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A revised back compressive force estimation model for ergonomic evaluation of lifting tasks

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Abstract. Occupational back pain and injury are common and costly issues. Biomechanical models are often used to quantify job risk by estimating back muscle forces. In general, the most accurate models are also the most complex, creating demand for models that are both straightforward and accurate. An existing, basic hand-calculation back compressive force estimation model (HCBCF v1.0) was revised in two iterations to reduce the error induced by original simplifying assumptions. Lifting tasks ($n = 6000$) from observational data were used to compare the HCBCF models with the University of Michigan 3D Static Strength Prediction Program (3DSSPP$^{\mathrm{TM}}$). The greatest r^2 (0.97) between the HCBCF v1.2 and the 3DSSPP$^{\mathrm{TM}}$ was achieved with gender-specific equations designed to account for differences between males and females and a more detailed estimation of torso flexion angle and upper body mass center location. This gender-specific back compression and risk estimation model is a relatively simple alternative to computer-based back compressive force models. In addition the hand-calculation can be used as a general survey tool to determine which jobs should be analyzed with more sophisticated computer-based models.

Keywords: Back compressive forces, job risk assessment, ergonomics, biomechanics

1. Introduction

Back pain severe enough to limit activity is a common complaint across society: 70–85% of all people will experience back pain at some point in their lives [1]. Low-back disorders are commonly reported and are more expensive for employers than any other types of injury [9,12]. Many of these workplace injuries develop over months and years of repeated physically stressful tasks, such as lifting and heavy, manual labor [12,13]. Regardless of cause, workers and employers seek to minimize the financial and human suffering costs that accompany low-back pain and associated disorders [2,13]. This has led to the implementation of ergonomics programs that evaluate and resolve potential injury-causing conditions [8,12].

Manual lifting tasks can be evaluated for back injury risk by analysis of the back compressive force, denoted F_c or BCF [2]. During a lift, accelerative forces act on the upper-body weight of the worker and the weight of the external load, creating a load moment in the low back. Posture is stabilized, and the gravitational force is counteracted by muscle contraction in the back, primarily from the erector spinae muscle group. Back compressive force (BCF) on the spine is believed to be a contributor to low-back pain and injury, especially at the L5/S1 intervertebral disc [2,13]. The National Institute for Occupational Safety and Health (NIOSH) Work Practices Guide for Manual Lifting guidelines state that "biomechanical compression forces on the L5/S1 disc are not tolerable over 650 kg (1430 lb) in most workers" and "a 350 kg (770 lb) compression

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force on the L5/S1 disc can be tolerated by most young, healthy workers" [11].

Multiple methods are used for computing BCF. Computerized biomechanical modeling is considered the most precise method for calculating BCF data [2]. More simple methods are often used in routine ergonomic evaluation to determine if or where a possible hazard exists, as well as which jobs are most hazardous [8]. These less complex tools have important roles and can benefit from fine-tuning to reduce the error resulting from simplifying assumptions. The desired end result is an accurate prediction of BCF with minimal data input and manipulation.

The purpose of this study was to create a more accurate, simple hand-calculation method for BCF (HCBCF) by adjusting the error-inducing assumptions made in a current HCBCF v1.0 model [2,8]. BCF estimations from the current and improved HCBCF models were compared to calculated BCF values generated using the University of Michigan 3D Static Strength Prediction Program (3DSSPP$^{\mathrm{TM}}$) to determine overall accuracy

2. Methods

2.1. Computer modeling

Previously gathered measurements, observations, and videotape data were obtained for approximately 500 jobs performed by 217 industrial workers in Utah. Since nearly all of the jobs had multiple, manual, material handling (MMH) tasks, data from nearly 6000 total lift/lower tasks were analyzed. Worker anthropometry data (height and weight), load measurements, hand locations, and video frames from jobs were used to model worker posture in the University of Michigan 3D Static Strength Prediction Program$^{\mathrm{TM}}$ software (3DSSPP$^{\mathrm{TM}}$, University of Michigan, Ann Arbor) for each task. These data served as the gold standard for comparison.

2.2. Hand Calculated Back Compressive Force (HCBCF) models

The musculature and physical anatomy of the spine is comprised of multiple muscle groups, nerve innervations, and intervertebral disk units. Simplifying assumptions can be made to model the spine with statically determined moment equations. These methods were employed as basis for the following HCBCF models and can be programmed into handheld devices for easy transport and utilization in a field setting, or be computed with a worksheet.

2.2.1. HCBCF v1.0

The HCBCF v1.0 model equation for BCF at the L5/S1 intervertebral disk is included as Eq. (1). BW is the person's weight (kg), L is the weight of the load (kg), HB is the horizontal distance from the hands to the L5/S1 (cm), and theta (θ) is the torso flexion angle from vertical (degrees) [2,8]. Only five values of theta (θ) were used in the original model. Figure 1 illustrates estimation model parameters and values of theta (θ).

$$BCF = 3(BW)\sin\theta + \frac{L(HB)}{5} + 0.8\left(\frac{BW}{2} + L\right) \quad (1)$$

Hand location data from 3DSSPP$^{\mathrm{TM}}$ were used for the horizontal hand location needed in Eq. (1). of the HCBCF v1.0 model. Hand locations (positions) were found by averaging the horizontal location of the right and left hands. The torso flexion angle was rounded to one of the five flexion angle categories corresponding to Fig. 1. Tasks that involved lifting with significant torso rotation ($> 10^0$) were not analyzed to avoid further complication to the model. A 'rotated torso' was considered to be any task where the asymmetry angle was greater than 10 degrees from a sagittal plane. BCF was calculated using the 3DSSPP$^{\mathrm{TM}}$ and the HCBCF v1.0 model equation.

A summary of the assumptions for HCBCF v1.0 is noted in Table 1.

2.2.2. HCBCF v1.1

For HCBCF v1.1, the torso angle variable theta (θ) was divided into ten angle categories rather than five.

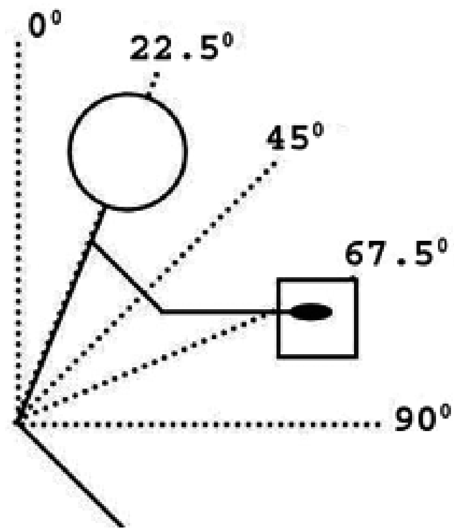

Fig. 1. Rounding of torso angle to the nearest quarter of bending.

Table 1
HCBCF v1.0 Model Assumptions

HCBCF v1.0 Component	Value
L5/S1 >> ES (Moment Arm from center of L5/S1 to Center of Erector Spinae)	5.0 cm
UBW (Upper Body Weight)	50% BW
UBCM (Upper Body Center of Mass-distance above L5/S1 along straight line to shoulder juint)	30.5 cm
L5/S1 Angle (Angle below Horizontal)	40°
Angle Categories	5

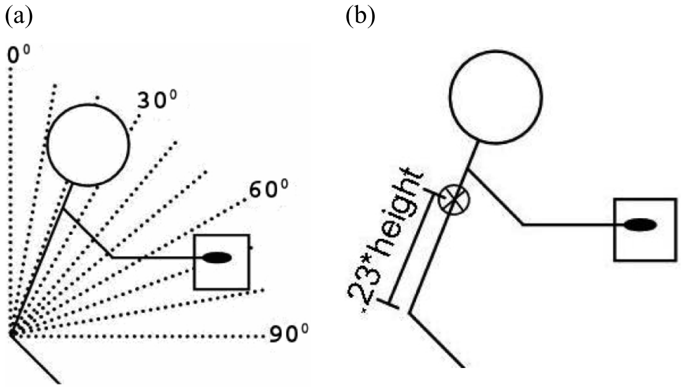

Fig. 2. (a) Modified torso angle; (b) modified torso length.

As noted earlier, torso length between the hip and upper-body center of mass in the HCBCF v1.0 model equation was assumed to be 30.5 centimeters (12 in), which is embedded into the constant of the first term in Eq. (1). In fact, this anatomical length is not constant across the population but varies from person to person. An expression for torso length as a function of worker height was determined to correct the original model simplification of torso length [3]. Hip to shoulder distance, as derived from study subjects, has been defined as 28% of height. Cadaver studies have suggested that the hip to center of mass of the torso length is 62% of the hip to shoulder distance [3]. Thus torso length, or hip to center of mass distance, can be written as Eq. (2), where H is worker height in cm.

$$\textit{torso length} = (0.62)(0.28)H \quad (2)$$

Although this relationship seemed reasonable to account for variations in upper body center of mass location, it was not directly substituted into HCBCF v1.1. To take into account the situation where the arms and head are not directly above the torso, but out in front of the body, the estimated center of mass location was modified still further to be just below the shoulder. This compensates for additional moment caused by the weights of the arms and head, but not directly accounted for in the original HCBCF v1.0 model. These modifications were embedded into HCBCF v1.1 and used to calculate BCF using Eq. (1) additional angle categories only, (2) modified torso length only and Eq. (3) modified torso length and torso angle together. Fig. 2a illustrates the 10 angle categories, and Fig. 2b illustrates the revised torso length estimate. The HCBCF v1.1 equation for BCF estimation is found in Eq. (3) below.

$$BCF = 0.023(BW)(H)\sin\theta + \frac{L(HB)}{5} + 0.8\left(\frac{BW}{2} + L\right) \quad (3)$$

A summary of the assumptions for HCBCF v1.1 is noted in Table 2.

2.2.3. *HCBCF v1.2*

The limitations of the HCBCF v1.1 model restrict the level of accuracy that can be achieved by revising torso angle and torso length alone. Additional modifications were performed to increase the accuracy of the model.

The erector spinae moment arm distance is assumed to be constant at 5.0 cm (2 in) in HCBCF v1.0 and v1.1. This value was sequentially adjusted in 2.5 mm (0.1 in) intervals between 5.0 cm (2 in) and 7.0 cm (2.75 in), and correlation analyses were performed to determine which value most accurately predicted the BCF values calculated using the 3DSSPP$^{\mathrm{TM}}$. The population was expanded to include all levels of torso rotation plus additional computer analyses that had been computed

Table 2
HCBCF v1.1 Model Assumptions

HCBCF v1.1 Component	Value
L5/S1 >> ES (Moment Arm from center of L5/S1 to Center of Erector Spinae)	5.0 cm
UBM (Upper Body Weight)	50% BW
UBCM (Upper Body Center of Mass-distance above L5/S1 along straight line to shoulder joint)	0.23* Height cm
L5/S1 Angle (Angle below Horizontal)	40°
Angle Categories	10

Table 3
HCBCF v1.2 Model Assumptions

HCBCF v1.2 Component	Value
L5/S1 >> ES (Moment Arm from center of L5/S1 to Center of Erector Spinae)	6.6 cm Female 6.9 cm Male
UBM(Upper Body Weight)	50% BW
UBCM (Upper Body Center of Mass-distance above L5/S1 along straight line to shoulder joint)	0.23* Height cm
L5/S1 Angle (Angle below Horizontal)	40°
Angle Categories	10

since the development of HCBCF v1.1 resulting in a sample size of approximately 6000 task analyses. In addition, male and female data were evaluated independently. The moment arm value in the revised estimation model resulting in the best fit was chosen and substituted into the HCBCF v1.2 model. The resulting model equations for HCBCF v1.2 are found in Eqs 4a and 4b for females and males respectively.

$$BCF = 0.0175(BW)(H)\sin\theta + 0.152(L)(HB) + 0.8\left(\frac{BW}{2} + L\right) + 20 \tag{4a}$$

$$BCF = 0.0167(BW)(H)\sin\theta + 0.145(L)(HB) + 0.8\left(\frac{BW}{2} + L\right) + 23 \tag{4b}$$

A summary of model assumptions for HCBCF v1.2 is found in Table 3.

The resulting model equations were also analyzed to determine their tolerance for torso rotation. This effect was determined by computing r^2 values for incremented rotation angles. Torso rotation categories were defined in ten-degree intervals. 5 groups were tested: 0 degrees rotation, 0 to 10 degrees, 0 to 20 degrees, 0 to 30 degrees, and greater than 30 degrees rotation.

2.3. Analysis techniques

Pearson correlation analyses ($\alpha = 0.05$) were performed using JMP® IN 5.1 to compare BCFs from 3DSSPP$^{\mathrm{TM}}$ with each of the following models: (1) HCBCF v1.0, (2) HCBCF v1.1 – modified torso angle only, modified torso length only, and modified torso angle and length, and (2) HCBCF v1.2 – including gender specific anthropometrics and torso rotation tolerance. Error values were calculated for each condition using the University of Michigan 3DSSPP$^{\mathrm{TM}}$ as the gold standard. Data were summarized using linear fit lines including r^2 and slope values.

3. Results

3.1. 3DSSPP$^{\mathrm{TM}}$ vs. HCBCF v1.0

Initially, 1559 lifting and lowering tasks meeting the criteria of two handed symmetrical lifts with torso asymmetry less than 10^0 were analyzed. A Pearson correlation coefficient (r^2) of 0.94 and a slope of 0.799 was determined, indicating that HCBCF v1.0 generally overestimated BCF compared to the 3DSSPP$^{\mathrm{TM}}$.

3.2. 3DSSPP$^{\mathrm{TM}}$ vs. HCBCF v1.1

As shown in Fig. 3, the modifications made to model parameters in HCBCF v1.1 produced estimated BCF values that demonstrated improved correlation with the 3DSSPP$^{\mathrm{TM}}$ value over the HCBCF v1.0 model equation. Fig. 3 contains a summary of the correlation coefficients for each iteration of HCBCF v1.1. The greatest improvement was seen when both angle and torso length modifications were applied. Modification of the torso angle alone improved the equation more than modification of the torso length alone.

In addition to having r^2 values greater than 0.96, the HCBCF v1.1 model equation also had a slope approximately equal to 1.0 when compared to the 3DSSPP$^{\mathrm{TM}}$, clearly indicating the HCBCF v1.1 is capable of reli-

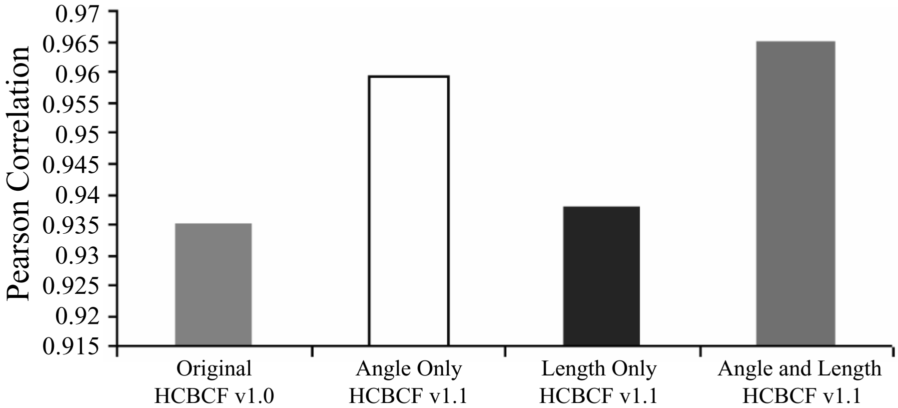

Fig. 3. Correlation between 3DSSPP^{TM} and HCBCF v1.0 model in various stages of revision (N = 1559).

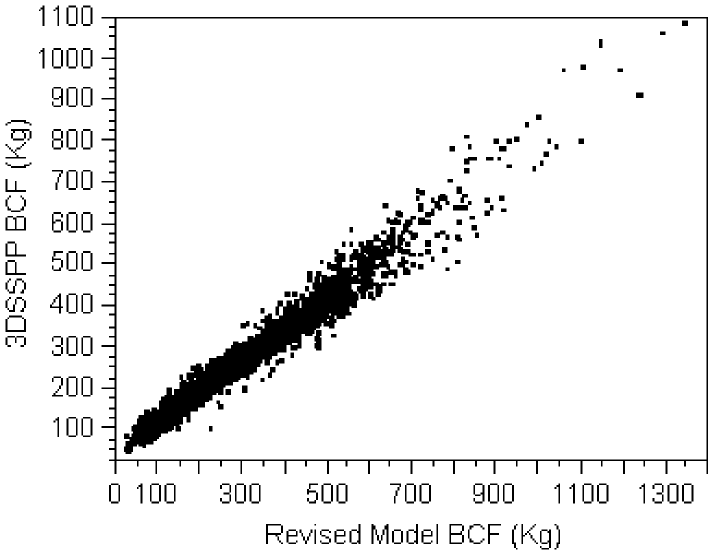

Fig. 4. Plot of 3DSSPP^{TM} vs. estimated HCBCF v1.1 ($r^2 = 0.9664$, N = 6000).

ably predicting the BCF computed using more complex techniques employed by computer based models.

The plot in Fig. 4 of HCBCF v1.1 versus 3DSSPP^{TM} values also shows that scatter increased slightly as BCF increased.

3.3. 3DSSPP^{TM} vs. HCBCF v1.2

The data were stratified by gender, resulting in gender specific model equations. The physiological difference between male and female vertebral body size and resultant moment arm of the erector spinae muscle group has been observed previously as reported by Jorgensen (2001). In addition to the simple correlation equations determined using a linear, best fit line, a constant value equal to 20 kg was added to the equation for females and 23 kg for males to shift y-intercept close to zero.

The equations also showed robustness for handling lifts and lowers with asymmetry angles greater than 10^0, up to 30^0. Because there was very little change in accuracy by introducing torso asymmetry angles greater than 10^0, the HCBCF v1.2 is acceptable to estimate BCF for a broader range of tasks than previously thought.

4. Discussion

The original design criteria – creation of a model similar to the original estimation model HCBCF v1.0 in simplicity but more accurate overall – was first achieved through improving the estimation of torso angle by providing additional angle categories and also including the worker height to determine upper body center of mass location (HCBCF v1.1), and second by observing accuracy in BCF through gender specific equations and including tasks with torso asymmetry greater than 10^0 (HCBCF v1.2).

4.1. HCBCF v1.0

Although the original estimation model possessed many over simplifications, the predictive capability and accuracy compared to 3DSSPP$^{\mathrm{TM}}$ was relatively high. It was determined by the research team that providing additional modification to the original model would likely improve accuracy and utility of the model.

4.2. HCBCF v1.1

Torso angle and torso length revisions from HCBCF v1.0 improved the accuracy of the estimation equation. Increasing the precision of individual components of the equation increased the accuracy of the model overall. HCBCF v1.0 has been cited as producing BCF values within 10–15% of a computer model [5]. Variability in BCF estimations resulting from large horizontal distances has been named as a cause of error for the estimation model [7]. HCBCF v1.1 reduced the average error, reaffirming that approximations made in order to simplify the model are at least partially responsible for model error.

Although the HCBCF v1.1 model has improved the accuracy of BCF estimation relative to the 3DSSPP$^{\mathrm{TM}}$ model, several residual limitations remain: (1) HCBCF v1.1 applied only to two-handed symmetric lifting tasks, (2) HCBCF v1.1 does not differentiate between males and females, and (2) HCBCF v1.1 does not recognize the body weight distribution and resulting center of mass differences between male and female subjects. Finally, HCBCF v1.1 made changes to only the first term of HCBCF v1.0. It was assumed that increased accuracy could be achieved by focus on additional assumptions contained in the constants of the second term of Eq. (2).

4.3. HCBCF v1.2

The final model (HCBCF v1.2) has an $\mathrm{r}^2 = 0.97$ for torso rotations 30 degrees or less for males and 0.96 for females, and $\mathrm{r}^2 = 0.95$ for torso rotation angles above 30 degrees in males. (Analysis of rotations greater than 30 degrees in females is not recommended due in part to the small sample size available for analysis.) Model worksheets have been included as Appendices at the end of this document to provide analysis tools for data collection and HCBCF v1.2 estimations.

To understand the terms described by the equation, and their relevance in computing an estimated BCF, it is important to summarize each factor individually. The terms in the HCBCF v1.2 equation can be summarized as written in Eq. (5).

$$F_c = A + B + C + D \tag{5}$$

Term A is the contribution from the erector spinae force reaction to the moment caused by the weight of the upper body. Term B is the contribution from the erector spinae force reaction to the load moment. Term C is the direct compression component from the upper body weight and load. The last component, term D, shifts the regression line so the y-intercept is approximately equal to zero to reduce the possibility of underestimating the BCF.

Torso rotation evaluation showed that the accuracy of sagittal lifts was maintained for asymmetrical lifts up to $+/-$ 30 degrees, shown in Fig. 5a and 5b. For values above 30 degrees sample sizes decreased for both males and females, and accuracy also decreased (shown in Fig. 6a and 6b). The limited sample size of females where asymmetry angle was greater than 30 degrees did not provide enough information to recommend using the BCF estimation model for these tasks.

5. Conclusion and recommendations for further work

Biomechanical models are a means of quantifying the forces and risks associated with a given task. The ultimate goal of these models is to provide tools that give ergonomics professionals sufficient information to make recommendations to minimize exposure to workplace risk factors associated with back pain and musculoskeletal disorders [4,6,11,13].

Current HCBCF models fail to account for movement during manual material handling. Accounting for inertial forces will provide additional information

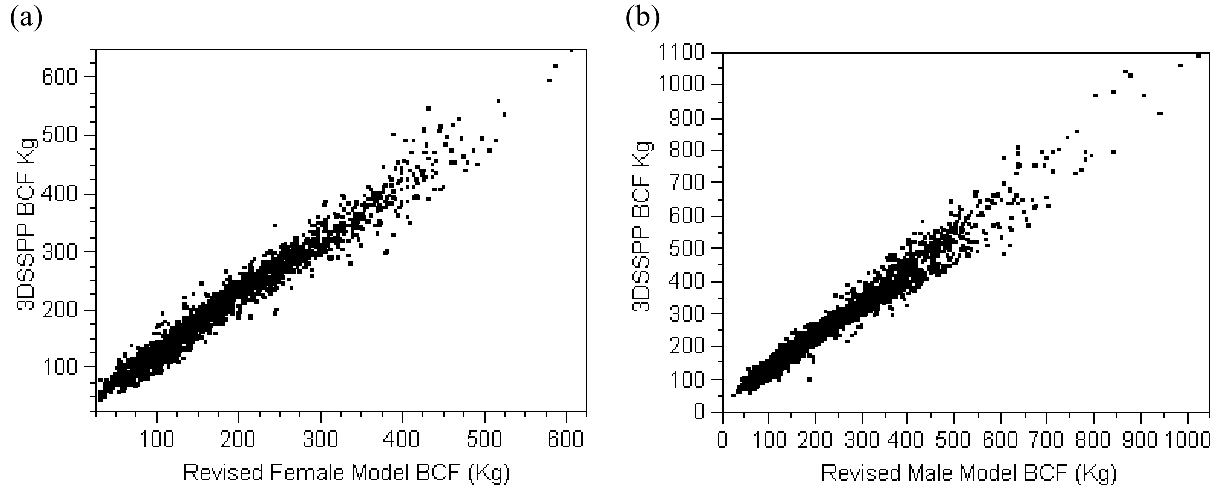

Fig. 5. Correlation between 3DSSPP^{TM} and HCBCF v1.2 (a) females ($r^2 = 0.9633$, N = 2179) and (b) males ($r^2 = 0.9684$, N = 3821) for torso rotation 30 degrees or less.

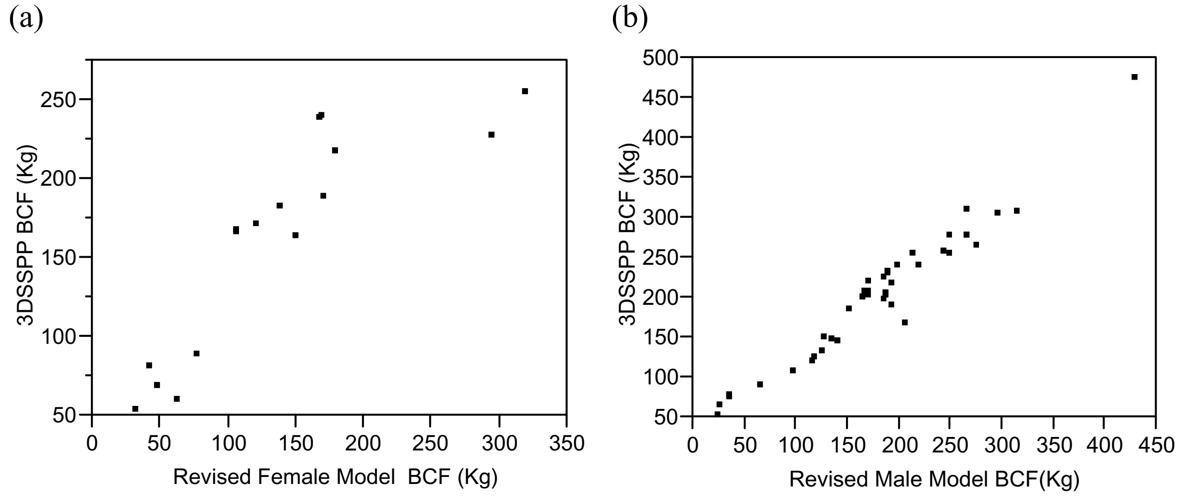

Fig. 6. Correlation between 3DSSPP^{TM} and HCBCF v1.2 for (a) females ($r^2 = 0.7475$, N = 29) and (b) males ($r^2 = 0.9559$, N = 76) for torso rotation greater than 30 degrees.

about spinal loading and give further insight into low back injury prevention methods. Modification to the HCBCF v1.2 model should be studied using a dynamic component in the model that recognizes the effects of acceleration in BCF estimations.

As research continues to investigate internal muscle forces, moment generation, and muscle response to loading, more accurate and realistic models will be developed. The current HCBCF v1.2 model only accounts for one muscle, but additional muscles could be added to the model equation. As biomechanical models become more accurate, they tend to gain complexity decreasing the usefulness of the model in practice [4]. Simple, straightforward models will continue to have a place in corporate ergonomic analysis due to their relative simplicity, ease of use, and low cost. HCBCF v1.2 provides a simple means of accurately estimating BCF.

Acknowledgements

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Appendices (Model Worksheets)

UTAH BACK COMPRESSIVE FORCE WORKSHEET (Female Asymmetry ≤ 30^0)

BW = BODY WEIGHT (kg) = ____________

HT = HEIGHT (cm) = ____________

L = LOAD IN HANDS (kg) = ____________

HB = HORIZONTAL DISTANCE FROM HANDS TO LOW BACK (cm) = ____________

SIN(θ) =TORSO ANGLE WITH VERTICAL = ____________

Select (θ) from the following table, refer to Figure 1.

Torso Angle (θ)	Sin (θ)
0	0.00
10	0.17
20	0.34
30	0.50
40	0.64
50	0.77
60	0.87
70	0.94
80	0.98
90	1.00

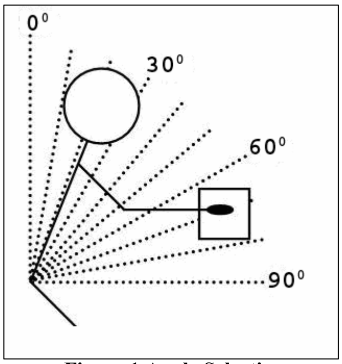

Figure 1 Angle Selection

For Females where asymmetry is ≤ 30^0 (r^2=0.96 compared to 3DSSPP)

Fc = A + B + C + 20

Where:

A = 0.0175(BW)(HT)SIN(θ) = 0.0175(________)*(_________)*(_________) = _________

B = 0.152(L *HB) = 0.152(________)*(_________) = _________

C = 0.8[(BW)/2 + L] =0.8[(________)/2+(_________)] = _________

\+ **20**

TOTAL COMPRESSIVE FORCE ESTIMATE (Kg) Fc = =========

Fc*9.81 = =======**(N)**

The above calculation may be used to determine task redesign priorities. The largest of the terms A, B, or C contribute most to the lifting hazard. Remember that:

A = 0.0175(BW)(HT)SIN(θ) = Back muscle force reactive to upper body weight. To lower this contribution one must change the upper body angle with the vertical.

B = 0.152(L *HB) = Back muscle force reacting to load moment. To lower this contribution one must change the magnitude of the load or the distance that the load is held out from the body.

C = 0.8[(BW)/2 + L] = Direct compressive component of upper body weight and load. To lower this contribution one must change the magnitude of the load (or the body weight).

NOTE: This is just an estimate and its accuracy varies depending on posture, especially as the hands move out in front of the body. There were insufficient data to recommended for use with females where asymmetry > **30^0.**

UTAH BACK COMPRESSIVE FORCE WORKSHEET (Male Asymmetry **≤ 30^0**)

BW = BODY WEIGHT (kg) = ____________

HT = HEIGHT (cm) = ____________

L = LOAD IN HANDS (kg) = ____________

HB = HORIZONTAL DISTANCE FROM HANDS TO LOW BACK (cm) = ____________

SIN(θ) =TORSO ANGLE WITH VERTICAL = ____________

Select (θ) from the following table, refer to Figure 1.

Torso Angle (θ)	Sin (θ)
0	0.00
10	0.17
20	0.34
30	0.50
40	0.64
50	0.77
60	0.87
70	0.94
80	0.98
90	1.00

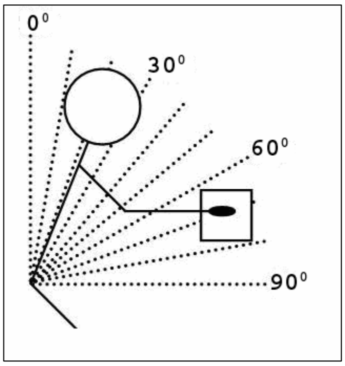

Figure 1 Angle Selection

For Males where asymmetry is ≤ 30^0 (r^2=0.97 compared to 3DSSPP)

Fc = A + B + C + 23

Where: A = 0.0167(BW)(HT)SIN(θ) = 0.0167(________)*(_________)*(_________) = _________

B = 0.145(L *HB) = 0.145(________)*(_________) = _________

C = 0.8[(BW)/2 + L] = 0.8[(________)/2+(_________)] = _________

+ **___23____**

TOTAL COMPRESSIVE FORCE ESTIMATE (Kg) Fc = =========

Fc*9.81 = =======**(N)**

The above calculation may be used to determine task redesign priorities. The largest of the terms A, B, or C contribute most to the lifting hazard. Remember that:

A = 0.0167(BW)(HT)SIN(θ) = Back muscle force reactive to upper body weight. To lower this contribution one must change the upper body angle with the vertical.

B = 0.145(L *HB) = Back muscle force reacting to load moment. To lower this contribution one must change the magnitude of the load or the distance that the load is held out from the body.

C = 0.8[(BW)/2 + L] = Direct compressive component of upper body weight and load. To lower this contribution one must change the magnitude of the load (or the body weight).

NOTE: This is just an estimate and its accuracy varies depending on posture, especially as the hands move out in front of the body. BCF is slightly underestimated for males with asymmetry > **30^0 (r^2=0.95 compared to 3DSSPP).**