International Journal of Industrial Ergonomics 53 (2016) 37–47

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Simulation of lifting motions using a novel multi-objective optimization approach

Jiahong Song [a], Xingda Qu [b], *, Chun-Hsien Chen [a]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore
[b] Institute of Human Factors and Ergonomics, College of Mechatronics and Control Engineering, Shenzhen University, Shenzhen, China

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form
12 May 2015
Accepted 12 October 2015
Available online 8 November 2015

Keywords:
Lifting
Human motion simulation
Multi-objective optimization
Physical effort
Load motion smoothness
Age

ABSTRACT

In this study, a novel lifting motion simulation model was developed based on a multi-objective optimization (MOO) approach. Two performance criteria, minimum physical effort and maximum load motion smoothness, were selected to define the multi-objective function in the optimization procedure using a weighted-sum MOO approach. Symmetric lifting motions performed by younger and older adults under varied task conditions were simulated. The results showed that the proposed MOO approach led to up to 18.9% reductions in the prediction errors compared to the single-objective optimization approach. This finding suggests that both minimum physical effort and maximum load motion smoothness play an important role in lifting motion planning. Age-related differences in the mechanisms for planning lifting motions were also investigated. In particular, younger workers tend to rely more on the criterion of minimizing physical effort during lifting motion planning, while maximizing load motion smoothness seems to be the dominant objective for older workers.

Relevance to industry: Lifting tasks are closely associated with occupational low back pain (LBP). In this study, a novel lifting motion simulation model was developed to facilitate the analysis of lifting biomechanics and LBP prevention. Age-related differences in lifting motion planning were discussed for better understanding LBP injury mechanisms during lifting.

1. Introduction

Low back pain (LBP) is one of the most prevalent and costly occupational injuries. In the US, the lifetime prevalence of LBP is over 60% (Krismer and van Tulder, 2007), and the corresponding annual costs exceed $100 billion (Katz, 2006). Manual lifting is a major risk factor for occupational LBP (Garg and Moore, 1992; Hoy et al., 2010), mainly because of the high loads imposed on the lumbar spine during lifting. Therefore, to well address the occupational LBP problem, there is a need for biomechanical analysis on the lifting task, including examining whole-body motions/postures, and estimating the loads imposed onto the body musculoskeletal system (Chaffin et al., 2006).

Many biomechanical models have been developed to estimate the loads exerted onto the human body (e.g., the low back joint moments and forces) during lifting tasks (Chaffin et al., 2006). Whole-body motions always become a necessary input to these models. The traditional way to collect actual human motions is using photographic, optical or inertial measurement systems in the field or lab-based experiment, which is time-consuming and usually results in high financial cost. The use of dynamic motion simulation models has recently evolved into a useful technology which can help predict human motions and reduce the time and costs spent on actual motion data collections (Abdel-Malek et al., 2006; Chaffin, 2005).

A majority of motion simulation models are based on the optimization principle. Various types of human motions, such as reaching (Jung et al., 1995; Jung and Shin, 2010; Mi et al., 2009), lifting (Lin et al., 1999) and walking (Xiang et al., 2009), have been predicted by these models. In these models, the central nervous system (CNS) is assumed to plan human motions using certain performance criteria. These criteria are then used to define objective functions in the optimization procedure to predict human motions. Many performance criteria have been proposed for lifting motion simulation, such as minimum efforts (Gündogdu et al.,

---

* Corresponding author. Institute of Human Factors and Ergonomics, College of Mechatronics and Control Engineering, Shenzhen University, 3688 Nanhai Avenue, Shenzhen, Guangdong Province 518060, China.

E-mail address: quxd@szu.edu.cn (X. Qu).

http://dx.doi.org/10.1016/j.ergon.2015.10.002
0169-8141/© 2015 Elsevier B.V. All rights reserved.

2005; Hsiang and Ayoub, 1994; Lin et al., 1999), maximum dynamic stability (Abedi et al., 2012; Dysart and Woldstad, 1996), minimum low back spinal forces (Xiang et al., 2012a), and maximum load motion smoothness (Hsiang and McGorry, 1997).

One major limitation of the optimization-based models is the difficulty in identifying the ‘true’ performance criteria. This limitation can result in inaccurate and unrealistic predicted motions. To address this limitation, hybrid approaches which incorporate actual human motions into the optimization have been proposed in recent research (Pasciuto et al., 2014; Song et al., 2015; Xiang et al., 2012b). For instance, Pasciuto et al. (2014) and Xiang et al. (2012b) simulated human motions by minimizing the weighted-sum value of a knowledge-based and a data-based objective function. The knowledge-based objective function was defined based on the minimum energy criterion, and the data-based objective function was defined as the minimum difference between the actual and predicted motions. In our prior work (Song et al., 2015), a hybrid optimization-based model was proposed for lifting motion simulation, in which minimum physical effort was used as the performance criterion, and the simulated joint angular velocities were bounded by the time-functional constraints determined by actual motion data.

Chang et al. (2001) suggested that more than one performance criterion might be needed to better predict and explain the lifting behaviour. However, few studies in the existing literature applied more than one performance criterion in their motion simulation. To the best of our knowledge, the only study that used multiple performance criteria for lifting motion simulation was conducted by Xiang et al. (2010) who used a multiple objective optimization approach (MOO) to examine the relative effects of minimum dynamic effort and maximum stability for lifting motion planning. Xiang et al. (2010) found that the MOO approach did not lead to significant improvements on the simulation accuracy compared to the single-objective optimization approach which used the minimum dynamic effort as a single performance criterion. Thus, they suggested that the maximum stability may not be an effective performance criterion for lifting motion simulation, and there is a need to further investigate alternative performance criteria which can be used in the MOO approach for better lifting motion simulation.

Another limitation of the existing models for lifting motion simulation is that they were only used to predict motions for young and/or middle-aged (20–40 years) adults (Chang et al., 2001; Dysart and Woldstad, 1996; Hsiang and McGorry, 1997; Lin et al., 1999; Xiang et al., 2010). Lifting motions of older adults (>55 years) have not been extensively studied using the motion simulation method. In fact, previous experimental studies showed significant distinctions in lifting motion patterns between young and older adults (Song and Qu, 2014a, b), which implies that there exist age-related differences in the mechanisms for planning lifting motions.

To address the limitations of the existing lifting motion simulation models, the objectives of the present study are twofold. First, we aimed to propose a novel lifting motion simulation model using the MOO approach. The second objective was to investigate age-related differences in the mechanisms for lifting motion planning using the proposed lifting simulation model. Specifically, the hybrid model proposed in the prior work (Song et al., 2015) was further developed, in which two performance criteria, including minimum physical effort and maximum smoothness of the external load motion, were investigated. The objective function in the MOO was defined as the weighted sum of the performance measures derived from these two criteria. Lifting motions of younger and older adults were simulated separately to examine age effects on lifting motion planning mechanisms.

2. Actual lifting data collection

Actual lifting motion data from the prior work (Song and Qu, 2014a) were used for the model development and evaluation. Eleven younger participants (six males and five females) aged between 20 and 30 years old and twelve older participants (seven males and five females) aged over 55 years old were recruited from the university and local community. All of them were free from any musculoskeletal disorders in the last six months. The demographic information about their age, height, body weight and maximum lifting capacity (MLC) was listed in Table 1. All participants signed the consent form approved by the Nanyang Technological University Institutional Review Board before the data collection.

Before lifting motion data collection, participants conducted an isokinetic lifting test to measure their MLC using a commercial dynamometer (Biodex System 4 Pro, Shirley, NY, USA). After the MLC measurement, 31 reflective markers were placed on the selected body landmarks of each participant, and the whole-body lifting motions were measured using an eight-camera optoelectronic motion capture system (Motion Analysis Eagle System, Santa Rosa, CA, USA). The MLC measurement protocol and the marker placement can be found in Song and Qu (2014a).

During the lifting task, participants lifted a load from the floor to a shelf (Fig. 1). The lifted load was a square box (length × width × depth: 0.34 m × 0.24 m × 0.26 m) with two handles on its sides. Both the box and the shelf were placed directly in front of participants before lifting. The distance from the shelf edge to the participants' standing point (i.e. the middle point of the two ankle joints) was 58 cm. The initial horizontal distance from the box centre to participants' standing point was 40 cm. Three shelf heights (wrist, elbow and shoulder during the erect stance) and three load weights (5%, 15% and 25% of participants' MLC) were involved in the experiments. Therefore, there were nine lifting task conditions (3 shelf heights × 3 load weights) for each participant. These task conditions were randomly ordered during experiment, and three repetitions were performed for each task condition. Before each lifting trial, participants were informed of the lifted load weight and the destination height. Participants were not allowed to move their feet during lifting, and they were instructed to lift the box by holding its handles and using self-selected lifting strategies and speeds. Prior to data collection, participants were provided with a practice session to get familiar with the lifting protocol. To minimize fatigue effects, a 30-second break (standing without load) was given after every lifting trial.

The motion data from one older male participant and 41 lifting trials from other 11 participants were excluded because of the significant asymmetric movement patterns. The remaining data were divided into two sets for the purposes of model development and evaluation, respectively. Specifically, the lifting motions (totally 315 trials) from 12 participants were selected to formulate a database for model development. These 12 participants consist of 6 younger (age: 23.3(2.1), height: 168.2(8.5) cm, weight: 52.3(4.7) kg) and 6 older (age: 64.5(5.24), height: 163.7(7.7) cm, weight: 61.3(11.5) kg), and each age group contains 3 males and 3 females. The lifting motions (totally 238 trials) performed by the other 10 participants (5 younger and 5 older) were used for model evaluation. Both the younger (age: 24(1.9), height: 165.6(4.5) cm, weight: 57.4(8.2) kg) and older (age: 68.6(5.6), height: 159.6(6.9) cm, weight: 58(7.3) kg) age groups contain three males and two females.

3. The lifting motion simulation model using the MOO approach

Symmetric lifting (i.e., in the sagittal plane) is very common in