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

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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

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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

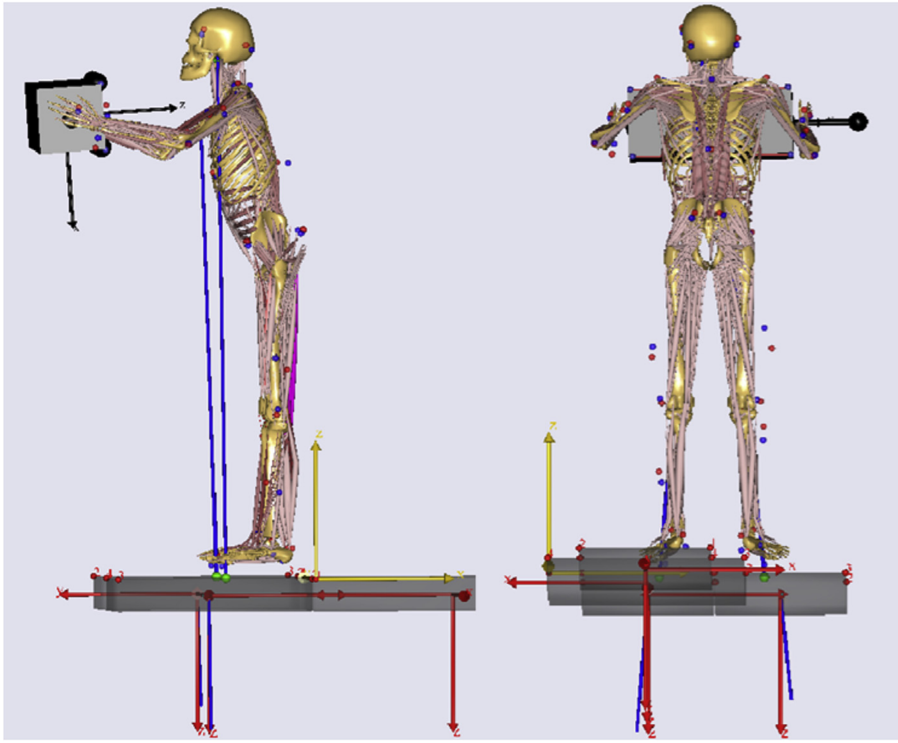

Fig. 1. The box lifting model.

three-dimensional kinematics, was imported into the AB optimization software. The AB modeling software used a polynomial solver with power three, a dynamic optimization methodology, to determine the trunk muscle activities (Rasmussen et al., 2001).

Fig. 2 shows the experimental set up and the corresponding AB post optimization model for the same lifting exercise. As shown, the subject is standing with each foot on one force plate, and the box has been lifted to the 50″ (127 cm) shelf. The shelf adjustable design allowed the shelf table to be lowered to a 30″ (76.2 cm) height. Also, the reflective motion capture markers are seen on the subject and on the Box Lifting Model from the posterior view of the subject.

4.2. Lab equipment

Kinematic data were captured and recorded at the University of Miami's Biomechanics Laboratory with the Vicon (Oxford Metrics, United Kingdom) Nexus software version 1.6 using 10 MX cameras providing 1024 x 1024 pixel resolution and sampling rate of 120 Hz. Force data was collected using two Kistler force plates (Model: 9253B, sampling rate: 2400 Hz). Additionally, EMG data was collected using a Noraxon Telemyo System (Noraxon USA., Inc., Scottsdale, Arizona) at 1800 Hz. Force and EMG data were synchronized and integrated into the Vicon Nexus system. (Eltoukhy and Asfour, 2010; Lisman et al., 2010) as shown in Fig. 3.

4.3. Experiment procedures

Seven male college subjects participated in this study. The subject's height and weight are shown in Table 1. All seven subjects were educated on the purpose of the study and the activities that they would perform during the study. Proper informed consent was obtained according to the University of Miami's Internal Review Board.

For each subject, the locations of the EMG electrodes were determined and the electrode area was shaved to remove any hair, fine sand paper was used to remove dead skin, and cleanser was used to remove all residues. EMG electrodes were placed on the subject's left and right erector spinae (ES) 3 cm lateral to L3 spinous

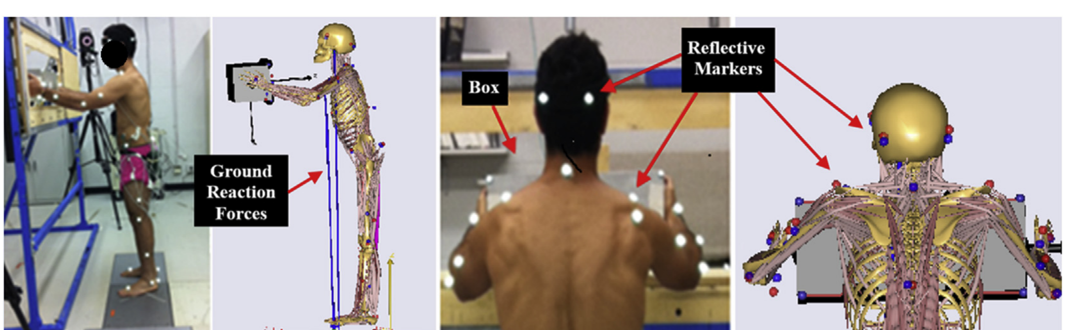

Fig. 2. The experimental setup and the posterior view of the subject and the Box Lifting Model.

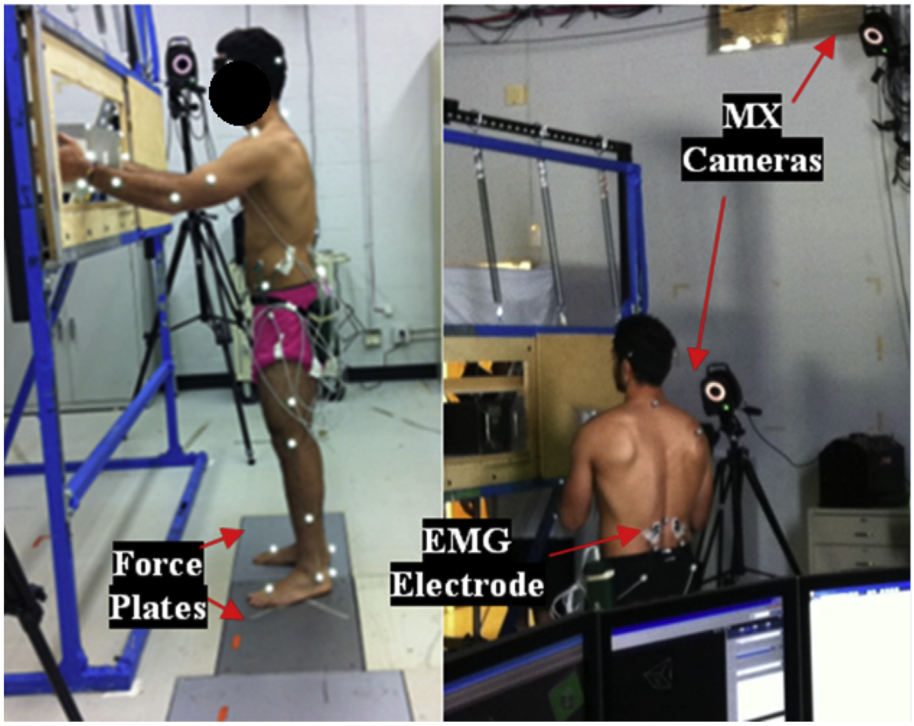

Fig. 3. Force plates, EMG electrodes and MX cameras.

Table 1
Subjects height and weight.

Subject	Height in inches (Cm)	Weight in pounds (Kg)
1	69.3 (176.0)	167.6 (76.0)
2	72.0 (182.8)	206.4 (93.6)
3	69.7 (177.0)	138.2 (62.7)
4	69.7 (177.0)	184.7 (83.8)
5	66.9 (170.0)	183.6 (83.3)
6	75.1 (190.7)	205.3 (93.1)
7	69.5 (176.5)	164.7 (74.7)
Mean	70.3 (178.6)	178.6 (81.0)
SD	2.6 (6.5)	24.0 (10.9)

SD: Standard Deviation.

process, external obliques (EO) approximately 15 cm lateral to the umbilicus, internal obliques (IO) below the external oblique electrodes and just superior to the inguinal ligament, and rectus abdominis (RA) 3 cm lateral to the umbilicus (McGill, 1992). Fig. 4 depicts the locations of the motion capture markers, and the approximate locations of the EMG electrodes in relation to the muscles in the Box Lifting Model.

For each of these muscles the subject performed Maximal Voluntary Contractions (MVC) (Konrad, 2005). The subject first performed the MVC exercise for the ES in a prone position; resistance was provided during the contractions. The RA, EO, and IO electrodes were then placed on the subject. Next the subject performed the MVC exercise for the RA, EO and IO muscles. The subject laid on a platform with the knees bent and feet restrained. During the RA's MVC sagittal exercise, the trunk angle was approximately 30°. During the Right EO's and Left IO's MVC, the subject aimed his right arm towards the left knee, and for the left EO's and right IO's, the subject aimed his left arm towards the right knee.

The reflective markers were then placed on the subject according to the Vicon Plug-In-Gait marker configuration. The subject was instructed to step with each foot within the corresponding force plate and then to proceed to place the box as carefully as possible so the outside edge of the box aligned with the outside edge of the 50″ (127.0 cm) shelf. Following that, the subject performed two practice lifts, and began the experimental lifts of placing the 30-pound (13.6 kg) box on the 50″ (127.0 cm) shelf. The same lifting and placement procedure was followed for the 30″ (76.2 cm) shelf. The lifts performed by the subjects were continuous and started from the floor and ended at the shelf (Fig. 5). To evaluate the careful placement portion of the lift, only a segment of the full lift motion capture was used in the analysis. This portion of the motion capture started when the box began to enter the shelf and ended when the box was carefully placed on the shelf as seen in frames three and four of Fig. 5.

5. Post experiment processing, analysis, and validation

5.1. Previous validations of the generic GaitFullModel

The trunk portion of the GaitFullModel was validated for several static lift postures by comparing the AB simulated L4-L5 forces with the L4-L5 intradiscal pressure. There were several different static postures analyzed and within these comparisons two box heights were evaluated. One evaluation with the box at shoulder height and the other evaluation with the box at thigh height. Using the same anthropometrics from the Wilke study (Wilke et al., 1999), and converting the intradiscal pressure to forces using the MRI measured L4-L5 disc area, the biomechanical model resulted in a L4-L5 axial force in comparison to the intradiscal pressure (de Zee et al., 2007). In 2008, the AB GaitFullModel was applied and validated for a wheel chair activity (Dubowsky et al., 2008). More recently the GaitFullModel was compared with 6 biomechanical tools (Rajaee et al., 2015). The AB model and the regression models (Arjmand et al., 2011, 2012) predicted 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

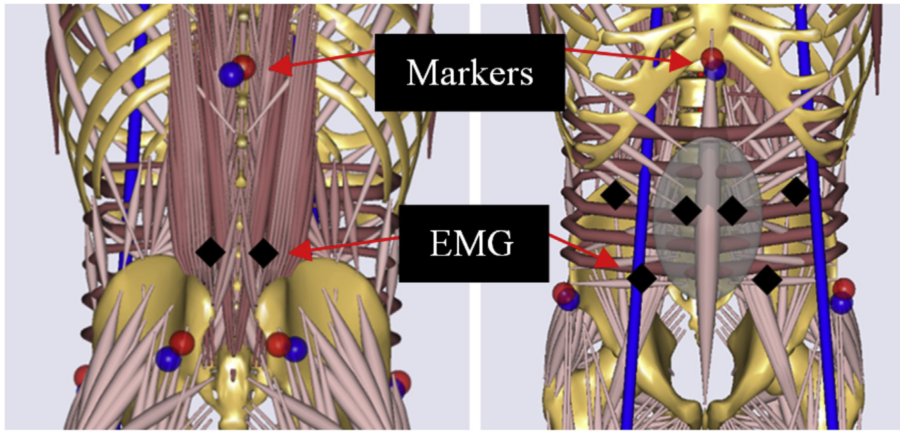

Fig. 4. Locations of the motion capture markers and the EMG electrodes.

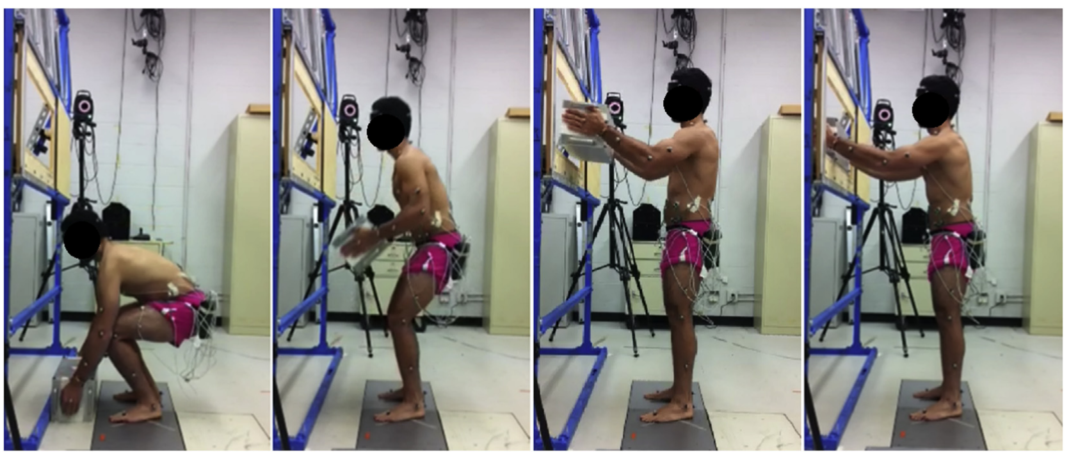

Fig. 5. Box lifting activity.

shoulder height and at waist height as is being studied in this paper. The Box Lifting Model used in the following sections was developed by including an additional code to introduce the box into this GaitFullModel human model.

5.2. Comparison of L5-S1 reactions to the increase in the box weight for verification purposes

This analysis started with the motion capture of the subjects lifting the 30-pound (13.6 kg) box and was run in the Box Lifting Model to generate the L5-S1 reactions for the 30-pound (13.6 kg) box weight. The box weight in the model code was then adjusted and run for a 15-pound (6.8 kg) box, and then again for a 45-pound (20.4 kg) box to generate the L5-S1 reactions for the 15-pound (6.8 kg) and 45-pound (20.4 kg) box weight. To ensure that the box weight was the only influence in this comparison, the body motions for the 15-pound (6.8 kg) and 45-pound (20.4 kg) L5-S1 reaction calculations were exactly the same as the body motions that took place with the 30-pound box, only the box weight value for the 15-pound (6.8 kg) and 45-pound (20.4 kg) box was numerically adjusted in the model. This was done for the 50″ (127.0 cm) shelf and for the 30″ (76.2 cm) shelf for all seven subjects. The L5-S1 reaction forces were averaged. As shown in Fig. 6, and for the proximal distal force, anterior posterior force, and medial lateral force, as the weight of the box increased from 15-pound (6.8 kg) to 30-pound (13.6 kg) to 45-pound (20.4 kg), the corresponding L5-S1 reaction forces also increased, and that is for all subjects except for two instances with the medial lateral force. The proximal distal force and the anterior posterior force all increased as the box weight increased, which for a sagittal lift the proximal distal force and the anterior posterior force are the major contributor to L5-S1 forces. With the medial lateral force, only subjects 2 and 6 at the 50″ (127.0 cm) shelf differed and showed a decrease in L5-S1 reactive forces instead of an increase. This outlier was only with the 2 out of all 42 trials performed.

5.3. Relative comparison of measured EMG to predicted AnyBody muscle activity for model verification

For each subject, the weight and height were entered into the Box Lifting Model code, and by importing the Vicon data file, each subject's lift specific motion capture data along with the synchronized force plate activity were included in the AB Box Lifting Model programming routine. The optimization routine in the AB software generated the predicted muscle activities, and EMG was used to determine the actual muscle activity. For each muscle the average of the Box Lifting Model predicted muscle activity were calculated. The EMG muscle activity is normalized EMG and the AB muscle activity is AB muscle force divided by AB muscle strength. As seen in Fig. 7. Thus the mathematical definition of AB simulated muscle activity is not exactly numerically to the same as the EMG muscle activation, therefore the AB muscle activity values will not be

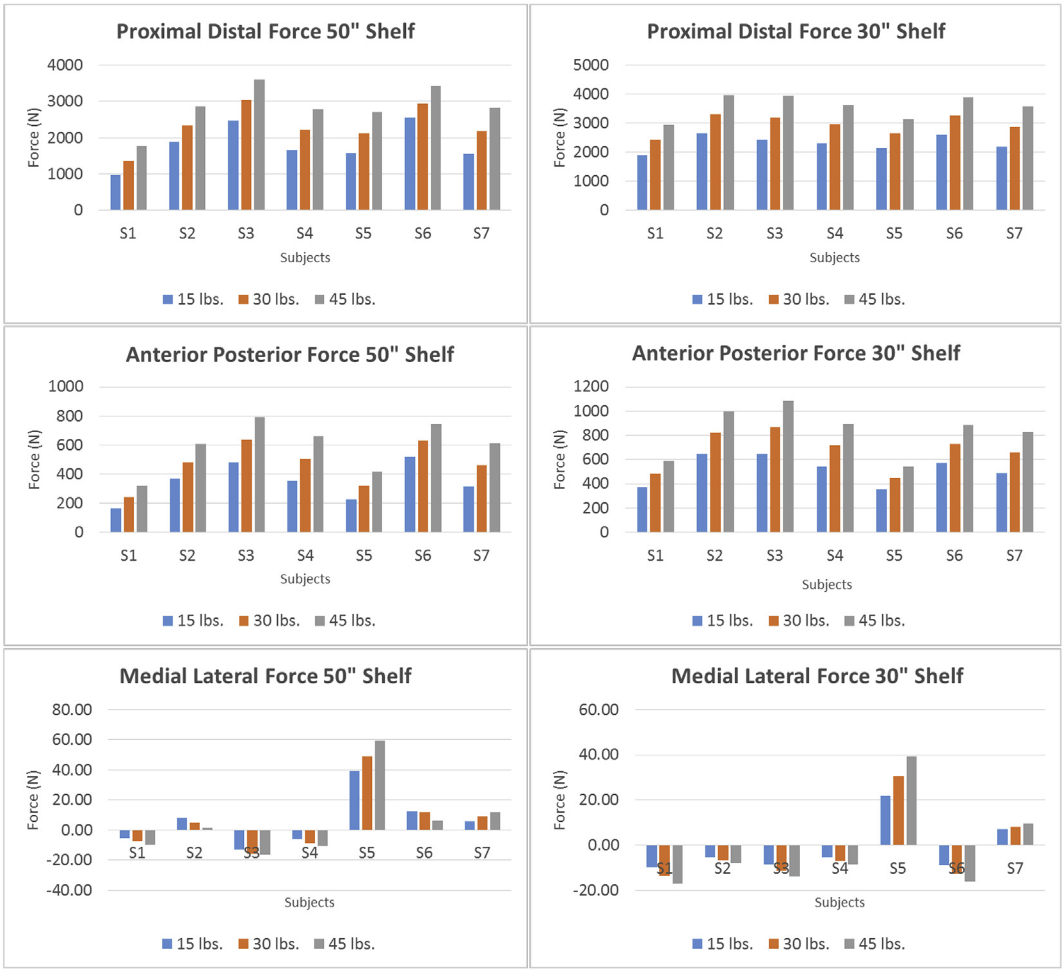

Fig. 6. Comparison of L5-S1 reactions to increases of box weight.

exactly the same as the EMG muscle activity values.

The raw EMG for the MVC and the muscle activities during the lifts were collected at 1800 Hz. These EMG trunk muscle activities for the MVC and lifting exercises for the left and right; ES, EO, RA, and IO were processed using the MyoResearch XP software (Master Edition 1.07.41). The EMG signal processing included high-pass Butterworth Filter at 30 Hz, rectification, low-pass Butterworth Filter at 1000 Hz, Smoothing RMS (60 Hz). For each lift the amplitude normalization for each left and right muscle EMG activities was based on the MVC values,,e.g., Right Rectus Abdominis (RRA) muscle activity during the lift was normalized with the RRA MVC muscle activity. This provided the subject specific percentage of muscle activity curve for each of the muscles per subject. For each muscle the average of the EMG muscle activity were calculated.

For this type of sagittal lift without twisting, the back muscles would be expected to be more active than the stomach muscles, and is shown in the relative comparisons of EMG activity to the Box Lifting Model's muscle activity.

This comparison was done for both the left and right muscle groups, for two shelf heights, and for one box weight. Each subject lifted the 30-pound (13.6 kg) box and carefully placed it on the 30″ (76.2 cm) shelf, and then the shelf was adjusted to the 50″ (127.0 cm) height. Then, the subject lifted the box and carefully placed it on the 50″ (127.0 cm) shelf. As can be shown in Fig. 7, the erector spinae back muscles are more active than the stomach muscles. This is expected with a sagittal lifting activity. With each individual comparison of EMG and Box Lifting Model the erector spinae is more active than the stomach muscles, and the rectus abdominis is the least active muscle, which is also expected. The external and internal oblique muscles are aiding in balancing the torso during the placement of the box. There was only one outlier. For the left 30″ shelf, the external oblique EMG muscle activity for the third subject was more active than the erector spinae.

5.4. Comparison of EMG to AnyBody muscle activity for validation of the model

This comparison was done between the AB predicted muscle activity and the EMG measured muscle activity, for the left and right muscles, for two shelf heights, and for one box weight. Each of the subjects carefully placed a 30-pound (13.6 kg) box on the 30″ (76.2 cm) shelf, and then the subject released the box. The same activity was performed for the shelf at the 50″ (127.0 cm) height. Since the major muscles reacting on the L5-S1 for a sagittal lift are the Erector Spine muscles, this comparison was done between the AB predicted muscle activity and the EMG measured muscle activity for these muscles. The follow shows the statistical analysis for this comparison. The linear correlation analysis was performed using the Palisade StatTools software version 6. Table 2 provides the correlation values for the relationship between the predicted and measured values for the 30″ shelf and the 50″ shelf for both left and right muscles. These correlation values were assessed using the t-

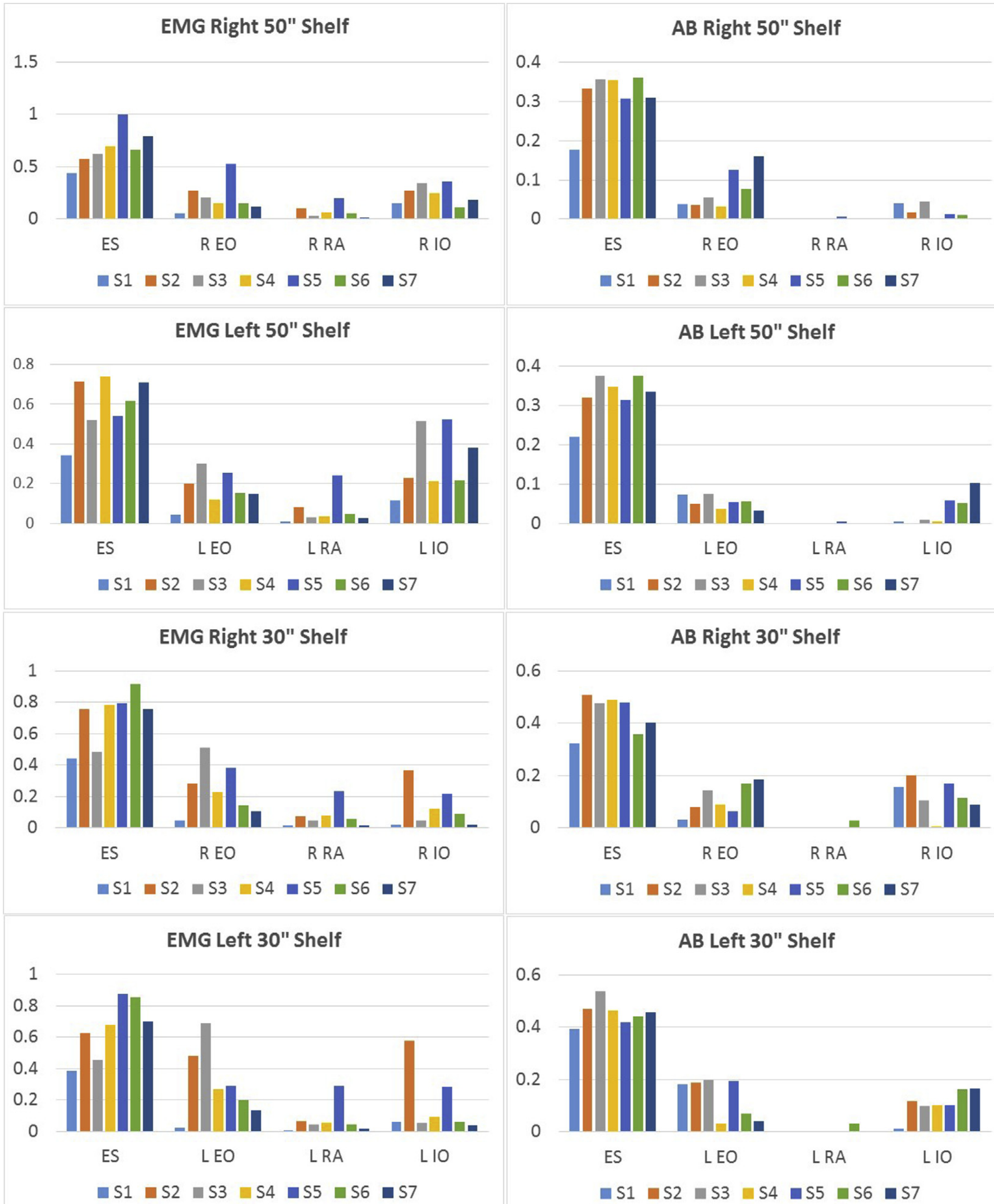

Fig. 7. Relative comparison of EMG to AnyBody muscle activity.

Table 2
Correlation and t-Test.

Subject	30″ left		30″ right		50″ left		50″ right	
	Correlation	t-Test	Correlation	t-Test	Correlation	t-Test	Correlation	t-Test
1	0.663	13.053	0.623	11.956	0.464	7.063	0.265	3.943
2	0.642	11.089	0.675	11.941	0.814	18.591	0.867	22.448
3	0.522	7.630	0.467	6.729	0.779	12.432	0.802	13.305
4	0.674	13.178	0.659	12.762	0.777	15.730	0.825	18.164
5	0.790	12.407	0.837	14.391	0.604	7.261	0.580	6.888
6	0.403	5.083	0.520	6.724	0.875	21.094	0.784	15.379
7	0.643	13.248	0.565	11.190	0.688	14.412	0.682	14.214

Test. At a 0.01 significance, the t-Test critical value is 2.575 for a two-sided t-distribution. There is sufficient sample evidence to support the claim that the AB predicated values linearly correlate with the EMG measured values at a 0.01 level of significance.

5.5. Applying the box lifting model

The Box Lifting Model was then applied to evaluate the box lifting activity on a 30″ (76.2 cm) shelf and on a 50″ (127.0 cm) shelf with the 30 pound box. As seen in Fig. 8 with the two shelf heights, the higher 50″ (127.0 cm) shelf height resulted in less stresses to the L5-S1 proximal distal forces and anterior posterior forces. This agrees with previous findings where an increase in lifting height is associated with a decrease to the load on the lower back (Hoozemans et al., 2008).

6. Discussion

To ensure that the modifications done by including the box into the GaitFullModel resulted in a valid biomechanical model, a comparison was done with the reaction forces on the L5-S1 as a function of box weight. For the major contributors to L5-S1 forces, the proximal distal force and the anterior posterior forces showed, for almost all trials, that an increase in the box weight resulted in an increase in the forces at the L5-S1. There were only 2 out of 42 trials that did not show an increase of reaction force with an increase of box weight, and this was with the medial lateral force. This analysis showed that the forces on the lower back increased as the box weight increased and verifies that the new code developed in the Box Lifting Model is correct. Additionally, a comparison of the measured EMG muscle activity with the predicted AB muscle activity was performed to verify that the muscles were acting correctly. With each subject, comparison of the EMG and the AB muscle activity showed that the erector spinae is more active than the stomach muscles, and the rectus abdominis is the least active muscle, which is also expected. With this comparison there was only one outlier. This comparison verified that the predicted AB lower back and stomach muscles' activities are an accepted representation of the actual muscles' activities. Furthermore the model was validated by determining the correlation between the predicted AB muscle activity to the measured EMG muscle activity, where all correlations obtained were statistically significant.

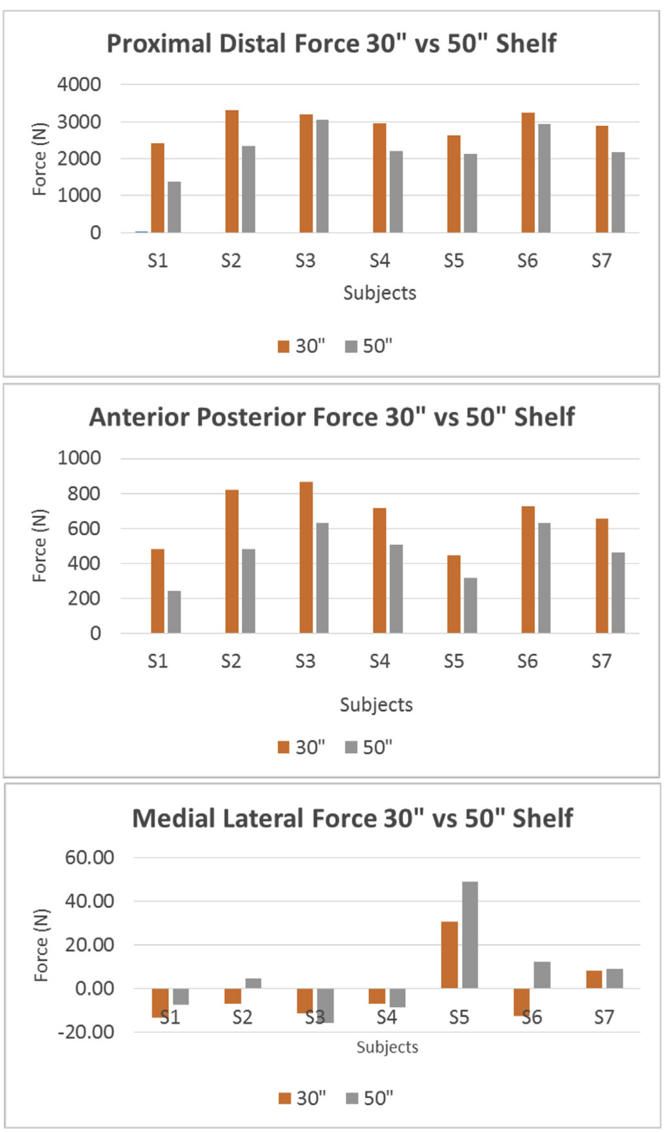

Fig. 8. Force comparison with two shelf heights.

7. Conclusion

This paper describes the development, verification and validation of a box lifting model using the AB generic open source human model. The lifting activity focused on placing a box carefully on a 30″ (76.2 cm) and on a 50″ (127.0 cm) shelf. The verification and validation included a literature review of previous validations of the generic model, verification after adding the developed code of the box into the generic model by comparison of the increased L5-S1 reaction forces to increases in the box weight, and comparing the relative EMG muscle activity to the relative AB muscle activity. The validation of the Box Lifting Model was performed by determining the correlations between the predicted AB muscle activity and the measured EMG muscle activity for the lower back Erector Spine muscles. Finally the model was applied to evaluate the box lifting activity at the two shelf heights and showed that the lower shelf possessed more stresses on the L5/S1, which was expected. With this validation the Box Lifting Model, was considered for similar carful box placement as defined in this paper, and that is in the sagittal plane on a 30″ (76.2 cm) and on a 50″ (127.0 cm) shelf heights. Future work would involve using the model in activities that involves twisting of the torso.

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