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BIOMEDICAL ENGINEERING | RESEARCH ARTICLE

Musculoskeletal model of awkward carrying postures

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Abstract: Improper posture of carrying loads can cause low back disorders. This study investigates the impact of using a footstool in spinal force and muscle activity when: (1) pushing/pulling load farther/nearer from the body and (2) twisting the trunk while carrying load. A whole body musculoskeletal model carrying a light load of 5, 7.5 and 10 kg is developed and inverse dynamics analyzes are conducted. Electromyography activities are also recorded to compare to the results from analyzes. Analyzes demonstrated that using a footstool when carrying a light load can reduce the intradiscal compression force. The results from the analysis are found to be consistent with the electromyogram measurement. This study suggests that load should be positioned closer to the body and footstool of 5 cm height should be used to reduce spinal forces and muscle activity on the lumbar region.

Subjects: Engineering & Technology; Biomedical Engineering; Biomechanics

Keywords: carrying load; muscle activity; musculoskeletal model; back pain

1. Introduction

Work-related musculoskeletal disorders can cause significant costs for medical treatment and lead to decrease of productivity. Improper manual carrying of load is considered an important risk factor for the occurrence of low back disorders (LBDs). Any job involving load carrying such as manual material handling (MMH) is at higher risks of lower back pain. Numerous studies have linked LBDs with both lifting (Bernard, 1997) and pushing/pulling tasks (Hoozemans, Van Der Beek, Fringsdresen, Van Dijk, & Van Der Woude, 1998; Van Dieën, Hoozemans, & Toussaint, 1999). Lifting tasks can be considered a combination of carrying tasks, which place large compressive loads on the spine and pushing/pulling tasks, which can create large shear loads on the spine. In addition, studies showed that there are elevated risk of LBDs in awkward carrying posture such as twisting, which refers to trunk rotation or torsion (Bernard, 1997). Although lifting is a common task in the industry, the risks to the spine

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PUBLIC INTEREST STATEMENT

Work-related musculoskeletal disorders can cause significant costs for medical treatment and lead to decrease of productivity. Improper manual carrying of load is considered an important risk factor for the occurrence of low back disorders. Any job involving load carrying such as manual material handling is at higher risks of lower back pain. Strategies to prevent or reduce low back disorders should focus on reducing the exposure to awkward postures at work. In this study, we use a computational human body model to observe the effect of using a footstool on the human spine and muscles around the lumbar region in several awkward load carrying postures.

associated with various awkward carrying postures have not been fully examined. Widanarko et al. (2012) conducted telephone survey of 3,003 samples to investigate on the workplace exposure and LBDs; the study found that the risk of LBDs increased with work in lifting tasks and awkward/ tiring positions. However, the amount of muscle activation on each muscles performing the activities were not measured. Maikala, Ciriello, Dempsey, and O'Brien (2009) demonstrated that a lower resultant forces was exerted when performing cart pushing on walkways with lower coefficient of friction. From this study, acceptable workload during pushing a cart was determined psychophysically. However, it is not known how the muscles responds and which particular muscles were activated.

The use of computational musculoskeletal models and the environment it interacts with can help researchers find solutions to various issues involving human body biomechanics. In general, the goal of musculoskeletal modeling and simulation is to predict muscle forces, joint reaction forces or other biomechanical parameters, which are impractical to be measured directly (Arnold, Blemker, & Delp, 2001; Mohamaddan, Jamali, Abd Majid, & Mohamad Suffian, 2016; Nolte, Augat, & Rasmussen, 2008; Van Drongelen, Wolf, & Fradet, 2014). Previous work using musculoskeletal model investigated the impact of stance width on muscle activation patterns and spine loading in several lifting techniques, i.e. squat, stoop and semi-squat lifting techniques (Mirakhorlo, Azghani, & Kahrizi, 2014). This paper investigates on the effect of footstool usage during awkward load carrying postures on the spinal force and muscle activity. Previous studies have used questionnaire and electromyogram (EMG) recording to observe the low back disorders (Maikala, Ciriello, Dempsey, & O'Brien, 2010; Widanarko et al., 2012). In this paper, a musculoskeletal simulator, namely Anybody Modeling System (Rasmussen et al., 2003) and its associated public-domain library of body models are being used and further developed to examine the muscle activity in several load carrying postures.

To examine the impact of footstool when carrying a light load and the effect of awkward postures during carry, two musculoskeletal models of different carrying postures are developed, which are: (1) pushing/pulling load farther/nearer from the body and (2) twisting the trunk while carrying load to quantify the forces generated in the lumbar spine and the muscle activity around the region. EMG measurement are also taken to compare the results with the analysis.

2. Methods

2.1. Anybody modeling system

The model in this study is constructed using AnyBody Modeling System ver. 4.2 (referred to as AnyBody). It is a musculoskeletal modeling and simulation software; described in detail by Rasmussen, Damsgaard, and Voigt (2001). The whole body model includes: (1) an upper extremity model containing 114 muscle units on each side of the body, (2) a spine model comprising sacrum, all lumbar vertebrae and a rigid thoracic-spine section with a total of 158 muscle units and (3) a pelvis and lower extremity model with a total of 159 muscle units. In total, the model contains more than 500 individual muscle units and, hence, considered as a comprehensive description of the human musculoskeletal system. Further description of the model is available from Rasmussen, Carbes, and Gomaa (2009), Rasmussen, Tørholm, and Zee (2009).

In the system, an inverse dynamic method is used to solve a typical musculoskeletal multi-body dynamics problem. The redundancy problem in muscle recruitment is solved using an optimization-based approach (Rasmussen et al., 2001). The mathematical form of the inverse dynamic problem is as follows:

Minimize the objective function:

$$G\left(f^{(M)}\right). \tag{1}$$

Subjected to the following constraints:

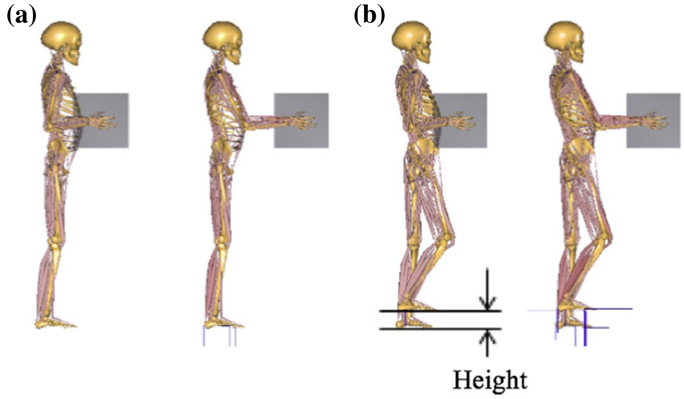


Figure 1. Pushing and pulling load carry movement: (a) Footstool height 0 cm and (b) Footstool height 10 cm.

$$\mathbf{Cf} = \mathbf{d}. \tag{2}$$

$$f_i^{(M)} \geq 0,\ i \in \{1, \ldots, n^{(M)}\}. \tag{3}$$

where G in Equation (1) is the objective function of the recruitment strategy stated in terms of the muscle forces $f_i^{(M)}$, and minimized with respect to all unknown forces in the problem, $\mathbf{f}$ (i.e. muscle forces and joint reactions). Equation (2) is the dynamic equilibrium equation, where $\mathbf{C}$ is the coefficient matrix for the unknown forces/moments in the system while $\mathbf{d}$ is a vector of the known applied loads and inertia forces. The non-negativity constraints on the muscle forces in Equation (3), states that muscle can only pull, not push.

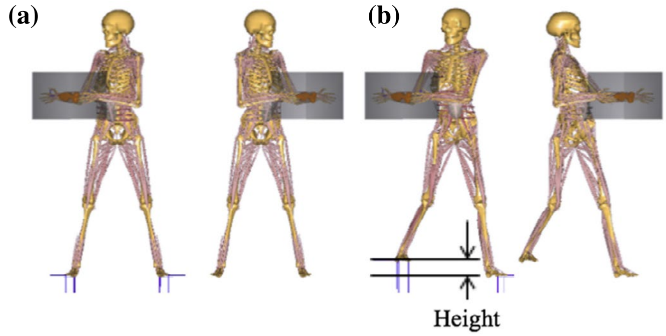
2.2. Musculoskeletal analysis

In this paper, two types of load carrying postures are analyzed. Figure 1 shows the model movement in pushing/pulling carry; the load is brought forward from 32 cm (nearest to the body) to 52 cm in the sagittal direction of the body. The twist carry model movement is shown in Figure 2. The model is twisted in the trunk; the load is rotated from −50° on the right side to 50° on the left side. These models are named as P-E model (push/pull-EMG model) and T-E model (twist-EMG model) respectively. The results from inverse dynamics analysis are then compared to experimentally measured EMG results of a healthy subject (65 kg, 173 cm) performing the same tasks. The analysis condition is shown in Table 1. In all cases, the height of the musculoskeletal model is 180 cm, the body weight is 75 kg and the anthropometrical dimensions of the model corresponds to a 50th percentile European male.

Table 1. Analysis condition

	Push/pull-EMG model (P-E model)	Twist-EMG model (T-E model)	Push/pull-footstool model (P-F model)	Twist-footstool model (T-F model)
Body height (cm)	180			
Body mass (kg)	75			
Movement	Push and pull	Twist	Push and pull	Twist
Weight (kg)	5, 7.5, 10		5	
Right foot height (cm)	–		0, 5, 10, 15	
Analysis object	• Right side muscle activity of erector spinae		• L4-L5 Compression force • Right side muscle activity of erector spinae	

Figure 2. Twisting load carry movement (from −50° on the right side to 50° on the left side): (a) Footstool height 0 cm and (b) Footstool height 10 cm.



Inverse dynamics analyzes are performed on these musculoskeletal model. The loading of the joint (N) and the amount of muscle activity (%), which is the ratio of active muscle force to the maximum muscle force are investigated. Here, the weight of the load is 5, 7.5 and 10 kg. The muscle activity of the right side of the erector spinae muscle are analyzed and compared to the results obtained from EMG.

Then the relationship impact of footstool during load carrying on the lumbar load and spinal muscle activity is observed. These models are called P-F model (push/pull – footstool model) and T-F model (twist–footstool model). In both cases, the load is set to 5 kg. The height of the footstool set as 0, 5, 10 and 15 cm. The L4-L5 intradiscal compression force (the portion between fourth and fifth lumbar vertebrae) and the right side of the erector spinae muscle is examined. The analysis condition is shown in Table 1.

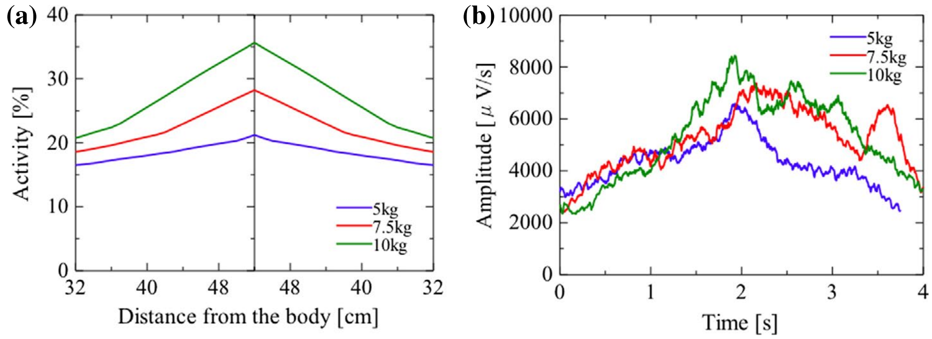
2.3. EMG measurement

A 24-year old healthy man (65 kg, 173 cm) took part in this study. The subject provided written informed consent for this study. EMG is measured by bipolar lead surface EMG (MWATCH, Wada Co. Ltd). The derived analog signal is sent to a computer at a sampling frequency of 1,000 Hz using A/D conversion. The surface EMG is attached along the direction of the muscle fiber with the electrode center distance of 25 mm. The materials of the electrode terminals are silver—silver chloride (Ag/AgCl), whereas conductive acrylic hydrogel is used as an adhesive gel. The electrodes are attached referring to the anatomy guide for EMG by Perotto, Morrison, Delagi, and Iazzetti (2005). The experiment is conducted according to the measurement conditions on Table 2. The load weight is set to 5, 7.5 and 10 kg in both cases. The myoelectric potential is measured at the right side of the erector spinae. The mean integral electromyogram (iEMG) waveform (μV/s) is created by averaging the value for every 300 ms. The results are then compared to the analysis results.

Table 2. Measurement condition

	Push and pull-EMG measurement (P-E measurement)	Twist-EMG measurement (T-E measurement)
Body height (cm)	173	
Body mass (kg)	65	
Movement	Push and pull	Twist
Weight (kg)	5, 7.5, 10	
Measurement object	Right side muscle potential (Erector spinae, Obliquus externus)	

Figure 3. Comparison of muscle activity with muscle potential of erector spinae muscle in push and pull lifting: (a) Muscle activity obtained from analysis and (b) Muscle potential obtained from electromyography.



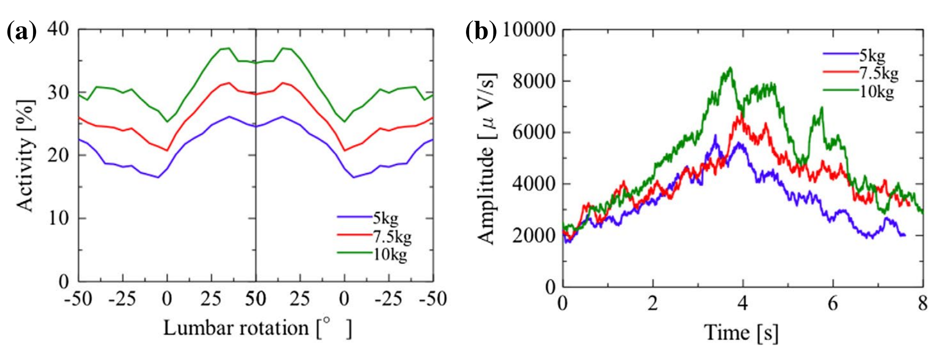
3. Results and discussion

3.1. Musculoskeletal analysis and EMG results comparison

Figure 3(a) shows the estimated muscle activity of the erector spinae in pushing and pulling carry movement from Anybody Software. When the load is nearest to the body (at 32 cm) the muscle activity is approximately 15–20%. The muscle activity almost doubled when the load is carried farther from the body and highest when the load is 10 kg; muscle activity 35%. To validate the model, we compare the trends between the estimated muscle activity with EMG signals as suggested by Zee, Lund, Schwartz, Olesen, and Rasmussen (2010). Figure 3(b) shows the EMG results of the erector spinae; at 0 s the load is nearest (32 cm) and at 2 s the distance is 52 cm to directly compare with the estimated muscle activity. In the EMG result, the muscle activity is also highest when the load is farthest away from the body. It can be seen that the amount of muscle activity increases even further when the load weight is increased. We found similar trends between these two results. It is thought that when large load is carried in front of the body, high moment is generated when the trunk is overthrown forward. This moment caused the erector spinae to contract actively, resulting in high muscle activation. Therefore, the increment of forward moment due to an increase in load and/or its distance to the body causes the increment of muscle activity in erector spinae. This result supported the guidelines by NIOSH (1981), which stated that when lifting a load, it should be moved as closely to the body as possible. When load is higher (i.e. 7.5 and 10 kg) the decrease in muscle activation is more pronounced if the load is brought closer to the body. As shown in Figure 3(a) and (b) we found similar patterns of muscle activation between analysis and EMG results. Muscle activity increases when the load is farther away from the body, and then decreases when the load is brought closer. This result is also consistent with previous study by Rose, Mendel, and Marras (2013).

Figure 4(a) shows the estimated muscle activity of the erector spinae muscle in twist lifting movement; lumbar rotation from −50° on the right side to 50° on the left side as shown in Figure 2 (without the footstool). The estimated muscle activity when load is 10 kg is 30% on the start of the movement then decreases when the load is directly in front of the body and then it increases by 5% when the load is brought to the left side of the body. The muscle activity for 10 kg load carrying is

Figure 4. Comparison of muscle activity with muscle potential of erector spinae muscle in twist lifting: (a) Muscle activity obtained from analysis and (b) Muscle potential obtained from electromyography.



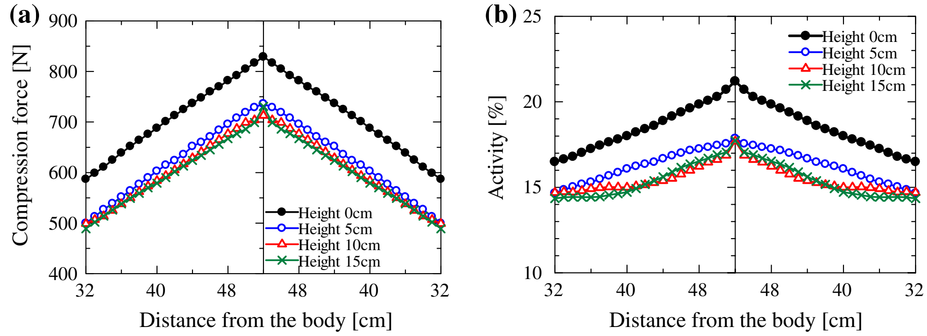


Figure 5. The impact of footstool height during push/pull load carrying: (a) L4-L5 intradiscal compression force and (b) Muscle activity of erector spinae muscle.

relatively high throughout the movement (between 30 and 35%). Figure 4(b) shows the EMG results of twist lifting. Here, we found that the muscle potential increases when the load is brought from right side (at 0 s) to the left side of the body (at 4 s). Trunk rotation while lifting load causes the abdomen, back and leg muscles to work harder to maintain dynamic balance. This would involve the erector spinae, semispinalis, trapezius, tibialis anterior, vastus lateralis and hamstring muscles (Cook & Neumann, 1987). Therefore, the subjects need to make more effort to keep the body more stable. As opposed to the estimated muscle activity from the musculoskeletal model, the decrease of muscle potential when the load is carried directly in from of the body is not shown.

3.2. Analysis on effectiveness of footstool

Figure 5(a) shows the estimated L4-L5 intradiscal compression force from analysis of P-F model in push/pull load carrying movement. When footstool is not used and distance of load from body is nearest, the force is 587 N. When footstool height is 5, 10 and 15 cm the force reduces significantly to 500 N. Figure 5(b) shows the muscle activity of the erector spinae muscle when footstool is added in the model. The muscle activity decreases from approximately 21 to 17% when footstool is used. From the result, footstool is beneficial in reducing lumbar load and muscle activity of the spine in pushing/pulling load carrying movement.

Figure 6(a) shows the L4-L5 intradiscal compression force in twist load carrying model (lumbar rotation from −50° on the right side to 50° on the left side). It can be seen that when the footstool is 5 cm, the force reduces significantly as compared to the model without footstool. However, the force is approximately two times higher at the start and end of twist movement when footstool height is 10 and 15 cm. Figure 6(b) shows the muscle activity of erector spinae muscle. From this figure, muscle activity increases about 10% at the start of the twist movement when a footstool of 10 and 15 cm is used. Therefore, it can be concluded that a footstool is not necessarily beneficial to the spine since it increases the spinal force and muscle activity during twist load carrying movement if the footstool is higher than 5 cm.

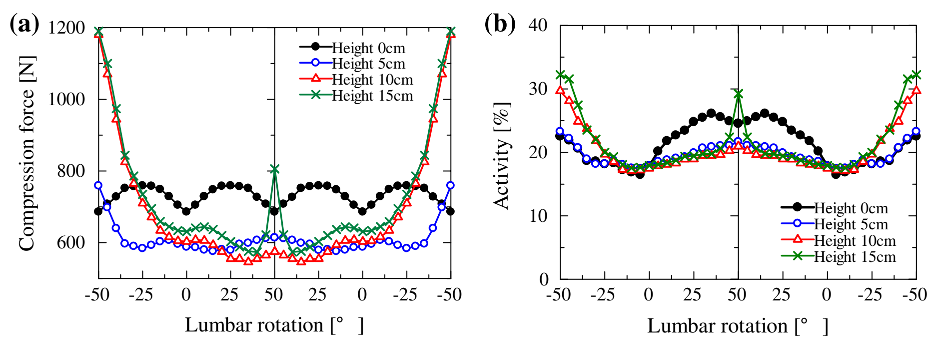
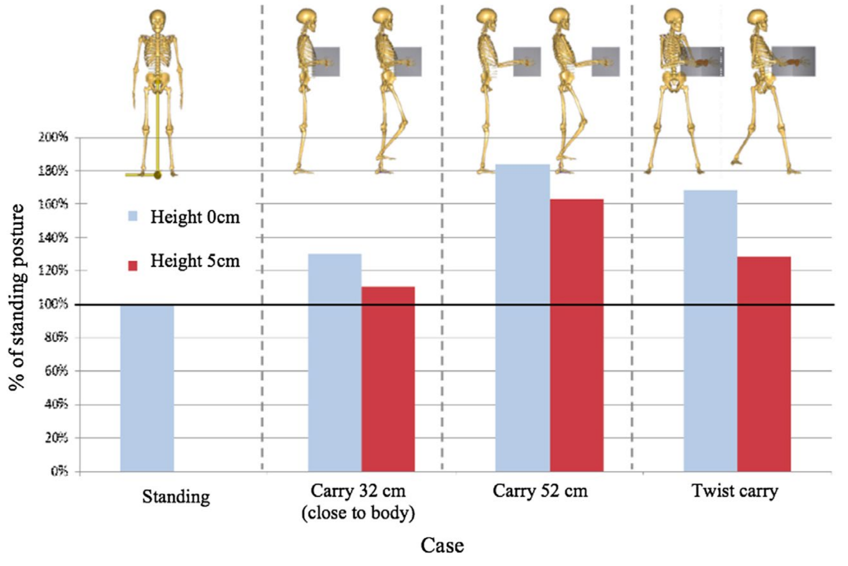


Figure 6. The impact of footstool height during twist load carrying: (a) L4-L5 disc compression force and (b) Muscle activity of erector spinae muscle.

Figure 7. Comparison of footstool height 0 and 5 cm on L4-L5 intradiscal compression force.



A comparison of the intradiscal compression force is shown in Figure 7 for four types of load carrying postures in the presence/absence of 5 cm footstool. The models in Figure 7 are: (a) standing upright, (b) carrying load close to body, (c) carrying load 52 cm away from body and (d) carrying load while twisting 25° to the left. The vertical axis represents the percentage of the intradiscal force, which is rationed to the force when the body is set to upright position. In both cases, i.e. the presence or absence of footstool the highest force is found when the model is carrying the load 52 cm away from the body. However, these loads are lower when the footstool is presence. In the models which carry load 32 and 52 cm away from the body and a 5 cm footstool is used, the spinal load is 20 and 40% lower respectively. This decrease of spinal load is also found in the twist model; 40% lower when footstool is used.

4. Limitations

One of the limitations that can be addressed in this paper is the fact that only one model is used and the results need to be confirmed in a greater number of subjects and for other load carrying postures. In addition, the body model was not scaled according to the subject's anthropometric measurements. Another limitation concerns the methodology used to validate the model. The present model was validated by comparing the muscle potential obtained from EMG with muscle activities analyzed by the model. These two activities are not exactly the same; there is no linear relationship between EMG amplitude and muscle force (Weir, Wagner, & Housh, 1992) during non-isometric movement, which is assumed within this model.

5. Conclusion

We found that using 5 cm footstool in light load carrying (below 10 kg) can be beneficial to reduce low back disorders (LBDs) since it reduces the L4-L5 intradiscal load and muscle activity in lumbar region. These results can provide information for manual material handling (MMH) assembly task design or redesign to possibly reduce LBDs risk for the workers. This study shows that musculoskeletal modeling and simulation can be a reliable tool in ergonomics.

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