Two-Dimensional Biomechanical Model for Estimating Strength Of Youth and Adolescents for Manual Material Handling Tasks

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ABSTRACT

Agriculture is one of the few occupations in which children and adolescents are considered an integral component of the workforce, yet children and adolescents are often asked to perform physically demanding tasks. These tasks include lifting and moving materials and equipment, operating farm equipment, and performing jobs requiring moderate to high levels of strength and coordination (NIOSH 2001).

It is difficult, however, to determine what percentage of youth/adolescents would have the strength capability to perform these jobs. Moreover, it has been shown that many of the jobs performed by youth on farms would be considered high risk for low back pain (Allread et al., 2003).

To address this need, a computerized two-dimensional biomechanical model was developed to determine what percent of youth would be capable of performing a specific manual material handling task. The computer model allows input of various task factors, such as age, gender, required body posture and hand forces/weights, for lifting, lowering, pushing, pulling, and holding tasks. The program then calculates a variety of biomechanical parameters, including the percent strength capability at each primary joint, the kinetic link segment parameters (weight, length, center of mass), the joint reaction forces and moments at the primary joints, the joint coordinates, and a detailed list of critical internal spinal forces (compressive, shear, erector spinae, and abdominal forces; abdominal pressure and torque; and, torque at L5/S1, etc.).

The program will be useful in evaluating jobs performed by youth in agriculture and other workplaces. It should be noted that the computer model is a preliminary version and additional validation is needed.

“The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health”
INTRODUCTION

Youth and adolescents are routinely engaged in manual material handling (MMH) tasks that may exceed their strength capability to perform the task. This work may place them at excessive risk for musculoskeletal disorders, such as upper extremity (UE) or low back disorders (LBDs). For example, in farming, where youth and adolescents are considered to be an acceptable component of the workforce, it is not uncommon to observe youth lifting or moving objects that far exceed the amount of weight that would be considered acceptable for adults, let alone for children and youth (Bartels et al., 2000).

These types of exposures occur often and have empirically been shown to have a high risk for low back disorders for youth working on farms. In a study of the risk of low back disorders for a wide range of MMH jobs performed by youth on farms in the Midwest United States, Allread et al. (2004) found that nearly one-half of the jobs routinely performed by youth would be considered moderate-to-high risk of low back disorders for adult workers. Young workers are exposed to the potential risks of musculoskeletal disorders due to excessive MMH in other workplaces as well, such as jobs in grocery stores, construction, fast food restaurants, and other types of summer work. Little is known, however, about how much weight is acceptable and safe for youth of different genders and ages. The North American Guidelines for Children’s Agricultural Tasks (NAGCAT) have proposed that youth not lift or carry any object weighing more than about 10% to 15% of his or her body weight (Marshfield Clinic, 1999). The empirical basis for this recommendation is not clear. It is worth noting that the amount of weight lifted is only one factor that determines whether a specific lift is acceptable or not. For example, the body posture assumed during the lift may be equally important in determining the acceptability of a specific manual lifting task.

Therefore, it is important to recognize that the amount of weight that would be considered excessive for a specific MMH task would likely be a function of several different factors, including the age and gender of the person performing the task, the body posture used during the task, and the geometric location of the hands at the time of peak load (Waters et al, 1994). When an individual performs a MMH task, such as a pushing, pulling, or lifting task, the muscles throughout the body are exerted in order to produce internal forces and moments to support externally applied loads. These muscle forces generate internal reaction forces at the joints, such as at the elbow, shoulder, and throughout the spine. These internal reaction forces can cause damage to the soft tissues in the joint and may result in musculoskeletal pain, discomfort, and injuries. Therefore, it is important to estimate the magnitude of these forces in order to determine whether the loads are excessive for a specific manual materials handling task.

This is accomplished by modeling the musculoskeletal system as a biomechanical system and calculating the internal joint torques (moments) and the compressive and shear reaction forces that would be developed at the joints as a result of the muscle exertions required to perform the task. These results can then be compared to known strength capabilities and recommended tissue tolerance limits to determine what percentage of youth would be capable of performing the specified task of interest.

In order to estimate what percentage of male and female youth of various ages who would be able to perform a specific manual material handling task, we developed a static, two-dimensional biomechanical model and computer program that would allow computation of the required muscle forces and the internal compressive and shear reaction forces needed to perform the prescribed MMH task. The model was previously presented (Waters, 2003), but the details of the development of the model are described in this paper. The model presented in this paper is a simple, practical 2-D biomechanical model designed to provide a rough estimate of stresses to the body from manual materials handling tasks performed by children and youth. The model ignores muscle co-contraction and kinematics, which are known to result in substantial higher stresses to the low back.
MODEL DEVELOPMENT

The NIOSH 2D Youth Static Strength Prediction Program (YSSPP) model is designed to estimate the required joint torques, muscle strength demands, and compressive and shear forces on the L5/S1 disc for children as a function of gender, age (3-21 years), body posture, and weight handled or applied force. The model is limited to symmetric sagittal plane MMH activities. The model logic computes forces and torques at each of the major articulations of the human body. The body is treated as a series of seven solid links which are articulated at the ankles, knees, hips, L5/S1 disc, shoulders, elbows, and hands. Each of the links in the model is considered to have the total mass of the segment acting at its center of mass. Biomechanical strength modeling involves comparison of resultant torques to maximum voluntary torques. This comparison is made at each of the six major body joints (ankles, knees, hips, L5/S1 disc, shoulders and elbows).

The heights and body weights as a function of gender and age used in the model are summarized in Table 1. These data were obtained from the National Center for Health Statistics (2000) (www.cdc.gov/growthcharts). Body link lengths were estimated as a function of height using the relationships between height and link lengths provided by Dempster et al. (1964). The locations for the "centers of mass" for each link were determined using the proportionate relationships provided by Dempster (1955). Mass of a body link as a proportion of total body mass was determined using data provided by Drills et al. (1963). These relationships were used for all age groups (3-21) and for both genders.

For children ranging in age from 3 to 10, strength data measured in standard postures by Owings et al. (1975) were used to estimate children’s strength capability in various postures. Since, in some cases, younger subjects had greater strength than the older subjects (for example, 5 year old with greater strength than 6 year old), these data were adjusted to reflect increasing strength with increasing age. For all other body postures (body joint angles), the relationships between muscle strengths and body joint angles reported by Chaffin and Andersson (1991) were used. The maximum voluntary torques for ages 11-21 were estimated assuming linear relationships between strength and age. For all practical purposes, Owings et al (1975) data also showed a linear relationship between strength and age (for children 3-10 years of age).

Maximum voluntary torques for adult males and females reported by Chaffin and Andersson (1991, Table 6.2) were assumed to represent the strength capability of 21 year old males and females. These torque values were adjusted to match the strength capabilities reported in the NIOSH Work Practices Guide (NIOSH 1981, Table 5.1, Page 70). This was necessary because there are some differences between the strength capabilities based on whole body exertion as compared to segmental strengths.

The logic presented in Chaffin and Andersson (1991) that employed in Garg and Chaffin model (1975) was used to estimate compressive and shear forces on the L5/S1 disc. It was assumed that the hips-to-L5/S1 link length is about 6% of the subject’s height (about 20% of hips to shoulder link length) (Garg and Chaffin 1975). Regarding segment mass, it was assumed that the weight of the hips to L5/S1 link is about 19% of the body weight (Garg and Chaffin, 1975). The superior surface of the sacrum was estimated to be at an angle of 40º from the horizontal. Further, it was assumed that as the torso is inclined forward in flexion, the pelvis contributes to the motion after 25º (Garg and Chaffin 1975, Chaffin and Andersson 1991) by rotating at the rate of 2º for each 3º of torso flexion. Conversely, if the knees are bent (flexed), the pelvis rotates counter-clockwise at the rate of 1º for each 3º of thigh flexion.

The abdominal pressure assumed to relieve stresses on the spine, is estimated using the logic presented in Chaffin and Andersson (1991). The estimate of diaphragm area and the moment arm for the abdominal force are assumed to be the same as those reported by Chaffin and Andersson (1991) and employed in the Garg and Chaffin
model (1975). For youths and children under age 21 the abdominal force is assumed to be proportional to the ratio of an individual height to that of 21 year old of the same gender.

For adult males and females (> 21 years of age), the moment arms for the erector spinae muscles are assumed to be 6 cm and 5.85 cm, respectively; and, for adult males and females, the moment arms for the rectus abdominis muscles are assumed to be 10.47 cm and 9.00 cm, respectively (Chaffin et al. 1990, Kumar 1988). The moment arm for abdominal force is calculated using the formula given in Chaffin et al. 1990. That is, 6.7 cm plus 8.2 cm times the sin of the angle that the trunk makes from the vertical. For this model, we assumed that the moment arms for the abdominal force, erector spinae muscles and rectus abdominis muscles would vary linearly with age. Based on this assumption, we estimated the moment arms for youth 3-21 by multiplying the adult moment arm value by the age-based height ratio. For example, the ratio of average height for a 3-year-old male compared to a 21 year old male is 37.4/70 inches or 0.53. Similarly, the ratio of average height for a 10-year-old female compared with a 21-year-old female is 54.3/64.3 or 0.84.

THE MODEL LOGIC

The model requires the user to provide a subject’s age and gender. The user can either select the 50th percentile height and weight or specify specific height and weight of interest. Regarding the task to be analyzed, the user can select one of the listed tasks (lifting, lowering, holding, carrying, pushing or pulling) or specify the force angle from the horizontal (for example -90º for lifting).

The user has to specify whether the exertion is with one hand or two hands along with the magnitude of the force exerted in each hand (e.g., weight of object lifted for a lifting task). Body posture is specified by providing ankle, knee, hip, shoulder, and elbow angles. All angles are measured from the horizontal using the same definitions as those used in the University of Michigan 2-D SSPP. Sample input screens are shown in Figures 1 and 2.

![Figure 1 Sample Input Screen for Anthropometry.](image1)

![Figure 2. Sample Input Screen for Task and Posture Data.](image2)
The model computes body link lengths, body segment weights, x and y coordinates for all body joints, and draws a stick diagram. Then the model computes resultant forces and torques on all body joints as well as voluntary torques for the specified gender and age. The resultant torques are compared with the known voluntary torque values to determine the percent of population that is capable of performing the specified exertion within that age and gender group. Lastly, the model computes forces for the erector spinae and rectus abdominis muscles and their moment arms, abdominal force and its moment arm, and resolves the body weight above the L5/S1 disc and hand force into force components perpendicular and parallel to the L5/S1 disc surface. These forces along with the muscle forces and intra-abdominal force are used to compute compressive and shear forces on the L5/S1 disc. A sample of the output screens are shown in Figures 3 and 4.

Figure 3. Sample Output Screen for Summary Report

Figure 4a and 4b. Sample Output Screens for Spinal Forces and Anthropometry
SENSITIVITY ANALYSIS AND MODEL ADJUSTMENT

A comprehensive sensitivity analysis was conducted to examine the response of the model to various input conditions. The purpose of the sensitivity analysis was to evaluate the response characteristics of the model for discontinuities or unexpected responses. The sensitivity analysis consisted of a systematic assessment of computed trunk strength, disc compression force, and shoulder strength values across a wide range of variable task conditions. These included calculations for various combinations of age, gender, load weight conditions, and body postures (as defined by starting vertical and horizontal hand location). A sample of the resulting sensitivity output charts are displayed in Figures 5-8.

Figure 5. Male Trunk Capacity for Floor Lift, by Weight Lifted and Age.

Figure 6. Female Trunk Capacity for Shoulder Lift, by Weight Lifted and Age.

Figure 7. Disc compression force (lbs) for 5 year old female lifting 5 lbs, by hand location.

Figure 8. Shoulder Capacity (%) for 12-YEAR-OLD Male Lifting 45 lbs, by Hand Location.
The resulting sensitivity charts were then systematically assessed to identify discontinuities in the model response characteristics and responses that appeared to be scientifically invalid. When we identified aberrant model behavior, we examined the model constructs and variables used in the model to determine which model parameters should be adjusted to compensate for the inappropriate response. We then adjusted the associated model parameters to smooth the model response characteristics. For example, our initial sensitivity analysis revealed that the model output for disc compression force did not vary for youth between the ages of 3 and 10. In evaluating our model input parameters, we noted that we had decided to set the spinal extensor moment arm as a constant for youth aged 3-10. Based on the sensitivity analysis, however, we decided to reduce our input parameter for the length of the spinal extensor moment arm for youth 3-10 years of age. Based on our belief that the moment arm would likely vary as a function of the height of the child, we decided to reduce the length of the extensor moment arm to a height-based percentage of an adult moment arm. This modification resulted in an improved model response across ages.

**APPLYING THE MODEL**

In order to demonstrate the application of the model, we can examine the results of the sample analysis of a task observed on a Midwest farm that was previously shown in Figures 1-4. The task consists of lifting the tongue of a farm implement to attach it to a tractor. The input data for the youth and task are shown in Figures 1 and 2. The person performing the lifting task is a 12-year-old male of average height and weight. The weight of the object to be lifted is 60 lbs. The observed posture at the liftoff point of the lift is shown in Figure 2. The summary of the results of the analysis using the NIOSH 2D YSSPP is shown in Figures 3 and 4. As can be seen from the analysis, the spinal disc compression force for this task is 773 lbs. and spinal shear force is 76 lbs. In terms of muscle strength, only 3% of 12-year-old males would have the trunk strength to do this task. Thus, the physical demands for this task would be considered excessive for a 12-year-old male. Additionally, the spinal disc compression force exceeds the NIOSH recommended maximum of 770 lbs for an adult (Waters et al., 1993). Based on the lifting criteria used by NIOSH for manual lifting (i.e., at least 75% of the exposed population should have the strength capability to do the task) the results of the analysis for this task would suggest that this youth should not do this task. Alternatively, the task could be modified by using some type of mechanical lift assist device to lift the tongue of the trailer, thereby reducing the amount of weight lifted and the risk of low back injury.

A second example is provided in which a 14-year-old male is lifting a bale of hay weighing 42 lbs. The youth is 62 inches in height and weighs 102 lbs. The input and summary output screens for this analysis are shown in Figures 9 and 10. For this task, the spinal disc compression force for this task is 879 lbs. and spinal shear force is 67 lbs. In terms of muscle strength, 55% of 14-year-old males would have the trunk strength to do this task. Thus, the physical demands for this task would be considered excessive for a 14-year-old male. Additionally, the spinal disc compression force exceeds the NIOSH maximum recommended limit of 770 lbs (Waters et al., 1993).
A third example is provided in which a 10-year-old female is pushing a cart that requires 45 lbs of pushing force to move. The youth is 52 inches in height and weighs 85 lbs. The input and summary output screens for this analysis are shown in Figures 11 and 12. For this task, the spinal disc compression force for this task is 522 lbs. and spinal shear force is -4 lbs. In terms of muscle strength, 0% of 10 year old females would have the trunk or shoulder strength to do this task. Thus, the physical demands for this task would be considered excessive for a 10-year-old female.
CONCLUSIONS

The NIOSH 2D YSSPP model presented in this paper provides a simple way to evaluate the strength demands of manual material handling (MMH) tasks such as lifting, pushing, and pulling tasks for youth 3-20 years of age. The model can be used to assess whether a MMH task exceeds the strength demands for youth of certain ages or genders, which internal muscle strengths are most affected, and the estimated spinal disc compression and shear force on the spine as a result of a specified MMH task.

In order to use the model to predict risk of musculoskeletal disorders for youth, however, validation studies will be needed. Nevertheless, the model should prove to be useful for assessing MMH tasks performed by youth across a wide range of work environments.

ACKNOWLEDGEMENTS

We wish to acknowledge the assistance of Mr. Timothy Morrow for conducting the sensitivity analysis, Dr. Soo Jin Lee for assisting with model evaluation, and Mr. Vijay Viswanathan for help with the computer programming.
REFERENCES


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# TABLE 1 HEIGHT (INCHES) AND BODY WEIGHT (LBS)

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