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Memory-based Back-support Exoskeletons Effectiveness Evaluation Model

메모리 기반 등 보조 착용 로봇 효과성 평가 모델

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서울대학교 대학원

산업공학과

정 성 우

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

Memory-based Back-support Exoskeletons Effectiveness Evaluation Model

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Back-support exoskeletons (BSEs) have been proposed as an emerging intervention to reduce biomechanical loads on lower back structures during spinal loading tasks. One important activity during the design and development of BSEs, or when deciding whether to adopt or deploy them, is the evaluation of their effectiveness. Currently, the evaluation of BSEs is primarily conducted empirically, using occupational biomechanical models, electromyography, or measurements of physiological parameters. However, data collection for empirical evaluation is known to be costly and time-consuming. To address the limitations of existing BSE evaluation methods, the current study aimed to propose a human simulation-based model for evaluating the effectiveness of BSEs. The model requires two inputs: a work scenario and the characteristics of a BSE. The model then follows three steps for evaluating the BSE: planning feasible working postures for the given scenario, assessing the effectiveness of the BSE by analyzing lumbar forces and moments for the generated working postures, and visually reporting the results. The illustrative examples demonstrated the applications of the model in BSE adoption and design decisions. The model eliminates the need for both empirical data collections for BSE evaluation and measurements from the actual environment as inputs. It is expected to help analysts determine whether the BSE is sufficiently effective for a given scenario, thereby supporting decision-making regarding BSE redesign or adoption.

Keywords: Back-support exoskeletons, Evaluation, Effectiveness, Modeling, Simulation
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Chapter 1

Introduction

1.1 Research Background

Low back pain (LBP) is one of the most common musculoskeletal disorders worldwide, affecting 60-80% of adults at some point in their lives [70]. LBP is particularly prevalent among workers engaged in tasks with high physical demands, such as manual material handling and lifting [16, 30, 31]. Recent studies indicate that approximately 25% of workers report experiencing LBP within the past three months [50, 72]. LBP can decrease workers' productivity [2] and lead to work absences, resulting in financial and economic burdens for both individuals and organizations [32, 47]. In the United States alone, the annual treatment costs for work-related LBP have been reported to exceed $12 billion [24].

Various ergonomic interventions have been proposed to reduce the risks of work-related LBP among industrial workers. These interventions include redesigning workstations and work processes, using mechanical aids, and training in work methods [19, 26, 48, 55]. While effective, these traditional interventions seem to have some limitations. Redesigning workstations and work processes, as well as using mechanical aids, can become infeasible or impractical in certain workplaces due to spatial and financial constraints [8]. Training in work methods is relatively unaffected by these constraints. However, studies have shown its limited effectiveness in reducing LBP risk [46, 56].

Recently, exoskeletons have been proposed as an emerging intervention to reduce LBP and other work-related musculoskeletal disorders [76]. An exoskeleton is defined as a wearable, external mechanical structure that enhances a person’s power. Exoskeletons are classified into active and passive types based on their power sources. Active exoskeletons use power sources such as electric motors and hydraulic actuators, while passive exoskeletons rely on mechanical components like springs and dampers to store and release energy [20]. Exoskeletons provide direct assistive moment to the wearer, thereby reducing biomechanical loads and lowering the risk of musculoskeletal disorders such as LBP [49]. Additionally, the wearable nature of exoskeletons helps preserve workers' creativity and flexibility during tasks, while also offering adaptability to various work environments [20]. These advantageous features of exoskeletons overcome the limitations of traditional ergonomic interventions, leading to increased interest in exoskeletons across various industries [51, 53].

Among different exoskeletons, back-support exoskeletons (BSEs) are specifically designed to reduce biomechanical loads on lower back structures during spinal loading tasks. This is achieved by applying assistive forces and moments between the user's torso and thighs [67]. Multiple research studies have empirically demonstrated that BSEs have significant potential to alleviate physical demands on the lower back [9, 38, 41, 51, 53].

1.2 Literature Review

One important activity during the design and development of a BSE is evaluation [17, 22, 71]. Different prototypes must be assessed for their efficacy to identify promising designs and iteratively improve them. Additionally, the finalized design must be comprehensively evaluated to confirm its benefits. Evaluating a BSE is also crucial when deciding whether to adopt or deploy it for a particular work context [17]. For a BSE to be recommended, the evaluation must demonstrate that it can provide the intended benefits (e.g., reductions in low back stress) to workers with varying physical characteristics across different tasks in the work environment.

Currently, the evaluation of BSEs is mostly conducted empirically. Occupational biomechanical models that compute forces and moments based on empirically measured motion and external force data have been utilized [45, 62]. Electromyography (EMG) and measurements of physiological parameters, such as breathing volume, the rate of oxygen consumption, and carbon dioxide production, have also been employed [6, 9]. However, data collection for such empirical evaluations is known to be time-consuming and costly [76]. It also requires specialized expertise to collect and interpret the data [7, 10, 52, 57].

To address the challenges associated with the empirical evaluation of BSEs, Delgado-Llamas et al. [21] and Zelik et al. [76] developed quantitative models for evaluating BSEs. However, these models still rely on empirical measurements from actual work environments as input. This constraint poses a significant challenge in minimizing the time and costs associated with the evaluation process, making it difficult to substantially reduce the resources required for the empirical evaluation of BSEs.

1.3 Research Objectives

To address the limitations of existing BSE evaluation methods described above, this study proposes a novel human simulation-based evaluation model. This new model first digitally represents a BSE and a work scenario, considering a worker's specific anthropometric characteristics, the work task, and the work environment. It then plans two sets of feasible postures, one for the scenario with the BSE and another for the scenario without it, each set probabilistically approximating the entire range of feasible working postures for the given work scenario. It subsequently evaluates the effectiveness of the BSE and reports the evaluation results. This helps the analyst determine whether the BSE is sufficiently effective for the scenario, thereby supporting decision-making regarding BSE redesign or adoption. This novel model eliminates the need for costly and time-consuming empirical data collection. Furthermore, as a digital human modeling approach, it removes the necessity for real human subject testing and physical mock-ups of work scenarios [4, 59, 74]. These characteristics allow for the rapid and efficient analysis of various BSE redesign ideas and changes in scenarios. The simulation-based evaluation model is built on the memory-based posture planning (MBPP) model [61].

Chapter 2

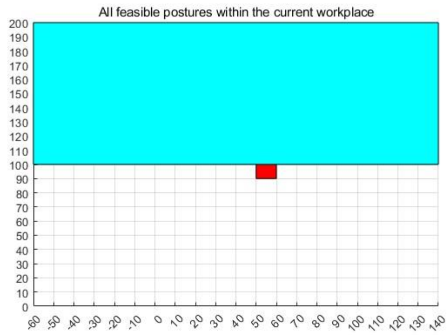
Memory-based back-support exoskeletons effectiveness evaluation (MBBEEE) model

2.1 Introduction

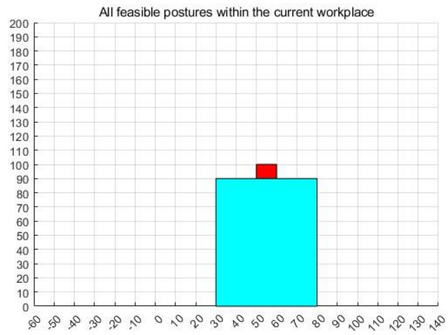
This section describes the MBBEEE model, which evaluates the effectiveness of BSEs. The MBBEEE model takes a work scenario and the characteristics of a BSE as inputs. The model then follows three steps for the evaluation of the BSE: Planning feasible working postures, evaluating the effectiveness of the BSE, and visually reporting the results. The following sub-sections provide a detailed description of each step.

2.2 MBPP model

The MBBEEE model utilizes the two-dimensional MBPP model to generate feasible and collision-free target reach postures for a given work scenario [61]. The work scenario includes a target location and obstructions. As illustrated in the examples in Figure 2.1, these are visually represented by a red square and geometric objects in blue, respectively.



(a) Low ceiling



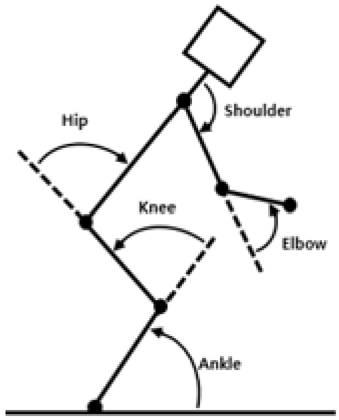
(b) Table

Figure 2.1. Illustrations of workplace scenarios

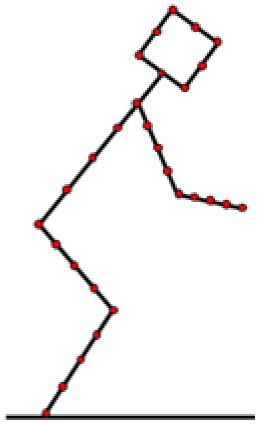
For generating collision-free postures, a geometric object is modeled as an artificial potential field [5]. The potential energy generated by an object is maximal at the center of the object and decreases to zero on or outside its surface. Collision between a point object and an obstruction configuration consisting of multiple geometric objects is computed as the sum of the potential energies generated by each constituent object. A point object is collision-free with respect to the obstruction configuration when the total potential energy is zero.

To represent the human body two-dimensionally, a five-segment kinematic linkage model was employed, as shown in Figure 2.2(a). This model consists of the lower legs, upper legs, trunk-neck-head, lower arms, and upper arms segments. Five joint degrees of freedom are defined at the ankle, knee, hip, shoulder, and elbow. Additionally, the hand position was assumed to be at the distal end of the lower arms.

To detect a collision between a human figure and an obstruction, the sensor approach is employed [5]. In this approach, sensors (point objects) are attached to the human figure (Figure 2.2(b)). Collision between the human figure and an obstruction is detected by testing the interactions between the sensors and the obstruction in the artificial potential field.



(a) A detailed kinematic linkage model of the human body in the sagittal plane



(b) A simplified model highlighting potential sensor placements

Figure 2.2. The kinematic linkage model representing

For planning feasible and collision-free target reach postures, the MBPP model requires a human figure defined in terms of linkages (L) and angles (θ), along with a workplace defined by a target location (E), and an obstruction configuration (C).

A posture is considered feasible in a given workplace scenario if it satisfies all of the following four constraints. First, the posture should have the hand reach the target position. Second, each of the five joints comprising the posture should be within its feasible range of motion. Third, the posture should not excessively lean forward, to the side, or backward such that its center of mass (CoM) is outside the boundary of its base of support. Lastly, the posture should not collide with any obstruction. Each constraint can be mathematically represented by the following equations:

$$Hand\ \ Location(\theta, L) = E \tag{2.1}$$

$$Lower\ \ Limit_j \leq \theta_j \leq Upper\ \ Limit_j\ \ \forall j(joint\ \ angle\ \ j = 1, \dots, J) \tag{2.2}$$

$$CoM(\theta, L) \in Base\ \ of\ \ Support \tag{2.3}$$

$$p(\theta, C) = \sum_{k=1}^{K} potential(S_k(\theta), C) = 0 \tag{2.4}$$

where S_k represents sensors attached to the human model. A collision between the human model and obstruction (C) is detected when an artificial potential field $p(\theta, C)$ is positive.

For rapid and robust posture planning, the MBPP model utilizes a posture memory structure. The workplace is divided into a set of 10 cm x 10 cm squares called ‘cells’, as shown in Figure 2.3. Each cell is connected to a memory space, referred to as a ‘memory cell’. The postures that allow the hand to reach each cell are stored in the corresponding memory cell.

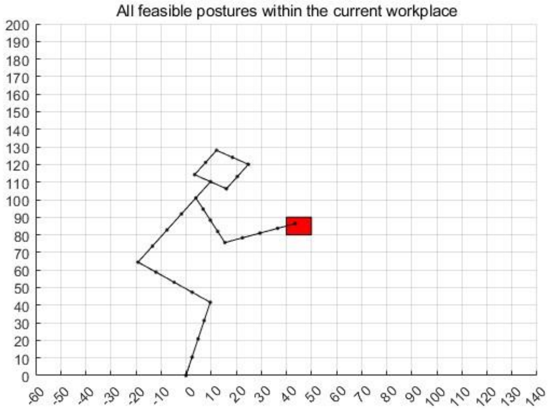


Figure 2.3. Illustration of the memory structure divided into cells, each storing posture memories

The content for each memory cell is pre-generated through a random posture generation and registration process until each memory cell is fully saturated. The process is largely composed of four steps, and each step is described in Figure 2.4.

Step 1.	A posture is generated in terms of angles (θ), which are randomly sampled from the uniform distribution of each joint range of motions.
Step 2.	The posture is checked to see whether it satisfies the body balance maintenance constraint. If it does not, the posture is discarded.
Step 3.	The posture is checked to see if there is a similar posture in the corresponding cell. If so, the posture is discarded.
Step 4.	If the posture passes the above conditions, it is registered in its corresponding cell. The process is repeated until cells are saturated with postures.

Figure 2.4. The random posture generation and registration process for constructing cell contents

The MBPP model requires two user-defined hyperparameters in the random posture generation and registration process. The first parameter is the posture spacing threshold (in degrees). In Step 3 of the process, this parameter ensures that any two postures stored in a cell are at lease the threshold degrees apart in terms of the Euclidean distance in the posture space. The second parameter is the number of feasible postures (satisfying Steps 1 and 2) randomly generated. This parameter affects whether each cell is sufficiently saturated with postures, thereby determining if the MBPP model can approximate the entire range of working postures for a given work scenario.

By registering pre-generated postures into memory cells, the MBPP model rapidly provides a feasible posture set. The model examines the postures in the cell corresponding to the target location of the input scenario. It then outputs postures that meet the collision avoidance constraint.

2.3 MBBEEE model

2.3.1 Introduction

The MBBEEE model extends the MBPP model described above, modifying its memory construction to incorporate the effects of a BSE. This modification is necessary because the CoM position of the BSE can affect the feasibility of postures. Based on these modified memory cells, the MBBEEE model plans a set of feasible postures for a given work scenario. Subsequently, the model evaluates the effectiveness of the BSE through a low back biomechanical analysis, comparing two posture sets: One planned by the MBPP model and the other by the modified memory cells. Finally, the model visually presents the results, clearly comparing the two posture sets.

2.3.2 Memory construction

The MBBEEE model modifies the memory construction of the MBPP model to incorporate a BSE. In (2.3) described in Section 2.1, the MBBEEE model verifies whether the combined CoM of the whole body and the BSE lies within the base of support of the posture. The modified equation is as follows:

$$\frac{M_1 * CoM(\theta, L) + M_2 * CoM_{BSE}}{M_1 + M_2} \in Base\ \ of\ \ Support \tag{2.5}$$

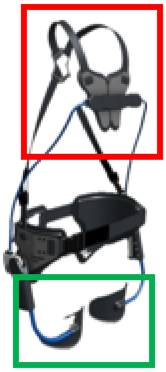
where M_1 represents the mass of the whole body and M_2 represents the total mass of a BSE.

The CoM position of BSE should be measured and provided as part of the input scenario. The remaining process of planning feasible working postures follows the same procedure as the MBPP model.

2.3.3 BSE evaluation based on low back biomechanical analysis

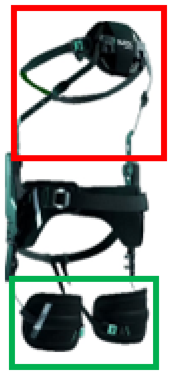
The MBBEEE model evaluates the effectiveness of a BSE by analyzing feasible postures using a low back biomechanical approach. This section explains the procedure of this analysis in the model.

A BSE consists of leg pads and upper components, such as chest pads and back frames. Some existing BSEs are illustrated in Figure 2.5, where the components are highlighted with different colors: Red boxes indicate the upper components that support torso extension, while green boxes show the leg pads that provide hip-extension support. These components allow a BSE to generate an assistive moment in the sagittal plane, supporting the extension of the user’s back and/or hip joints [67].

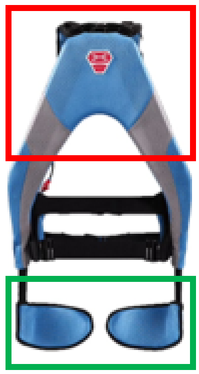


(a) Laevo V2

(b) Laevo FLEX



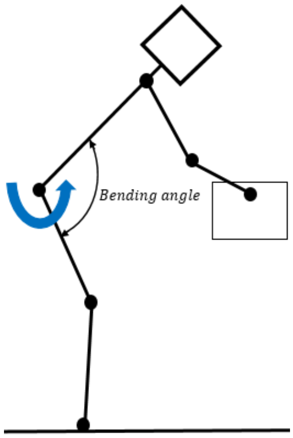
(c) SuitX IX BACK AIR



(d) Innophys Muscle Suit Every

Figure 2.5. Examples of commercially available BSEs

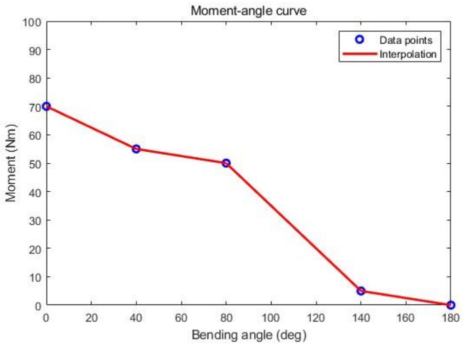
The assistive moment generated by a BSE is a crucial parameter in its evaluation, as it directly influences the extent to which the BSE reduces the risk of LBP [68]. Figure 2.6(b) illustrates the application of the assistive moment to the five-segment kinematic model in the MBBEEE model.



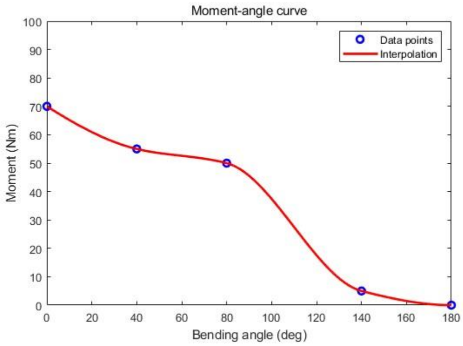
(a) A person wearing a BSE (b) Schematic illustration of kinematic model

Figure 2.6. Representations of a BSE in a five-segment kinematic model

The MBBEEE model employs a moment-angle curve to represent assistive moment, as shown in Figure 2.7. A moment-angle curve has been used in various studies to show how the assistive moment varies with the bending angle [44, 54, 64]. The moment-angle curve of BSEs is derived through several iterations in a unique measurement setup environment, using either a human subject or a manikin to establish the relationship between the bending angle and the assistive moment [54, 68, 69]. This approach is applicable regardless of whether a BSE is active or passive [15, 63, 68].



(a) Linear interpolation



(b) Cubic spline interpolation

Figure 2.7. Representations of assistive moment in the MBBEEE model

In a moment-angle curve, the x-axis represents bending angles (in degrees), while the y-axis indicates the assistive moment (in Newton-meters, Nm) provided by the BSE. In the MBBEEE model, the bending angle is determined according to the angle formed between upper legs and trunk in the human body linkage model (Figure 2.6(b)). To specify a moment-angle curve, a user inputs multiple control points that the moment-angle curve must pass through. The MBBEEE model then presents a curve interpolated from these data points as the moment-angle curve. The model supports both linear and cubic spline interpolation.

The mass of a BSE's upper components is important for a detailed evaluation of the BSE effectiveness in reducing LBP risks. Depending on the postures, the upper components can generate a lumbar flexion moment that may counteract the lumbar extension moment (assistive moment) provided by a BSE [76]. Thus, accounting for the mass of the upper components is crucial for a comprehensive evaluation across different postures. The CoM position and the mass of a BSE's upper components should be measured and provided as part of the input scenario.

For a given work scenario and BSE, the MBBEEE model evaluates the effectiveness of the BSE by analyzing lumbar forces and moments. Analyzing lumbar forces and moments provides a direct approach for evaluating LBP risks across different task scenarios. Various studies have demonstrated the association between compressive forces and LBP incidence [14, 25, 65]. Based on these findings, the National Institute for Occupational Safety and Health (NIOSH) developed criteria for evaluating the risk of LBP associated with lifting tasks [60].

The NIOSH criteria incorporate two critical thresholds for compressive force at the L5/S1 disc. The first threshold, known as the action limit (AL), corresponds to a 3,400 N compressive force on the L5/S1 disc. The second threshold is the maximum permissible limit (MPL), representing a 6,400 N compressive force on the L5/S1 disc. Lifting tasks are categorized into three risk levels based on these two biomechanical thresholds:

(1) L5/S1 compressive force ≤ AL: Tasks within this range can be performed safely without special control measures.

(2) AL < L5/S1 compressive force ≤ MPL: Tasks within this range are potentially hazardous for some workers and require appropriate training and improved working conditions.

(3) MPL < L5/S1 compressive force: Tasks exceeding this threshold are hazardous to most workers, requiring job redesign or implementation of additional control measures.

Studies using cadaver data have validated the NIOSH criteria [13, 37]. These studies have shown that the two threshold values (AL and MPL) are within the range of compressive failure forces observed in lumbar specimens.

Given the advantages of analyzing lumbar forces and moments using the NIOSH criteria in evaluating BSEs for LBP risk, the MBBEEE model employs this approach. It is necessary to quantify L5/S1 compressive forces for feasible postures in a given work scenario. The following content describes how to quantify L5/S1 compressive forces for each posture.

The MBBEEE model utilizes the Chaffin model to calculate the L5/S1 compressive force for each posture [12]. As shown in Figure 2.8, the original equations of the Chaffin model were modified to incorporate the effect of wearing a BSE. Table 2.1 presents the notations and definitions used in the equations.

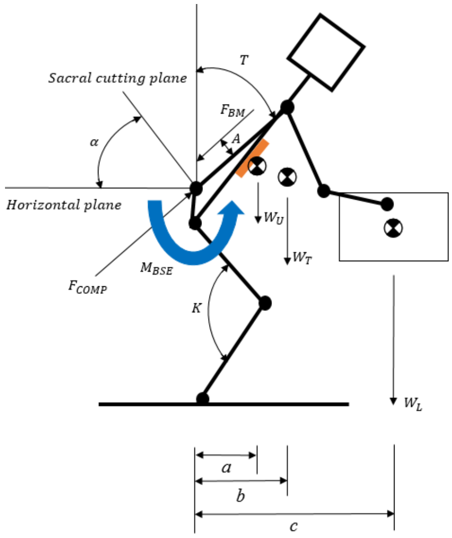


Figure 2.8. Modified Chaffin model incorporating the application of a BSE

Table 2.1. Notations and definitions for L5/S1 compressive force calculation in the MBBEEE model

Notation	Definition
F_{Comp}	L5/S1 compressive force
F_{BM}	Back muscle force
W_U	Weight of BSE's upper components
W_T	Weight of hands, arms, head, neck, and torso above L5/S1 disc
W_L	Load weight
M_{BM}	Back muscle-generated moment
M_{BSE}	BSE-generated assistive moment
a	Horizontal distance between L5/S1 disc and the CoM of BSE's upper components
b	Horizontal distance between L5/S1 disc and the CoM of hands, arms, head, neck, and torso above L5/S1 disc
c	Horizontal distance between L5/S1 disc and center of target
A	Distance from L5/S1 disc to the line of action of back muscle force

α	Sacral cutting plane angle relative to horizontal plane
T	Torso flexion angle from vertical
K	Knee flexion angle

The modified equations of the Chaffin model are as follows:

$$M_{BM} + M_{BSE} = W_U a + W_T b + W_L c \tag{2.6}$$

To achieve static equilibrium, the body generates M_{BM} to counteract external moments from $W_U, W_T,$ and W_L. During this process, M_{BSE} helps reduce M_{BM} required by the body. M_{BSE} is determined by the bending angle of a posture, as defined by the BSE's moment-angle curve. For postures planned by the MBPP model, M_{BSE} and W_U values are set to zero. The L5/S1 compressive forces for feasible postures are computed at the moment when W_L is lifted off from the supporting surface.

$$M_{BM} = F_{BM} A \tag{2.7}$$

The Chaffin model quantifies A as 50 mm, representing the distance from the L5/S1 disc to the line of action of F_{BM} [12]. The MBBEEE model also adopts the same value as A.

$$F_{BM} = \frac{W_U a + W_T b + W_L c - M_{BSE}}{A} \tag{2.8}$$

$$F_{Comp} = W_U \cos(\alpha) + W_T \cos(\alpha) + W_L \cos(\alpha) + F_{BM} \tag{2.9}$$

F_{BM} can be determined using (2.6) and (2.7), as shown in (2.8). The sum of all external forces acting on the L5/S1 disc must be zero to maintain static equilibrium. Hence, we can derive the compressive force acting on the L5/S1 disc, F_{Comp}.

$$\alpha = 40 + \beta \tag{2.10}$$

$$\beta = -17.519 - 0.11863T + 0.22687K + 0.0011904TK + 0.00499T^2 - 0.000753K^2 \tag{2.11}$$

The α angle is a function of the β angle, which represents sacral rotation from the position in an erect posture. The β angle varies as a function of T and K angles [3].

Using the series of equations described above, the MBBEEE model calculates the two sets of L5/S1 compressive forces for feasible postures in scenarios with and without a BSE. Using these two sets, the model generates visual results for feasible postures categorized into three risk levels based on the NIOSH criteria. As illustrated in Figure 2.9, these levels are presented using a color-coding system: Green for the first level (≤AL), red for the second level (>AL and ≤MPL), and black for the third level (>MPL).

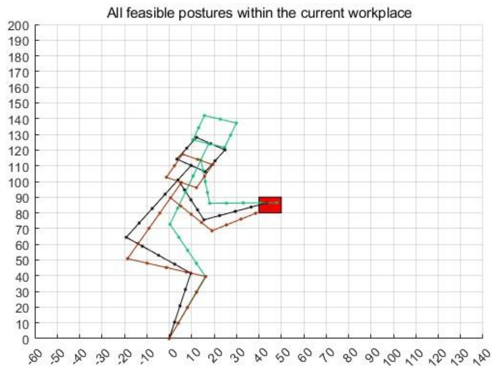


Figure 2.9. Illustration of feasible postures categorized into three risk levels using a color-coding system based on the NIOSH criteria

2.3.4 Visualization and reporting

For a given BSE and input work scenario, the MBBEEE model visually presents results to evaluate the effectiveness of the BSE. The model results are divided into two sections: visualization of feasible working postures within the work scenario and distributions of L5/S1 compressive forces for scenarios with and without the BSE.

Figures 2.10(a) and 2.10(b) show the feasible working postures a worker can adopt within the workplace constraints, without and with the BSE, respectively. The postures are color-coded into three risk levels based on the NIOSH criteria, indicating whether the BSE supports postures with safe low back stress levels.

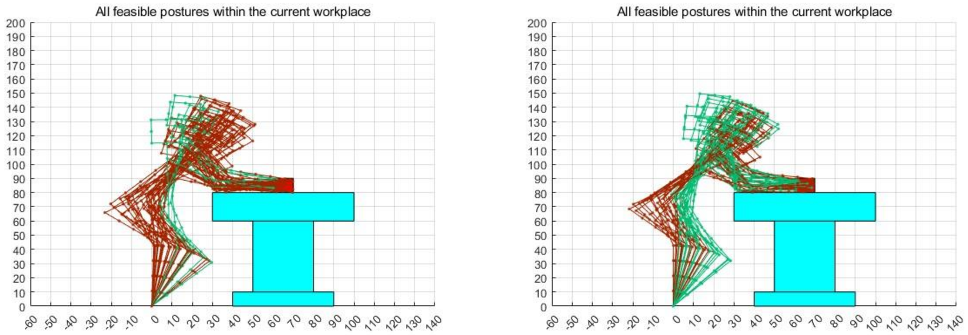
As illustrated in Figure 2.11, the model presents histograms depicting the distributions of L5/S1 compressive forces for scenarios with and without the BSE. The x-axis represents L5/S1 compressive forces in Newtons (N), while the y-axis shows the percentage of postures at each force level relative to the total number of postures. The red bars illustrate the force distribution without the BSE, whereas the blue bars represent the distribution with the BSE. In cases where multiple BSEs are considered, additional histograms added using green, yellow, and other colors. The NIOSH lifting thresholds (AL and MPL) are marked as black bold lines based on the distribution of forces for scenarios with and without the BSE, as follows:

(1) When the forces fall within the first (≤AL) and second (>AL and ≤MPL) NIOSH risk levels, only the AL threshold is displayed.

(2) When the forces fall within the second (>AL and ≤MPL) and third (MPL<) NIOSH risk levels, only the MPL threshold is displayed.

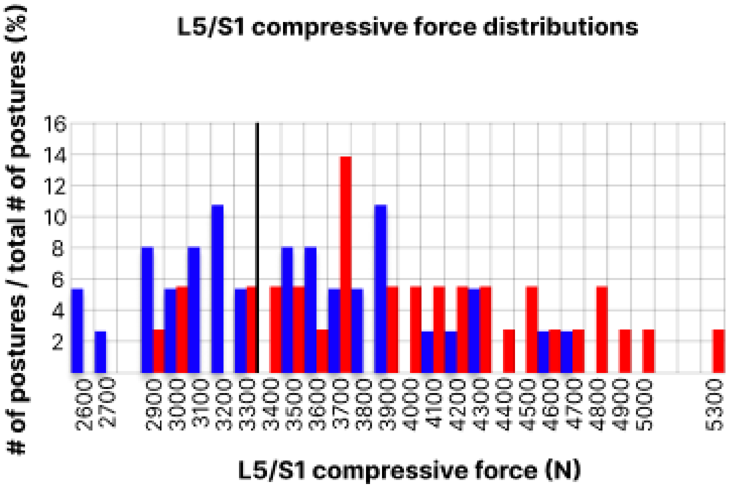
(3) When the forces are distributed across all three NIOSH risk levels, both AL and MPL thresholds are displayed.

The histograms provide a straightforward comparison of how the BSE affects spinal loads. Below the histograms, the MBBEEE model displays a table that outlines the distribution of postures across the three NIOSH risk levels, along with the total number of postures for scenarios with and without the BSE. In cases where multiple BSEs are considered, additional rows are added to the table to reflect each BSE condition.



(a) Without the BSE (b) With the BSE

Figure 2.10. Visual overview of the workplace and feasible postures



	≤ AL	> AL and ≤ MPL	MPL <	Total postures
With BSE	17 (45.9%)	20 (54.1%)	0 (0.0%)	37
Without BSE	5 (13.9%)	31 (86.1%)	0 (0.0%)	36

Figure 2.11. Distributions of L5/S1 compressive forces for scenarios with and without the BSE

When multiple BSEs are considered, the MBBEEE model generates comparative results for each BSE in a given work scenario. The model visualizes feasible working postures, both without a BSE and with each BSE. The histograms use blue, green, yellow, and other colors to depict the distributions of L5/S1 compressive forces for each BSE scenario. The table below the histograms includes rows presenting the results for each BSE (Figure 2.11).

An evaluation threshold is required to determine if BSE is effective enough for a given scenario based on the model results. In this paper, BSE is considered sufficiently effective when more than 50% of postures with BSE fall within the first NIOSH risk level ($\leq$AL) based on the L5/S1 compressive force. This criterion can be adapted by analysts to accommodate the requirements of distinct work scenario.

Chapter 3

Illustrative examples

3.1 Introduction

This section presents examples demonstrating the applications of the MBBEEE model in BSE design or adoption decisions.

3.2 Application of the MBBEEE model for BSE adoption

3.2.1 Scenario

In a logistics warehouse, workers lift a 25 kg object from various shelf heights, as illustrated in Figure 3.1. Workers frequently report lower back discomfort when lifting from the lowest shelf. Consequently, the warehouse ergonomist is considering adopting a BSE to mitigate the risk of LBP.

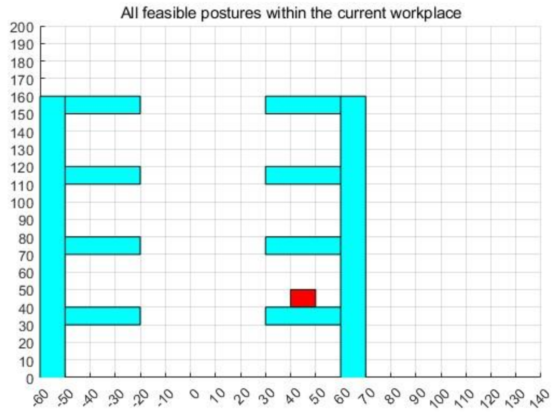


Figure 3.1. The workplace considered in the BSE adoption scenario

To analyze and compare workers with different body types, two kinematic linkage systems were used. These systems represent the 5th percentile female (150 cm height, 50 kg weight) and the 95th percentile male (188 cm height, 124 kg weight) of the U.S. civilian population, based on Fryar et al. [27]. For each system, body segment lengths were determined as proportions of stature following the Drillis and Contini proportionality constraints [23]. Body segment masses were calculated as proportions of total body mass using percentile data from the U.S. civilian population. Table 3.1 provides these values [13].

Table 3.1: Estimated body segment mass distribution (kg) for selected percentiles of U.S.

adult males and females

Segment	Male			Female		
	5%	50%	95%	5%	50%	95%
Hand	0.40	0.54	0.74	0.30	0.41	0.64
Forearm	1.06	1.42	1.97	0.73	1.00	1.56
Upper arm	1.78	2.38	3.30	1.35	1.84	2.88
Head, neck, and trunk	31.22	41.84	57.95	24.61	33.71	52.66
Arms, head, neck, and torso above L5/S1 disc	29.93	40.11	55.56	22.85	31.29	48.89

The two user-defined hyperparameters, the posture spacing threshold and the number of feasible postures generated, were set to be $20°$ and 10^6, respectively. Park et al. [61] reported that these values were sufficient to approximate the entire range of working postures for a given work scenario.

The specifications of a BSE considered in this scenario were derived from realistic parameters based on commercial BSEs (e.g., Laevo, SuitX, and Innophys), research papers, and official manufacturer documentation [21, 35, 66, 68]. The BSE has a total mass of 4.6 kg, and a maximum assistive moment of 65 Nm. Its CoM is assumed to be positioned at the wearer's hip joint, where main joint is located [68]. The mass of the upper components is assumed to be half of the total mass (2.3 kg). Their CoM position is assumed to be in the chest of each kinematic linkage system, according to the Drillis and Contini proportionality constraints [23]. Figure 3.2 illustrates the assistive moment-angle curve of the BSE.

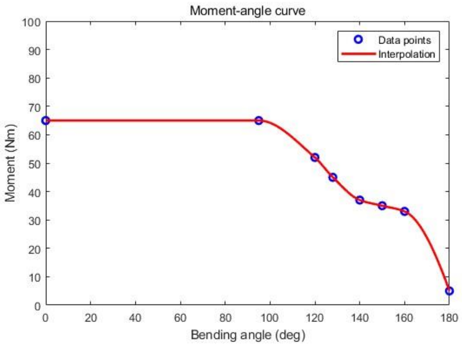


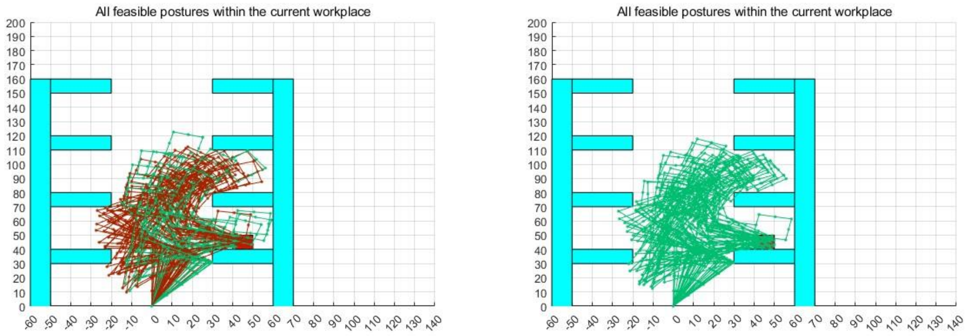
Figure 3.2. The assistive moment-angle curve of the BSE considered in the adoption scenario

By evaluating the effectiveness of the BSE using the MBBEEE model, the warehouse ergonomist can determine whether the BSE is sufficiently effective in reducing workers' risk of LBP and make an informed decision regarding BSE adoption.

3.2.2 Results

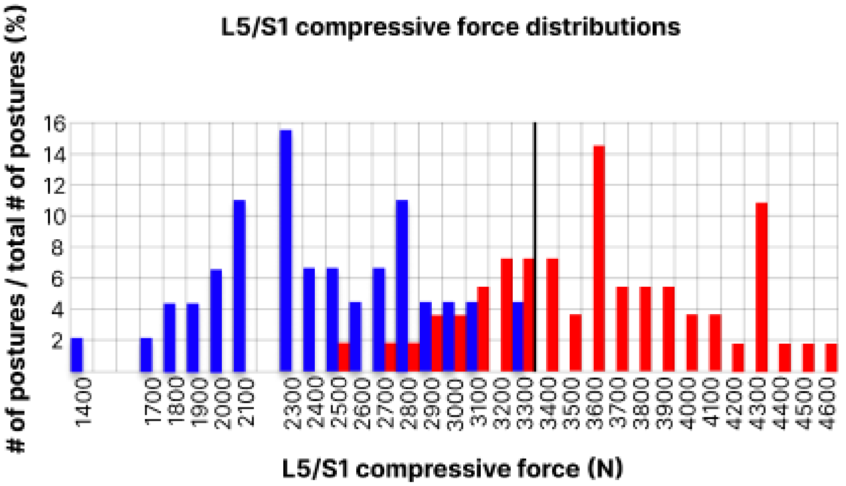
The results of the MBBEEE model for the 5th percentile female under the adoption scenario are presented in Figures 3.3 and 3.4. Figures 3.3(a) and 3.3(b) show color-coded feasible working postures without and with the BSE, respectively. In Figure 3.3(b), all lifting postures are shown in green, indicating that the BSE enables all lifting postures with a safe level of low back stress.

The histograms in Figure 3.4 show the distributions of L5/S1 compressive forces, indicating a significant reduction in spinal loading with the BSE compared to without. The table below the histograms presents the quantitative data supporting these findings. The MBBEEE model generated 45 feasible lifting postures for the scenario with the BSE. All 45 postures were classified as safe to perform without special control measures (≤AL). Therefore, the BSE is deemed sufficiently effective for the 5th percentile female in this scenario, based on the evaluation threshold described in Section 2.3.4.



(a) Without the BSE (b) With the BSE

Figure 3.3. Visual overview of the workplace and feasible postures for the 5th percentile female in the adoption scenario

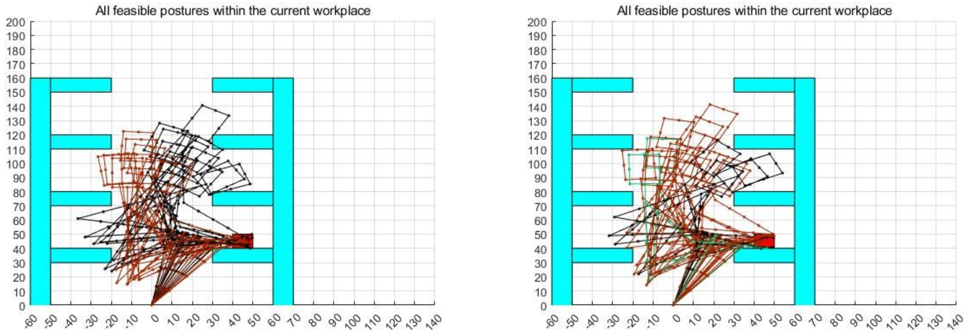


	≤ AL	> AL and ≤ MPL	MPL <	Total postures
With BSE	45 (100.0%)	0 (0.0%)	0 (0.0%)	45
Without BSE	18 (32.7%)	37 (67.3%)	0 (0.0%)	55

Figure 3.4. Distributions of L5/S1 compressive forces for the 5th percentile female in the adoption scenario

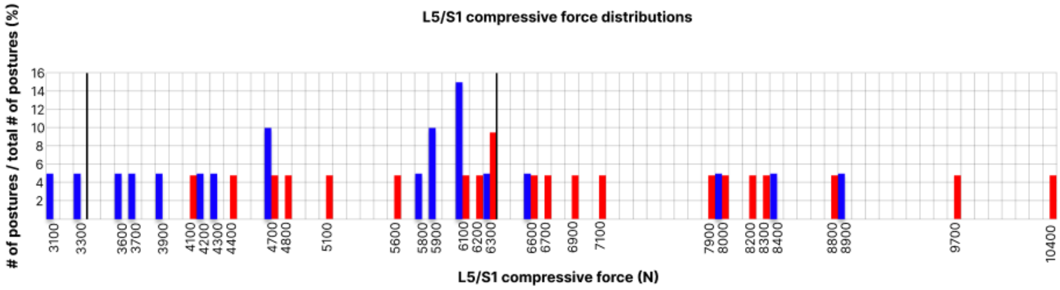
The results of the MBBEEE model for the 95th percentile male are presented in Figures 3.5 and 3.6. Figures 3.5(a) and (b) show color-coded feasible working postures without and with the BSE, respectively. In Figure 3.5(b), although the BSE was implemented, nearly all postures are shown in red or black, indicating that additional measures are required to mitigate LBP risk.

Figure 3.6 histograms illustrate the distributions of L5/S1 compressive forces. Although the histograms with the BSE are left-shifted compared to those without, the BSE is not considered effective enough for the 95th percentile male in this scenario. In the table below the histograms, the model generated 20 feasible postures with the BSE. Of the 20 postures, 2 (10.0%) were classified as safe (≤AL). This result represents an improvement over the scenario without the BSE. However, the BSE is not deemed sufficiently effective based on the evaluation threshold. This result is likely attributed to the anthropometric characteristics of the 95th percentile male (188 cm height, 124 kg weight). These characteristics result in longer body segments and heavier masses, leading to high L5/S1 compressive forces even with minimal trunk flexion.



(a) Without the BSE (b) With the BSE

Figure 3.5. Visual overview of the workplace and feasible postures for the 95th percentile male in the adoption scenario



	≤ AL	> AL and ≤ MPL	MPL <	Total postures
With BSE	2 (10.0%)	14 (70.0%)	4 (20.0%)	20
Without BSE	0 (0.0%)	10 (47.6%)	11 (52.4%)	21

Figure 3.6. Distributions of L5/S1 compressive forces for the 95th percentile male in the adoption scenario

In this scenario, the MBBEEE model results showed that the BSE was effective for the 5th percentile female but unsuitable for the 95th percentile male. Therefore, further investigation into alternative BSEs is recommended to more effectively reduce LBP risk in this scenario.

3.3 Application of the MBBEEE model for BSE design

3.3.1 Scenario

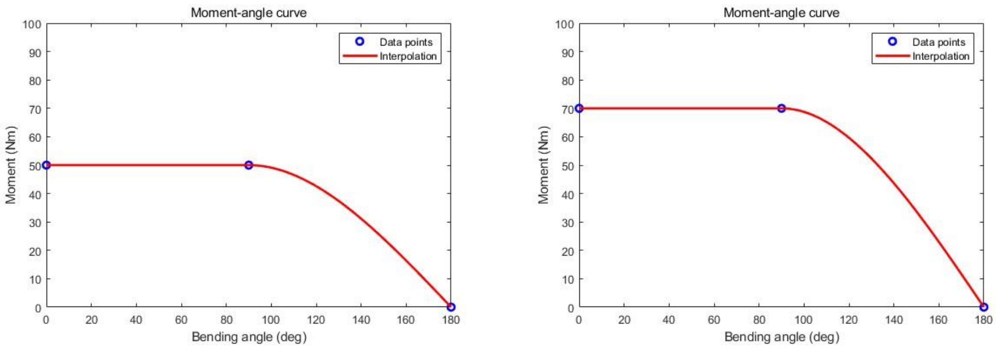
A manufacturer of passive BSEs received a design request for a BSE suitable for lifting a 25 kg object in a spatially constrained workplace. As illustrated in Figure 3.7, the workplace features a low ceiling and limited space. Such restricted environments are commonly found in settings like ships or submarines [11, 43].

Figure 3.7. The workplace considered in the BSE design scenario

This scenario also considers the two kinematic linkage systems representing the 5th percentile female and the 95th percentile male. The two user-defined hyperparameters for the random posture generation and registration process were identical to those used in the previous illustrative example.

The manufacturer has two BSE design alternatives. The first design weighs 5 kg and provides a maximum assistive moment of 50 Nm, with the CoM positioned at the wearer's hip joint. The upper components weigh 2 kg, with their CoM located at the wearer's chest. Figure 3.8(a) illustrates the assistive moment-angle curve for this design, indicating that the maximum assistive moment occurs when the bending angle is between 0° and 90°.

The second design uses higher-tension springs compared to the first, resulting in an increased total mass of 8 kg, with 5 kg for the upper components. As a trade-off, the design provides an enhanced maximum assistive moment of 70 Nm. Figure 3.8(b) shows the assistive moment-angle curve for the second design, indicating that the maximum assistive moment occurs when the bending angle is between 0° and 90°. The CoM positions for both the BSE and its upper components are identical to those in the first design.



(a) The first design (b) The second design

Figure 3.8. The moment-angle curves of two BSE design alternatives

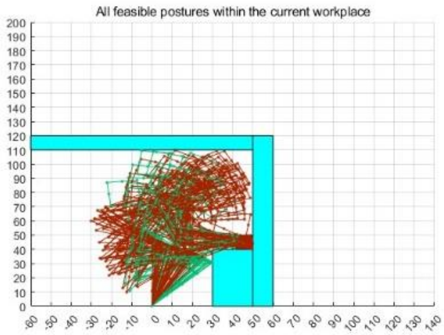
In this design scenario, the MBBEEE model is used to compare the effectiveness of the two BSE designs.

3.3.2 Results

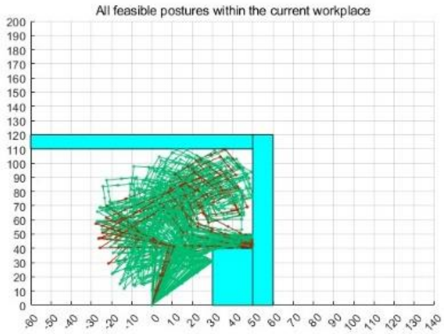
The MBBEEE model results for the 5th percentile female in the design scenario are shown in Figures 3.9 and 3.10. Figures 3.9(a), (b), and (c) show the feasible postures without a BSE, with the first design, and with the second design, respectively. In Figure 3.9(a), most postures without a BSE are shown in red, indicating potential hazards. The predominance of green postures in Figures 3.9(b) and (c) suggests that both BSE designs allow most lifting postures to be performed safely.

Figure 3.10 histograms show the distributions of L5/S1 compressive forces for each BSE condition. The red bars represent the distribution without a BSE, while the blue and green bars represent the first and second designs, respectively. Both designs significantly reduce spinal loading compared to without a BSE.

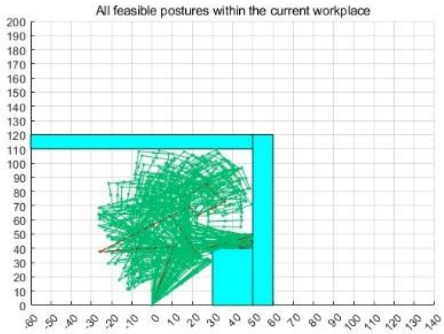
In the table in Figure 3.10, the MBBEEE model generated 63 feasible lifting postures with the first design, 53 of which (84.1%) were classified as safe (≤AL). For the second design, the model generated 59 postures, 58 of which (98.3%) were classified as safe (≤AL). Both designs are deemed sufficiently effective for the 5th percentile female in this scenario, based on the evaluation threshold. The second design showed a 14.2% improvement in safe postures (≤AL) compared to the first. These findings suggest that the second design is more effective for the 5th percentile female in this scenario.



(a) Without a BSE

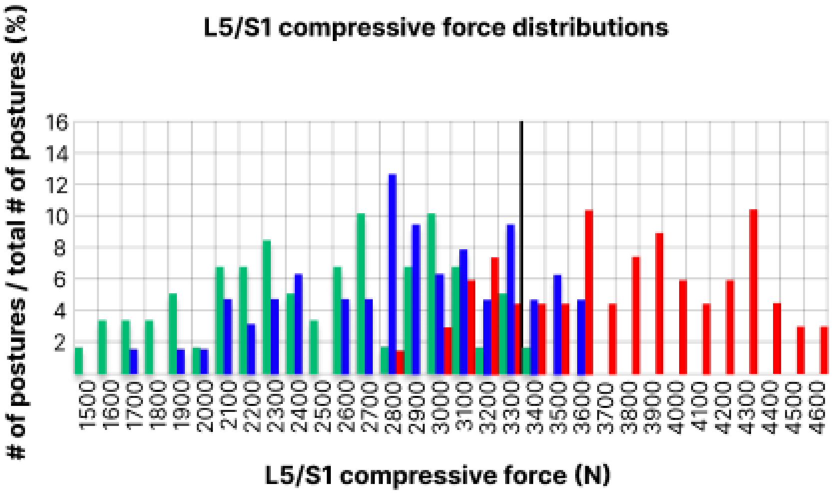


(b) With the first design alternative



(c) With the second design alternative

Figure 3.9. Visual overview of the workplace and feasible postures for the 5th percentile female in the design scenario

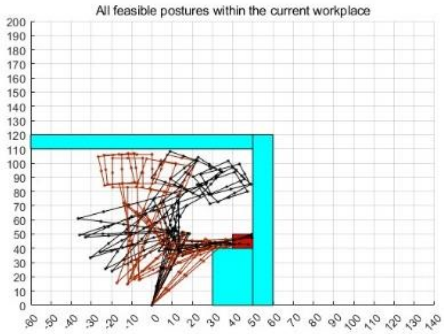


	≤ AL	> AL and ≤ MPL	MPL <	Total postures
With First	53 (84.1%)	10 (15.9%)	0 (0.0%)	63
With Second	58 (98.3%)	1 (1.7%)	0 (0.0%)	59
Without BSE	15 (22.4%)	52 (77.6%)	0 (0.0%)	67

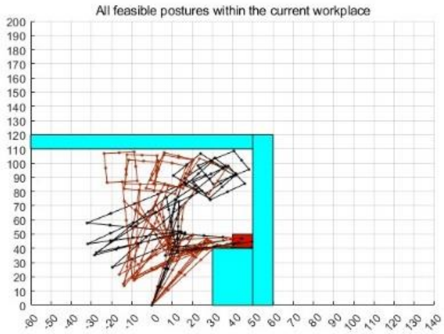
Figure 3.10. Distributions of L5/S1 compressive forces for the 5th percentile female in the design scenario

For the 95th percentile male, Figures 3.11(a), (b), and (c) show the feasible postures without a BSE, with the first design, and with the second design, respectively. In Figure 3.11(a), all postures without a BSE are shown in red or black, indicating that interventions are needed to reduce the risk of LBP. In Figures 3.11(b) and (c), most postures remain in red or black, although a few postures in Figure 3.11(c) appear in green.

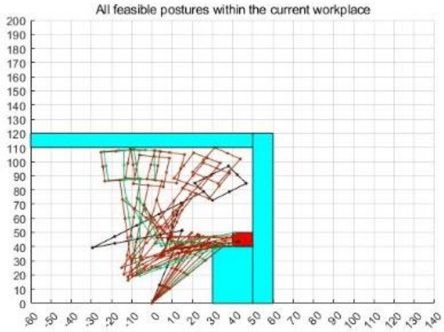
In Figure 3.12, the histograms for the first design (blue bars) are slightly left-shifted compared to those without a BSE, while the histograms for the second design (green bars) show a significant reduction in spinal loading. The table below the histograms supports these findings. For the first design, the model generated 12 feasible postures, none classified as safe (≤AL). For the second design, the model generated 10 feasible postures, with 2 (20%) classified as safe (≤AL). These results suggest that the second design is more effective for the 95th percentile male in this scenario. However, neither design meets the evaluation threshold, indicating that they are effective enough for the 95th percentile male.



(a) Without a BSE

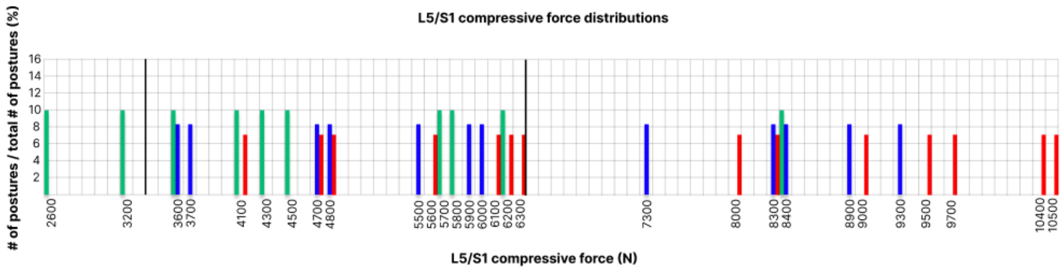


(b) With the first design alternative



(c) With the second design alternative

Figure 3.11. Visual overview of the workplace and feasible postures for the 95th percentile male in the design scenario



	≤ AL	> AL and ≤ MPL	MPL <	Total postures
With First	0 (0.0%)	7 (58.3%)	5 (41.7%)	12
With Second	2 (20.0%)	7 (70.0%)	1 (10.0%)	10
Without BSE	0 (0.0%)	7 (50.0%)	7 (50.0%)	14

Figure 3.12. Distributions of L5/S1 compressive forces for the 95th percentile male in the design scenario

The MBBEEE model reveals that the second BSE design is more effective in reducing LBP risk for both the 5th percentile female and the 95th percentile male. However, neither design is suitable for the 95th percentile male. Therefore, alternative improvements, such as using higher-tension springs, are recommended to enhance the BSE design in this scenario.

Chapter 4

Discussion

4.1 Introduction

The objective of this study was to propose a human simulation-based model for evaluating the effectiveness of BSEs, thereby addressing the limitations of existing BSE evaluation methods. By considering a given work scenario and BSE, the model plans two sets of feasible postures that probabilistically approximate the entire range of feasible postures for both scenarios with and without the BSE. It then evaluates the effectiveness of the BSE by analyzing lumbar forces and moments based on the NIOSH criteria. Subsequently, the model visually presents the evaluation results in two ways: visualizing the feasible working postures in the scenario and illustrating the distributions of L5/S1 compressive forces. Illustrative examples demonstrated how the MBBEEE model supports decision-making for BSE adoption and design.

4.2 Implications

The MBBEEE model serves as a promising modeling and simulation approach for evaluating the effectiveness of BSEs. Existing methods for designing and evaluating exoskeletons can be broadly categorized into empirical/experimental methods and modeling/simulation approaches [28]. As a modeling/simulation approach, the MBBEEE model offers distinct advantages.

The MBBEEE model is more economical and safer than empirical methods. It does not require empirical data collection for low back biomechanical and anthropometric analyses. Unlike previously proposed BSEs evaluation models [21, 76], it also eliminates the need for empirical measurements in actual work environments. Additionally, as a digital human model that removes the need for experimental setups, human subjects, and additional resources [4, 59, 74] and allows easier and earlier identification of ergonomic problem [75], the MBBEEE model significantly reduces the time and costs associated with BSE evaluation. It allows for rapid and efficient analyses of various BSE design concepts and scenario modifications, supporting decision-making for BSE design or adoption.

Moreover, the MBBEEE model enables low back biomechanical analysis by calculating joint forces and moments experienced by exoskeleton users. This capability provides valuable insights for evaluating the effectiveness of BSEs, offering a level of biomechanical detail that is challenging to achieve through empirical studies alone [52].

However, it should be acknowledged that modeling/simulation approaches and empirical/experimental methods are not mutually exclusive [52]. While modeling/simulation approaches provide cost-effective and rapid evaluations, empirical methods remain essential for collecting data on EMG, physiological parameters, and subject comfort [28]. These two methods should be considered complementary, working together as alternatives and supplements in the comprehensive evaluation of BSEs.

The MBBEEE model may be a useful tool for evaluating BSEs in terms of both low back safety and workers' creativity and flexibility. Exoskeletons are widely recognized for their potential to reduce musculoskeletal disorders among workers, particularly in dynamic task environments that demand adaptability, without compromising creativity and flexibility [20, 40]. Thus, evaluating the effectiveness of BSEs should focus on how well they mitigate LBP risks while simultaneously preserving the wearer's creativity and flexibility. In Section 3, the illustrative examples demonstrated that a BSE can affect the range of feasible postures. These findings suggest that when designing a BSE, components such as the overall CoM position and mass of the BSE, its assistive moment profile, and the CoM position and mass of its upper components should be considered to ensure that the number of feasible postures at a safe level is large enough to support both back safety and postural creativity and flexibility. To the authors' best knowledge, no existing tool currently evaluates BSEs in terms of both low back safety and workers' creativity and flexibility simultaneously. The MBBEEE model may serve as an effective tool for addressing this gap.

The MBBEEE model can serve as a valuable tool for workplace design incorporating a BSE, particularly for enhancing low back safety. The effectiveness of a BSE in reducing biomechanical loads on lower back structures can be significantly improved through strategic workplace redesign. Therefore, after adopting the most suitable exoskeleton for each specific workstation, the next key step includes the optimization of the workplace design and adjustment according to the workstation's boundaries, conditions, and constraints [18]. However, a key challenge in developing suitable work environments with integrated exoskeletons is the lack of design and planning methods necessary for equipping future workplaces with this enabling technology [36]. Although established posture analysis tools such as OWAS, RULA, and REBA are widely used to evaluate postural stresses in workplace designs [33, 39, 58], they do not account for BSE integration. A key advantage of the MBBEEE model is its ability to digitally simulate workplace conditions without requiring empirical data collection. This capability supports decision-making in identifying suitable workplaces equipped with a BSE for enhancing low back safety. It facilitates the rapid analysis of interactions between environmental modifications and BSE implementation. Consequently, the model can efficiently evaluate the effectiveness of BSE alongside workplace redesign alternatives, such as adjusting workbench height or repositioning obstructions, to identify optimal configurations for enhancing low back safety.

4.3 Cautions

The MBBEEE model requires an evaluation criterion to determine whether a BSE is effective for a given scenario based on model results. In this paper, the criterion was set such that BSE is considered sufficiently effective when 50% or more of postures with the BSE fall within the first NIOSH risk level (≤AL). This criterion, however, serves only as an example and can be adjusted by the analyst to better suit specific work scenarios. For instance, the criterion could be set to evaluate whether the distributions of L5/S1 compressive forces with the BSE are significantly left-shifted compared to those without it. Alternatively, the analyst might change the NIOSH risk level threshold from ≤AL to ≤MPL or introduce additional conditions. A more comprehensive criterion could be set to combine low back safety with workers' creativity and flexibility. For example, a BSE could be deemed sufficiently effective if more than 50% of the postures with the BSE fall within the first NIOSH risk level (≤AL) while simultaneously preserving a minimum of 20 feasible postures. The evaluation criterion can be determined based on diverse scenarios and objectives.

Regarding the analyses provided in the illustrative examples, it should be noted that more considerations are required in real-world analyses. Specifically, the illustrative examples focused on two kinematic linkage systems: the 5th percentile female and the 95th percentile male. This approach was adopted to maintain the simplicity of the study while covering the majority of the workforce by addressing two extreme anthropometric conditions. Furthermore, the evaluation of such distinct linkage systems confirmed the MBBEEE model's rapid and robust performance across diverse body size parameters. However, real-world analyses should consider various scenarios, including not only a wider range of workers' anthropometric data but also variations in target and obstruction positions, as well as target loads. Such comprehensive analyses are essential for effectively informing decisions related to the design or adoption of BSE.

Chapter 5

Conclusion

5.1 Conclusion

This study presented a human simulation-based model for evaluating the effectiveness of BSEs. The model takes a work scenario and the characteristics of a BSE as inputs. Using these inputs, it plans feasible postures for the scenario, evaluates the effectiveness of the BSE through a low back biomechanical analysis, and provides a visual report of the results. The model can significantly reduce the costs and time required for empirical evaluations of BSEs. It helps determine whether the BSE is effective for the given scenario, thereby supporting decision-making in BSE design or adoption.

5.2 Limitations and Future Research Direction

The MBBEEE model has some limitations, discussed below along with future research directions. First, the model only considers sagittally symmetric postures. Future studies should extend the model to a three-dimensional version to evaluate BSEs under non-sagittal trunk postures, such as torso twisting. Second, the MBBEEE model evaluates BSEs for static postures based on the NIOSH lifting criteria [60]. However, it does not support the evaluation of dynamic human motions. Future research should extend the model to assess BSEs during motion using a motion trajectory generation algorithm based on the MBPP model [73]. Third, the human model used in the MBBEEE model is a stick figure model consisting of line segments, which does not represent body segment volumes. This limitation may lead to inaccuracies in posture planning or the evaluation of BSEs. A more accurate representation of the human body is currently under investigation, utilizing body segment volume data as described by Chaffin et al. [13].

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국문초록

등 보조 착용 로봇은 척추 부하 작업 중 허리 구조에 대한 생체 역학적 부하를 줄이기 위한 새로운 대안으로 제안되었다. 등 보조 착용 로봇의 설계 및 개발, 혹은 이를 채택하거나 배치할지 여부를 결정하는 과정에서 중요한 활동 중 하나는 효과성을 평가하는 것이다. 현재 이러한 평가는 주로 생체역학 모델, 근전도, 생리적 매개변수의 측정을 통한 실증적인 방법으로 이루어지고 있다. 그러나 실증적 평가를 위한 데이터 수집은 비용이 많이 들고 시간이 오래 걸리는 것으로 알려져 있다. 기존 등 보조 착용 로봇 평가 방법의 한계를 해결하기 위해 본 연구는 기기의 효과성을 평가하기 위한 인간 시뮬레이션 기반 모델을 제안한다. 본 모델은 작업 시나리오와 등 보조 착용 로봇의 특성이라는 두 가지 입력 데이터를 필요로 하며, 기기 평가를 위해 세 가지 단계를 따른다. 주어진 시나리오에 대해 실행 가능한 작업 자세를 계획하고, 생성된 작업 자세에 대해 요추에 가해지는 힘과 모멘트를 분석하여 효과성을 평가하며, 평가 결과를 시각적으로 보고한다. 예시를 통해 등 보조 착용 로봇 채택 및 설계와 관련된 의사 결정 시 본 모델의 응용 가능성을 입증하였다. 본 모델은 등 보조 착용 로봇 평가를 위한 실증적 데이터 수집과 실제 환경에서의 측정을 입력 데이터로 사용할 필요성을 제거하여, 분석가가 특정 시나리오에 대해 기기가 효과적인지 빠르게 판단하도록 도와주며, 재설계 또는 채택에 대한 의사 결정을 지원할 수 있을 것으로 예상된다.

주요어: 등 보조 착용 로봇, 평가, 효과성, 모델링, 시뮬레이션

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