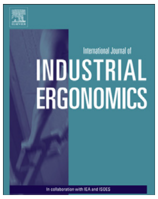
International Journal of Industrial Ergonomics 54 (2016) 10–18

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

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



Development and validation of a three dimensional dynamic biomechanical lifting model for lower back evaluation for careful box placement

Damon Stambolian [a], Moataz Eltoukhy [b], Shihab Asfour [a], *

[a] College of Engineering, University of Miami, 1251 Memorial Drive, McArthur Engineering Building, Room 268, Coral Gables, FL 33146, USA
[b] Department of Kinesiology and Sport Sciences, School of Education & Human Development, University of Miami, 1507 Levante Avenue, Max Orovitz Building, Room 132, Coral Gables, FL 33146, USA

A R T I C L E I N F O

Article history:
Received 31 August 2015
Received in revised form
23 December 2015
Accepted 27 December 2015
Available online 8 January 2016

Keywords:
AnyBody
Biomechanics
Dynamic lifting
Ergonomics
Optimization
Electromyography (EMG)

A B S T R A C T

One of the major causes to low back injury is the box lifting activity, thus for many years biomechanics has been utilized by designers for ergonomic evaluations of the box lifting activity which includes the placement of the box. More recently these ergonomic investigations have focused on the careful placement of the box. The AnyBody (AB) biomechanical models and optimization within the AB software system in conjunction with motion capture has been shown to obtain adequate estimates of joint reaction forces of the body. To date there has not been a dynamic 3D box lifting model developed and validated for carefully placing a box using the AB modeling system and motion capture. Thus the focus of this paper is on the development, verification and validation of a box lifting full body model for lower back evaluations for a dynamic lifting activity for carefully placing a box on a shelf.

1. Introduction

The lifting activity is one of the major causes to low back injury, and for this reason for many years biomechanics has been utilized by designers for ergonomic evaluations of the box lifting activity, which includes the placement of the box. More recently these box lifting investigations have focused on the careful placement of the box. (Davis, 2001), (Stambolian et al., 2011), (Stambolian et al., 2014a,b). There is a long history of full-body-models. Some models use electromyography (EMG) (Marras and Granata, 1997), and some models use optimization (Brown and Potvin, 2005), (de Zee et al., 2007), while other models use a hybrid of EMG and optimization (Cholewicki and McGill, 1994). All three methods establish the level of muscle activity of the trunk. EMG requires special equipment and expertise, whereas the advantage of using optimization is that the muscle activity through calculations can be accomplished by knowing the movement of the subject and the subject's weight and height.

Over the last 10 years, the AnyBody (AB) Modeling System (Damsgaard et al., 2006), which uses optimization to determine the muscle activities for all muscles in the human model, and the open source human models have evolved from the lower extremity GaitUniMiami model (Eltoukhy and Asfour, 2010; Asfour and Eltoukhy, 2011) to the full body generic GaitFullModel of the human. The generic GaitFullModel model is driven by motion capture and has very detailed anthropometrics for the bones and muscles. The programing code is open source and is easily available for the community to modify to a specific human activity.

The inclusion of the spine into the AB model was validated by comparing the estimated lower back kinetics in the model to the intradiscal pressures (de Zee et al., 2007) for several different lifting postures. This was accomplished by applying a single force vector to the upper torso of the AB model to emulate the force of holding a box, which through the optimization of the muscles in the torso derived the lumbar vertebrae kinetics. The results concluded that the intradiscal pressure did agree with the forces at the L4-L5 vertebrae. A more recent study compared 6 biomechanical tools used for estimating spinal forces (Rajaee et al., 2015). The AB model and the regression models (Arjmand et al., 2011, 2012) predicted

---

* Corresponding author.
E-mail addresses: d.stambolian@umiami.edu (D. Stambolian), meltoukhy@miami.edu (M. Eltoukhy), sasfour@miami.edu (S. Asfour).

http://dx.doi.org/10.1016/j.ergon.2015.12.005

L4-L5 intradiscal pressure values that were in close agreement with the in vivo intradiscal pressure for several postures which included a box being held at shoulder height and at waist height as is being performed in this paper.

The dynamic motion of the human is typically recorded using motion capture systems. Motion capture coupled with the biomechanical model ensures a realistic movement of body joints, and is capable of estimating spinal segments' kinematics and loads (Eltoukhy et al., 2015). A dynamic wheel chair model was developed using the AB modeling system, which was validated when using motion capture (Dubowsky et al., 2008). To date there has not been a motion capture driven dynamic box lifting model developed and validated using the AB modeling system. Thus this paper's focus is on the development and validation of a box lifting full body model for lower back evaluations for a dynamic lifting activity using optimization through the AB modeling system and motion capture.

2. Development of the box lifting model

2.1. AnyBody generic model

The AB modeling software was chosen because of the following reasons. 1) The model calculations for kinematics, external and internal kinetics are all mathematically solved within the same software, 2) Research questions can be answered without having to start all over again to define the model, segments, joints, muscles, and equations of motion, 3) The model which runs in the AB system is open source, so the programming code can be altered and the work done in the studies can be shared with the modeling community and different research groups, 4) Availability of this model to the community drives same modeling techniques which makes comparison of results between different research groups more meaningful, and 5) The GaitFullModel has very detailed anthropometric construction of bones and contains over 1000 muscles, and the lumbar spine portion of the model includes a thoracic part, the pelvis, and the lumbar vertebrae with 188 muscle fascicles, ligaments, and facet joints.

2.2. Development of the box lifting model

The Box Lifting Model was developed by modifying the generic GaitFullModel programming code provided by the AB library. Within this model there are several programming files for defining the human body, bones, muscles, and anthropometrics; these files are executed through the main programing file. To develop the Box Lifting Model, most of the programming was done in this main programming file. This additional programing code generated the box in the model and established the box mass, orientation, location, size, inertia, and linked kinetic reaction connections from the box to the hands. The motion capture markers were also defined exactly in the programming code as they were defined during the motion capture, including the markers on the human per the Vicon Plug-in-gait setup (Stambolian et al., 2014a,b), and the markers defining the box. The model first runs a motion and parameter optimization, which optimizes the markers' locations, and the bone sizes based on the subject's height and weight. In order for the motion and parameter optimization to run properly, the initial human posture in the Box Lifting Model needs to be adjusted in close proximity with the initial human posture of the motion capture for the first frame of the motion capture sequence. This requires adjusting the skeleton for the initial conditions according to each subject's initial joints angles, which is very time consuming. Thus a process was developed by adding a code to the Box Lifting Model to approximate the initial human posture. This approximation is used to set the Box Lifting Model's initial human posture. Once the motion and parameter optimization is completed, the model is run a second time for the inverse dynamic analysis sequence, which adds the muscles into the model and then establishes the internally generated kinetics for each time step of the motion. During this second run of the model the reaction forces for the joints and the muscle activities are created and can be visualized in a graph as part of the AB software. Additional code was also developed in the main programming file to create and export a text file that includes the predefined required data such as the joint reaction force or muscle activity. Fig. 1 depicts the Box Lifting Model showing the muscles, bones, force plates, markers on the body and the box, and the Z vectors (blue line).

3. Box lifting model verification and validation

The Box Lifting Model verification and validation is comprised of four phases, 1) The first phase is a literature review to show evidence that the generic GaitFullModel is valid prior to including the programming code for adding the box to the model to create the Box Lifting Model. Since the generic GaitFullModel was previously shown to be valid then the Box Lifting Model should also be valid if the additional programming code developed in the Box Lifting Model is correct. 2) The second phase is a verification to show that the new code developed in the Box Lifting Model is correct by comparing the reaction forces on the lower back based only on the weight of the box. If the forces on the lower back increase as the box weight increases, then the new code developed in the Box Lifting Model is correct. 3) The third phase is a verification process by comparing the human EMG muscle activity to Box Lifting Model's simulated muscle activity. It is well accepted to compare EMG activity of the subject's muscles to the estimated muscle activity derived using optimization (Hughes et al., 1994; McMulkin, 1996; Thaxton, 2009). Thus this verification is to show evidence that the Box Lifting Model's muscles acting on the lower back and stomach are adequately representing the human muscles. For example, when lifting a box in the sagittal plane the lower back muscles should be more active than the stomach muscles because the lower back muscles are working harder to hold the box up, whereas the stomach muscles are used only to help balance the torso. 4) The fourth phase is a validation of the model by comparing the predicted AB muscle activity to the measured EMG muscle activity.

4. Methods

4.1. Experimental setup

The sagittal-plane lifting setup with the box and shelf directly in front of the subject included a shelf height at 50″ (127 cm), a shelf at 30″ (76.2 cm), and a box weighing 30 pounds (13.6 Kg) (Stambolian et al., 2011). Each subject was instructed to walk onto the force plates and then lift a box from the ground up to a shelf. The box was in front of the subject's feet and the shelf was in front of the box, and there was no twisting involved in the lift. The subjects were instructed to: (1) place his feet on the force plates and (2) lift and place the box evenly with the edge of the shelf. Placing the box evenly to the edge of the shelf promoted the careful placement of the box by requiring the subject to slowly place the box edge alongside the shelf edge. Reflective markers were used to record the three-dimensional location of the box relative to the shelf to ensure that the start and stop locations between subjects were consistent. Reflective markers were placed on the subject using the Vicon Plug-In-Gait marker configuration. For each subject the Vicon data file generated during the lift, which contains the subject's