whether visual MMH instructions can reduce factors associated with LBP risk regardless of whether they are based on the individual real-time feedback of the compression force of the intervertebral disc in L5/S1 or on a paper-based tutorial. The results revealed a significant decrease in peak and mean compression force of the intervertebral disc in L5/S1, the execution time of the MMH task as well as the peak and mean trunk flexion for intervention conditions compared to the baseline condition. Secondly, it was investigated whether visual MMH instructions with individual real-time feedback of the compression force of the intervertebral disc in L5/S1 significantly decrease factors associated with LBP risk compared to MMH instructions with a paper-based tutorial. The results reveal a significantly lower mean and peak compression force of the intervertebral disc in L5/S1 and peak trunk flexion for the visual instructions given by the individual real-time feedback of the compression force of the intervertebral disc in L5/S1 compared to the visual instructions by a paper-based tutorial. The secondary variables of the mean trunk and knee flexions and their associated muscle activities significantly were not significantly affected. However, possible neck extensions were not investigated. From the results of the study, it can be concluded that visual MMH instructions can decrease factors associated with LBP risk and therefore can lead to a healthier lifting technique. Furthermore, it seems that the individual real-time feedback of the compression force of intervertebral disc in L5/S1 is advantageous over a paper-based tutorial in reducing factors associated with LBP.

There is still little evidence of the effectiveness of MMH training in general (Denys Denis et al., 2020; Hogan et al., 2014), the results of the study indicate that visual instructions can be effective in reducing factors associated with LBP risk and therefore be part of MMH training. This is in line with the results obtained by Vignais et al. (2013) and Faucett et al. (2002). Studies using other approaches found similar effects (Oppici et al., 2021; Punt et al., 2020). Thus, it seems that real-time feedback can be a good approach to motion learning. Referring to the results of this study, namely that people without instructions perform lifting techniques with significantly higher LPB risk, the fundamental question arises as to why. When performing movements, humans usually aim for the lowest perceivable exertion. As exertions on the intervertebral disc of the spine and the skeleton are not directly perceivable, movements are usually adapted to low muscular and cardiovascular exertion. This could be a reason why movements are often learned in such a way that they contribute to a long-term risk of work-related musculoskeletal disorders. Moreover, according to the regulation theory, once a movement has been learned, it is extremely difficult to change, as it is performed as a skill-based behavior in the lowest regulation level. This is supported by the findings of Brueckner et al. (2019) and Schaefer and Scornaienchi (2020) who showed a decrease in cognitive demands for motor control as well as physical exertion over time. Furthermore, the human organism is subject to autonomous adaptation processes as a reaction on load over time, e.g., to strengthen muscles and the cardiovascular system. As a result, the perceived exertion in the muscular and cardiovascular system decreases and with it the subconscious needs to perform lifting techniques that are associated with higher risks of musculoskeletal disorders in the long term. Consequently, the very early learning of healthy and ergonomic movements should not only be a goal of occupational safety and health, but also of (early) childhood education.

The measured significant differences between baseline and intervention conditions may, however, also be due to a change in the lifting technique, as no instructions were given regarding the lifting technique to be used. It was observed that the execution of the MMH task without instructions was primarily performed applying the stoop technique, whereas the instructions with a paper-based tutorial led to a primary application of the squat technique. Instructions with individual real-time feedback of the compression force of the intervertebral disc in L5/S1 encourage the application of the straddle or kneeling technique (Fig. 5). These changes in lifting technique could also be a possible explanation for the differences from RRF and LRF muscle activity. Changes in secondary parameters were not the focus of this study, so investigations of whether changes in lifting technique lead to increased risk to other body areas, such as the knee, must be the subject of specific follow-up studies. According to Straker (2002), however, knee loads are no criteria in the evaluation of lifting techniques.

The approach described in this article allows people to find and improve their own MMH technique based on posture- and motion-oriented feedback based on CF. Additional education and instructions by occupational safety and health practitioners could help in finding an even better MMH technique or take other conditions such as workplace design or gripping method into account. For example, turning the chainsaw down could reduce the lever arm and consequently the CF.

The study also revealed a significant increase of the execution time, which can be explained by the change in lifting technique described above and a slightly slower movement during lifting. Besides the human need to quickly perform MMH tasks, this increase in the execution time can also be related to findings of regulation theory (Rasmussen, 1983) and can be explained by the change from a skill-based behavior to a higher regulation level. Consequently, it can be assumed that this increase in the execution time can be reduced by continuous repetitions in an effective MMH training using individual real-time feedback of the compression force of the intervertebral disc in L5/S1 when the information processing necessary for the execution of the MMH task takes place again in the regulation level of skill-based behavior. However, the increase in the execution time leads to a fundamental problem of interpretation regarding the effectiveness in reducing the risk of work-related musculoskeletal disorders or LBP, which is considered a well-known challenge of ergonomic research, namely that little is known about the relative importance of each risk factor (G. Li and Buckle, 1999; Takala et al., 2010). Accordingly, the weighting of the different risk factors is in constant scientific discussion, e.g., the effect of peak vs. time in cumulative loads (Gallagher and Schall, 2017; Johnen et al., 2021b; Waters et al., 2006). In ergonomic assessment methods, the influence of load intensity is basically weighted higher than that of load duration. However, the ergonomic assessment of different lifting techniques in MMH, which in turn causes differences in execution time

Fig. 5. Manual materials handling task applying the stoop technique (left), squat technique (middle) and straddle technique (right).

and load intensity, is still an unsolved issue that needs to be addressed. However, cumulative load could be used as another variable to investigate, as cumulative load could be increased, when intensity is lower, and duration is higher as shown in the study results.

It should further be pointed out that all executions of the MMH task are biased by the experimental task, e.g. participants could choose their own lifting technique, partly asymmetry and unbalance in lifting of the chain saw and lab environment. It should also be noted that this study has not considered possible age- and sex-based physiological differences, which certainly warrant systematic research, as they may lead to different conclusions regarding the use and instruction of lifting techniques. Low number of repetitions, type of clothes and free sight between participant and range sensor should be mentioned as further limitations of the study results. Shear forces were not included in the study as biomechanical criteria to be investigated, as it was expected that trunk flexion would improve. However, peak shear forces are relevant for assessing associated LBP risk in MMH tasks, particularly when a certain intensity of trunk flexion, pushing or pulling are involved (Gallagher and Marras, 2012; Straker, 2002). It must be further mentioned that despite a large number of studies that evaluated Kinect V2 range sensors as sufficiently accurate for applications in ergonomics as shown in the methods section, there are also studies that come to more conservative conclusions (Asadi and Arjmand, 2020). The identification of the load's transfer phase by manual observation and pressing a button is quite inaccurate. However, as human movements are analyzed between a distance of 1 m before and 1 m after the chain saw, the influence of this inaccuracy on the study results should not be too large. Before implementing such a system in practice an automated identification of the load's transfer phase should be implemented.

If, in contrast to this study, the long-term effects of MMH training are investigated, there is the major challenge that other work or leisure exposures increase the variance of the measured variables, which can be almost standardized when investigating short-term effects. However, when investigating short-term effects, it is difficult to assess whether body systems are affected reversibly or irreversibly and whether the long-term LBP risk changes. From a practical perspective, however, it is still unclear how individual real-time feedback of CF will affect knowledge retention. If individual real-time feedback can be sustained by continuous repetitions over several weeks or months, it may be concluded that such MMH training promotes long-term effectiveness. Following this, the study results indicate that the still limited evidence of the long-term effectiveness of MMH training in the prevention of LBP might be more related to the ineffectiveness of the training rather than to the instructions, as the effectiveness itself was shown to be short term.

5. Conclusions

The results show that visual MMH instructions with a paper-based tutorial and with individual real-time feedback of the compression force of the intervertebral disc in L5/S1 lead to reduced factors associated with LBP when executing MMH tasks compared to no instructions given. Accordingly, it can be concluded that MMH instructions can provide proper assistance for a better execution of MMH tasks.

Regarding the type of instructions, the results show that visual MMH instructions with individual real-time feedback of the compression force of the intervertebral disc in L5/S1 have significant advantages in improving the lifting technique compared to instructions with a paper-based tutorial. Therefore, using individual real-time feedback of the compression force of the intervertebral disc in L5/S1 based on markerless optical motion capture could be a suitable element for instruction in MMH training programs or on-the-job training to reduce or prevent LBP in the future.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdoli-Eramaki, M., Agababova, M., Janabi, J., Pasko, E., Damecour, C., 2019. Evaluation and comparison of lift styles for an ideal lift among individuals with different levels of training. Appl. Ergon. 78, 120–126. https://doi.org/10.1016/j.apergo.2019.02.007.
Anwer, S., Li, H., Antwi-Afari, M.F., Wong, A.Y.L., 2021. Associations between physical or psychosocial risk factors and work-related musculoskeletal disorders in construction workers based on literature in the last 20 years: a systematic review. Int. J. Ind. Ergon. 83 (12), 103113 https://doi.org/10.1016/j.ergon.2021.103113.
Asadi, F., Arjmand, N., 2020. Marker-less versus marker-based driven musculoskeletal models of the spine during static load-handling activities. J. Biomech. 112, 110043 https://doi.org/10.1016/j.jbiomech.2020.110043.
Beach, T.A.C., Frost, D.M., Callaghan, J.P., 2014. Fms™ scores and low-back loading during lifting–whole-body movement screening as an ergonomic tool? Appl. Ergon. 45 (3), 482–489. https://doi.org/10.1016/j.apergo.2013.06.009.
Beach, T.A.C., Stankovic, T., Carnegie, D.R., Micay, R., Frost, D.M., 2018. Using verbal instructions to influence lifting mechanics - does the directive "lift with your legs, not your back" attenuate spinal flexion? J. Electromyogr. Kinesiol. : Official Journal of the International Society of Electrophysiological Kinesiology 38, 1–6. https://doi.org/10.1016/j.jelekin.2017.10.008.
Bonnechère, B., Jansen, B., Salvia, P., Bouzahouene, H., Sholukha, V., Cornelis, J., Rooze, M., van Sint Jan, S., 2014. Determination of the precision and accuracy of morphological measurements using the Kinect™ sensor: comparison with standard stereophotogrammetry. Ergonomics 57 (4), 622–631. https://doi.org/10.1080/00140139.2014.884246.
Brandl, C., Mertens, A., Schlick, C.M., 2017. Ergonomic analysis of working postures using OWAS in semi-trailer assembly, applying an individual sampling strategy. Int. J. Occup. Saf. Ergon. : JOSE 23 (1), 110–117. https://doi.org/10.1080/10803548.2016.1191224.
Brueckner, D., Göpfert, B., Kiss, R., Muehlbauer, T., 2019. Effects of motor practice on learning a dynamic balance task in healthy young adults: a wavelet-based time-frequency analysis. Gait Posture 70, 264–269. https://doi.org/10.1016/j.gaitpost.2019.03.019.
Brunner, O., Mertens, A., Nitsch, V., Brandl, C., 2022. Accuracy of a markerless motion capture system for postural ergonomic risk assessment in occupational practice. Int. J. Occup. Saf. Ergon. : JOSE 28 (3), 1865–1873. https://doi.org/10.1080/10803548.2021.1954791.
Burgess-Limerick, R., 2003. Squat, stoop, or something in between? Int. J. Ind. Ergon. 31 (3), 143–148. https://doi.org/10.1016/S0169-8141(02)00190-7.
Chan, V.C.H., Welsh, T.N., Frost, D.M., Beach, T.A.C., 2019. Using visual aids to influence manual lifting techniques: acute effects of viewing static images on spine motion. Int. J. Occup. Saf. Ergon. : JOSE. https://doi.org/10.1080/10803548.2019.1620489, 1–8.
Chan, V.C.H., Welsh, T.N., Tremblay, L., Frost, D.M., Beach, T.A.C., 2022. A comparison of augmented feedback and didactic training approaches to reduce spine motion during occupational lifting tasks. Appl. Ergon. 99, 103612 https://doi.org/10.1016/j.apergo.2021.103612.
Clark, R.A., Bower, K.J., Mentiplay, B.F., Paterson, K., Pua, Y.-H., 2013. Concurrent validity of the Microsoft Kinect for assessment of spatiotemporal gait variables. J. Biomech. 46 (15), 2722–2725. https://doi.org/10.1016/j.jbiomech.2013.08.011.
Clark, R.A., Pua, Y.-H., Fortin, K., Ritchie, C., Webster, K.E., Denehy, L., Bryant, A.L., 2012. Validity of the Microsoft Kinect for assessment of postural control. Gait Posture 36 (3), 372–377. https://doi.org/10.1016/j.gaitpost.2012.03.033.
Clemes, S.A., Haslam, C.O., Haslam, R.A., 2010. What constitutes effective manual handling training? A systematic review. Occup. Med. (Oxf.) 60 (2), 101–107. https://doi.org/10.1093/occmed/kqp127.
Colloca, C.J., Hinrichs, R.N., 2005. The biomechanical and clinical significance of the lumbar erector spinae flexion-relaxation phenomenon: a review of literature. J. Manipulative Physiol. Therapeut. 28 (8), 623–631. https://doi.org/10.1016/j.jmpt.2005.08.005.
Daltroy, L.H., Iversen, M.D., Larson, M.G., Lew, R., Wright, E., Ryan, J., Zwerling, C., Fossel, A.H., Liang, M.H., 1997. A controlled trial of an educational program to prevent low back injuries. N. Engl. J. Med. 337 (5), 322–328. https://doi.org/10.1056/NEJM199707313370507.

David, G.C., 2005. Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders. Occup. Med. (Oxf.) 55 (3), 190–199. https://doi.org/10.1093/occmed/kqi082.

Denis, D.[D.], Lortie, M., Rossignol, M., 2000. Observation procedures characterizing occupational physical activities: critical review. Int. J. Occup. Saf. Ergon. : JOSE 6 (4), 463–491. https://doi.org/10.1080/10803548.2000.11076467.

Denis, D [Denys], Gonella, M., Comeau, M., Lauzier, M., 2020. Questioning the value of manual material handling training: a scoping and critical literature review. Appl. Ergon. 89, 103186 https://doi.org/10.1016/j.apergo.2020.103186.

Diego-Mas, J.A., Alcaide-Marzal, J., 2014. Using Kinect™ sensor in observational methods for assessing postures at work. Appl. Ergon. 45 (4), 976–985. https://doi.org/10.1016/j.apergo.2013.12.001.

Dutta, T., 2012. Evaluation of the Kinect™ sensor for 3-D kinematic measurement in the workplace. Appl. Ergon. 43 (4), 645–649. https://doi.org/10.1016/j.apergo.2011.09.011.

Faber, G.S., Kingma, I., van Dieën, J.H., 2011. Effect of initial horizontal object position on peak L5/S1 moments in manual lifting is dependent on task type and familiarity with alternative lifting strategies. Ergonomics 54 (1), 72–81. https://doi.org/10.1080/00140139.2010.535019.

Faucett, J., Garry, M., Nadler, D., Ettare, D., 2002. A test of two training interventions to prevent work-related musculoskeletal disorders of the upper extremity. Appl. Ergon. 33 (4), 337–347. https://doi.org/10.1016/S0003-6870(02)00006-6.

Gagnon, D., Plamondon, A., Larivière, C., 2016. A biomechanical comparison between expert and novice manual materials handlers using a multi-joint EMG-assisted optimization musculoskeletal model of the lumbar spine. J. Biomech. 49 (13), 2938–2945. https://doi.org/10.1016/j.jbiomech.2016.07.009.

Gallagher, S., Marras, W.S. [William S., 2012. Tolerance of the lumbar spine to shear: a review and recommended exposure limits. Clin. BioMech. 27 (10), 973–978. https://doi.org/10.1016/j.clinbiomech.2012.08.009.

Gallagher, S., Schall, M.C., 2017. Musculoskeletal disorders as a fatigue failure process: evidence, implications and research needs. Ergonomics 60 (2), 255–269. https://doi.org/10.1080/00140139.2016.1208848.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10 (5), 361–374. https://doi.org/10.1016/S1050-6411(00)00027-4.

Hermens, H.J., Freriks, B., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C., Hääg, G., 1999. European recommendations for surface ElectroMyoGraphy: results of the SENIAM project. SENIAM, 8. Roessingh Research and Development.

Hogan, D.A.M., Greiner, B.A., O'Sullivan, L., 2014. The effect of manual handling training on achieving training transfer, employee's behaviour change and subsequent reduction of work-related musculoskeletal disorders: a systematic review. Ergonomics 57 (1), 93–107. https://doi.org/10.1080/00140139.2013.862307.

Jäger, M., 1987. Biomechanisches Modell des Menschen zur Analyse und Beurteilung der Belastung der Wirbelsäule bei der Handhabung von Lasten. Zugl. Biotechnik. In: Fortschritt-Berichte/VDI Reihe 17, vol. 33. Dortmund, Univ., Diss, 1986 VDI-Verl.

Jäger, M., 2018. Extended compilation of autopsy-material measurements on lumbar ultimate compressive strength for deriving reference values in ergonomic work design: the Revised Dortmund Recommendations. EXCLI Journal 17, 362–385. https://doi.org/10.17179/excli2018-1206.

Jäger, M., Jordan, C., Theilmeier, A., Wortmann, N., Kuhn, S., Nienhaus, A., Luttmann, A., 2013. Lumbar-load analysis of manual patient-handling activities for biomechanical overload prevention among healthcare workers. Ann. Occup. Hyg. 57 (4), 528–544. https://doi.org/10.1093/annhyg/mes088.

Jäger, M., Luttmann, A., 1989. Biomechanical analysis and assessment of lumbar stress during load lifting using a dynamic 19-segment human model. Ergonomics 32 (1), 93–112. https://doi.org/10.1080/00140138908966070.

Jäger, M., Luttmann, A., Laurig, W., 1991. Lumbar load during one-handed bricklaying. Int. J. Ind. Ergon. 8 (3), 261–277. https://doi.org/10.1016/0169-8141(91)90037-M.

Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2021a. Comparison of dose models for the assessment of spinal load and implications for the calculation of cumulative loading. In: Black, N.L., Neumann, W.P., Noy, I. (Eds.), Lecture Notes in Networks and Systems. Proceedings of the 21st Congress of the International Ergonomics Association, 18, 2021: Volume IV: Healthcare and Healthy Work, vol. 222. Springer International Publishing, pp. 93–100. https://doi.org/10.1007/978-3-030-74611-7_13 *(IEA 2021), held online on June 13-*.

Johnen, L., Mertens, A., Nitsch, V., Brandl, C., 2021b. Why cumulative loading calculated using non-weighted integration may not be suitable for assessing physical stress of the lower back: an empirical investigation of strain during lifting and lowering tasks. Ergonomics 35 (3), 1–13. https://doi.org/10.1080/00140139.2021.1962547.

Kamachi, M., Owlia, M., Dutta, T., 2021. Evaluating a wearable biofeedback device for reducing end-range sagittal lumbar spine flexion among home caregivers. Appl. Ergon. 97, 103547 https://doi.org/10.1016/j.apergo.2021.103547.

Kernozek, T., Iwasaki, M., Fater, D., Durall, C., Langenhorst, B., 2006. Movement-based feedback may reduce spinal moments in male workers during lift and lowering tasks. Physiother. Res. Int. : The Journal for Researchers and Clinicians in Physical Therapy 11 (3), 140–147. https://doi.org/10.1002/pri.335.

Kingma, I., Faber, G.S., Bakker, A.J.M., van Dieën, J.H., 2006. Can low back loading during lifting Be reduced by placing one leg beside the object to Be lifted? Phys. Ther. 86 (8), 1091–1105. https://doi.org/10.1093/ptj/86.8.1091.

Lavender, S. A [Steven A.], Lorenz, E.P., Andersson, G.B.J., 2007. Can a new behaviorally oriented training process to improve lifting technique prevent occupationally related back injuries due to lifting? Spine 32 (4), 487–494. https://doi.org/10.1097/01.brs.0000255203.96898.f2.

Li, G., Buckle, P., 1999. Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods. Ergonomics 42 (5), 674–695. https://doi.org/10.1080/001401399185388.

Li, L., Martin, T., Xu, X., 2020. A novel vision-based real-time method for evaluating postural risk factors associated with musculoskeletal disorders. Appl. Ergon. 87, 103138 https://doi.org/10.1016/j.apergo.2020.103138.

Lind, C.M., Yang, L., [Liyun], Abtahi, F., Hanson, L., Lindecrantz, K., Lu, K., Forsman, M., Eklund, J., 2020. Reducing postural load in order picking through a smart workwear system using real-time vibrotactile feedback. Appl. Ergon. 89, 103188 https://doi.org/10.1016/j.apergo.2020.103188.

Linton, S.J., van Tulder, M.W., 2001. Preventive interventions for back and neck pain problems: what is the evidence? Spine 26 (7), 778–787. https://doi.org/10.1097/00007632-200104010-00019.

Maher, C.G. [Christopher G., 2000. A systematic review of workplace interventions to prevent low back pain. Aust. J. Physiother. 46 (4), 259–269. https://doi.org/10.1016/S0004-9514(14)60287-7.

Manghisi, V.M., Uva, A.E., Fiorentino, M., Bevilacqua, V., Trotta, G.F., Monno, G., 2017. Real time RULA assessment using Kinect v2 sensor. Appl. Ergon. 65, 481–491. https://doi.org/10.1016/j.apergo.2017.02.015.

Marras, W.S.[W.S.], Parakkat, J., Chany, A.M., Yang, G., Burr, D., Lavender, S.A.[S.A., 2006. Spine loading as a function of lift frequency, exposure duration, and work experience. Clin. BioMech. 21 (4), 345–352. https://doi.org/10.1016/j.clinbiomech.2005.10.004.

Martimo, K.-P., Verbeek, J., Karppinen, J., Furlan, A.D., Takala, E.-P., Kuijer, P.P.F.M., Jauhiainen, M., Viikari-Juntura, E., 2008. Effect of training and lifting equipment for preventing back pain in lifting and handling: systematic review. Br. Med. J. 336 (7641), 429–431. https://doi.org/10.1136/bmj.39463.418380.BE.

McDermott, H., Haslam, C., Clemes, S., Williams, C., Haslam, R., 2012. Investigation of manual handling training practices in organisations and beliefs regarding effectiveness. Int. J. Ind. Ergon. 42 (2), 206–211. https://doi.org/10.1016/j.ergon.2012.01.003.

Mehrizi, R., Xu, X., Zhang, S., Pavlovic, V., Metaxas, D., Li, K., 2017. Using a marker-less method for estimating L5/S1 moments during symmetrical lifting. Appl. Ergon. 65, 541–550. https://doi.org/10.1016/j.apergo.2017.01.007.

Mullineaux, D.R., Underwood, S.M., Shapiro, R., Hall, J.W., 2012. Real-time biomechanical biofeedback effects on top-level rifle shooters. Appl. Ergon. 43 (1), 109–114. https://doi.org/10.1016/j.apergo.2011.04.003.

Oppici, L., Grütters, K., Garofolini, A., Rosenkranz, R., Narciss, S., 2021. Deliberate practice and motor learning principles to underpin the design of training interventions for improving lifting movement in the occupational sector: a perspective and a pilot study on the role of augmented feedback. Frontiers in Sports and Active Living 3, 746142. https://doi.org/10.3389/fspor.2021.746142.

Overton, M., Reynolds, E., Clark, N., Bhana, H., Mulligan, H., Elliott, K., Minnoch, P., 2016. Physical activity levels and injury prevention knowledge and practice of a cohort of carpentry students. N. Z. J. Physiother. 44 (2), 84–90. https://doi.org/10.15619/NZJP/44.2.03.

Owlia, M., Kamachi, M., Dutta, T., 2020. Reducing lumbar spine flexion using real-time biofeedback during patient handling tasks. Work 66 (1), 41–51. https://doi.org/10.3233/WOR-203149.

Patrizi, A., Pennestrì, E., Valentini, P.P., 2016. Comparison between low-cost marker-less and high-end marker-based motion capture systems for the computer-aided assessment of working ergonomics. Ergonomics 59 (1), 155–162. https://doi.org/10.1080/00140139.2015.1057238.

Pinto, B.L., Beaudette, S.M., Brown, S.H.M., 2018. Tactile cues can change movement: an example using tape to redistribute flexion from the lumbar spine to the hips and knees during lifting. Hum. Mov. Sci. 60, 32–39. https://doi.org/10.1016/j.humov.2018.05.004.

Plantard, P., Auvinet, E., Le Pierres, A.-S., Multon, F., 2015. Pose estimation with a Kinect for ergonomic studies: evaluation of the accuracy using a virtual mannequin. Sensors 15 (1), 1785–1803. https://doi.org/10.3390/s150101785.

Plantard, P., Shum, H.P.H., Le Pierres, A.-S., Multon, F., 2017. Validation of an ergonomic assessment method using Kinect data in real workplace conditions. Appl. Ergon. 65, 562–569. https://doi.org/10.1016/j.apergo.2016.10.015.

Potvin, J.R., McGill, S.M., Norman, R.W., 1991. Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. Spine 16 (9), 1099–1107. https://doi.org/10.1097/00007632-199109000-00015.

Punt, M., Nematimoez, M., van Dieën, J.H., Kingma, I., 2020. Real-time feedback to reduce low-back load in lifting and lowering. J. Biomech. 102, 109513 https://doi.org/10.1016/j.jbiomech.2019.109513.

Rasmussen, J., 1983. Skills, rules, and knowledge; signals, signs, and symbols, and other distinctions in human performance models. IEEE Transactions on Systems, Man, and Cybernetics, SMC- 13 (3), 257–266. https://doi.org/10.1109/TSMC.1983.6313160.

Ray, S.J., Teizer, J., 2012. Real-time construction worker posture analysis for ergonomics training. Adv. Eng. Inf. 26 (2), 439–455. https://doi.org/10.1016/j.aei.2012.02.011.

Riley, A.E., Craig, T.D., Sharma, N.K., Billinger, S.A., Wilson, S.E., 2015. Novice lifters exhibit a more kyphotic lifting posture than experienced lifters in straight-leg lifting. J. Biomech. 48 (10), 1693–1699. https://doi.org/10.1016/j.jbiomech.2015.05.022.

Roman-Liu, D., 2014. Comparison of concepts in easy-to-use methods for MSD risk assessment. Appl. Ergon. 45 (3), 420–427. https://doi.org/10.1016/j.apergo.2013.05.010.

Sarsfield, J., Brown, D., Sherkat, N., Langensiepen, C., Lewis, J., Taheri, M., McCollin, C., Barnett, C., Selwood, L., Standen, P., Logan, P., Simcox, C., Killick, C., Hughes, E., 2019. Clinical assessment of depth sensor based pose estimation algorithms for technology supervised rehabilitation applications. Int. J. Med. Inf. 121, 30–38. https://doi.org/10.1016/j.ijmedinf.2018.11.001.

Schaefer, S., Scornaienchi, D., 2020. Table tennis experts outperform novices in a demanding cognitive-motor dual-task situation. J. Mot. Behav. 52 (2), 204–213. https://doi.org/10.1080/00222895.2019.1602506.

Sedgwick, A.W., Gormley, J.T., 1998. Training for lifting; an unresolved ergonomic issue? Appl. Ergon. 29 (5), 395–398. https://doi.org/10.1016/S0003-6870(97)00078-1.

Spector, J.T., Lieblich, M., Bao, S., McQuade, K., Hughes, M., 2014. Automation of workplace lifting hazard assessment for musculoskeletal injury prevention. Annals of Occupational and Environmental Medicine 26, 15. https://doi.org/10.1186/2052-4374-26-15.

Steffens, D., Maher, C. G [Chris G.], Pereira, L.S.M., Stevens, M.L., Oliveira, V.C., Chapple, M., Teixeira-Salmela, L.F., Hancock, M.J., 2016. Prevention of low back pain: a systematic review and meta-analysis. JAMA Intern. Med. 176 (2), 199–208. https://doi.org/10.1001/jamainternmed.2015.7431.

Straker, L., 2002. A review of research on techniques for lifting low-lying objects: 1. Criteria for evaluation. Work 19, 9–18.

Straker, L., 2003. Evidence to support using squat, semi-squat and stoop techniques to lift low-lying objects. Int. J. Ind. Ergon. 31 (3), 149–160. https://doi.org/10.1016/S0169-8141(02)00191-9.

Takala, E.-P., Pehkonen, I., Forsman, M., Hansson, G.-A., Mathiassen, S.E., Neumann, W. P., Sjøgaard, G., Veiersted, K.B., Westgaard, R.H., Winkel, J., 2010. Systematic evaluation of observational methods assessing biomechanical exposures at work. Scand. J. Work. Environ. Health 36 (1), 3–24. https://doi.org/10.5271/sjweh.2876.

Tarabini, M., Marinoni, M., Mascetti, M., Marzaroli, P., Corti, F., Giberti, H., Villa, A., Mascagni, P., 2018. Monitoring the human posture in industrial environment: a feasibility study. 2018 IEEE Sensors Applications Symposium (SAS) 1–6. https://doi.org/10.1109/SAS.2018.8336710. IEEE.

van Dieën, J.H., Hoozemans, M.J., Toussaint, H.M., 1999. Stoop or squat: a review of biomechanical studies on lifting technique. Clin. BioMech. 14 (10), 685–696. https://doi.org/10.1016/S0268-0033(99)00031-5.

van Poppel, M.N.M., Hooftman, W.E., Koes, B.W., 2004. An update of a systematic review of controlled clinical trials on the primary prevention of back pain at the workplace. Occup. Med. (Oxf.) 54 (5), 345–352. https://doi.org/10.1093/occmed/kqh065.

van Poppel, M.N.M., Koes, B.W.[B.W.], Smid, T., Bouter, L.M., 1997. A systematic review of controlled clinical trials on the prevention of back pain in industry. Occup. Environ. Med. 54 (12), 841–847. https://doi.org/10.1136/oem.54.12.841.

Verbeek, J.H., Martimo, K.-P., Karppinen, J., Kuijer, P.P.F., Viikari-Juntura, E., Takala, E.-P., 2011. Manual material handling advice and assistive devices for preventing and treating back pain in workers. Cochrane Database Syst. Rev. 6, CD005958. https://doi.org/10.1002/14651858.CD005958.pub3.

Verbeek, J.H., Martimo, K.-P., Kuijer, P.P.F.M., Karppinen, J., Viikari-Juntura, E., Takala, E.-P., 2012. Proper manual handling techniques to prevent low back pain, a Cochrane systematic review. Work 41 (Suppl. 1), 2299–2301. https://doi.org/10.3233/WOR-2012-0455-2299.

Vignais, N., Miezal, M., Bleser, G., Mura, K., Gorecky, D., Marin, F., 2013. Innovative system for real-time ergonomic feedback in industrial manufacturing. Appl. Ergon. 44 (4), 566–574. https://doi.org/10.1016/j.apergo.2012.11.008.

Washmuth, N.B., McAfee, A.D., Bickel, C.S., 2022. Lifting techniques: why are we not using evidence to optimize movement? International Journal of Sports Physical Therapy 17 (1), 104–110. https://doi.org/10.26603/001c.30023.

Waters, T., Yeung, S., Genaidy, A., Callaghan, J., Barriera-Viruet, H., Abdallah, S., Kumar, S., 2006. Cumulative spinal loading exposure methods for manual material handling tasks. Part 2: methodological issues and applicability for use in epidemiological studies. Theor. Issues Ergon. Sci. 7 (2), 131–148. https://doi.org/10.1080/14639220500111459.

Widanarko, B., Legg, S., Stevenson, M., Devereux, J., Eng, A., Mannetje, A. 't, Cheng, S., Pearce, N., 2012. Gender differences in work-related risk factors associated with low back symptoms. Ergonomics 55 (3), 327–342. https://doi.org/10.1080/00140139.2011.642410.

Xu, X., McGorry, R.W., 2015. The validity of the first and second generation Microsoft Kinect™ for identifying joint center locations during static postures. Appl. Ergon. 49, 47–54. https://doi.org/10.1016/J.APERGO.2015.01.005.

Xu, X., McGorry, R.W., Chou, L.-S., Lin, J.-H., Chang, C.-C., 2015. Accuracy of the Microsoft Kinect for measuring gait parameters during treadmill walking. Gait Posture 42 (2), 145–151. https://doi.org/10.1016/j.gaitpost.2015.05.002.

Xu, X., Robertson, M., Chen, K.B., Lin, J.-H., McGorry, R.W., 2017. Using the Microsoft Kinect™ to assess 3-D shoulder kinematics during computer use. Appl. Ergon. 65, 418–423. https://doi.org/10.1016/j.apergo.2017.04.004.

Yang, L [Lin], Zhang, L., Dong, H., Alelaiwi, A., Saddik, A.E., 2015. Evaluating and improving the depth accuracy of Kinect for windows v2. IEEE Sensor. J. 15 (8), 4275–4285. https://doi.org/10.1109/JSEN.2015.2416651.