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Original Article

A Field Evaluation Method for Assessing Whole Body Biomechanical Joint Stress in Manual Lifting Tasks

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Abstract: Work-related musculoskeletal injuries are often associated with overexertion of the body at work. The manual materials handling activity of lifting is a major source of work-related musculoskeletal disorders. Biomechanical evaluation offers useful information about the physical stress imposed on the worker's body joints; however, biomechanical analysis is usually tedious and complex. For evaluation purpose, the biomechanical method needs to be easy to apply in a field environment. Manual lifting occurs as one of the most common manual materials handling tasks in the workplace. A biomechanical evaluation method was developed based on the ratio of joint moment to joint capacity. The method was applied to evaluate the physical stress of manual lifting in truck loading jobs using a nine-link whole body joint model. Thirty eight industrial tasks were evaluated using the developed joint moment ratio. The moment ratio was compared with subjectively rated body discomfort, overall workload, and the NIOSH lifting index. The moment ratio was found to have a high correlation with the NIOSH lifting index. The biomechanical method can be used with relatively simple equipment and procedure which may be suitable for on-site ergonomic evaluation.

Key words: Manual Materials Handling, Lifting, Field evaluation, Joint moment

Introduction

Manual materials handling (MMH), especially lifting, represents a major occupational safety and health risk in industry. Musculoskeletal and low back disorders are often attributed to overexertion of the body when the operator works to meet the demand of MMH tasks. The use of ergonomic principles in the design and evaluation of human work has been advocated and promoted in the workplace to minimize the occurrence of work-related musculoskeletal injuries. Many methods exist in ergonomics research for evaluation of MMH tasks. Li and Buckle1) provides a review of current techniques for assessing physical exposure to work-related musculoskeletal risks. It can be seen that many postural observation and recording techniques have been proposed and, perhaps they are currently the most widely used methods in ergonomics practice. Several methods are available for whole body evaluation and analysis such as OWAS2), REBA3), QEC4), ARBAN5), ROTA6), and TRAC7). These methods are either based on categorized body postures or estimated scores and risk levels of body postures. In general, the main concern in these methods is the postural risk in the workplace. The scores or risk levels indicated by these methods do not reveal the relative stress or workload with respect to a person's capacity.

On the other hand, biomechanical analyses have been used in ergonomics research and most often in laboratory studies. The biomechanical approach has linked musculoskeletal risks with overloading of the body joint and has focused on the spinal loading such as the L5/S1 compression. Biomechanical analysis offers joint kinematics and kinetics that are often helpful in understanding what actually happens to the body in terms of mechanical load such as force and moment. Videotaping of the person performing the work is usually the first step in biomechanical analysis. Specialized equipment is then called for digitization to estimate the body

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coordinates. Tedious digitization and complex motion analysis is then performed, which often makes the practitioner hesitate to use the biomechanical analysis. A user-friendly biomechanical data collection and analysis technique is needed to increase the field application usefulness of the approach[8]. Nonetheless, if the biomechanical analysis can be carried out with simple videotaping device, the analysis can be simplified, and the result can be used to indicate the physical stress with respect to a person's capacity, the approach is still a valuable tool for ergonomists to evaluate the job and workplace.

A very basic concept in ergonomics is that the task demand should be within the limit of a person's capacity. As the demand approaches a person's capacity, the risk associated with the task will increase. This concept was used in the lifting strength rating (LSR) which is the ratio of maximum lifted load by a person to the lifting strength[9]. The concept has also been used in the development of the NIOSH lifting index (LI)[10] and the job severity index (JSI)[11, 12]. These ratios compare the weight of the load with the predicted lifting capacity, without looking at the individual joint capacity. More recently, the biomechanical lifting motion simulation method[13, 14] used a similar notion, but in greater detail, in their model. Each individual joint has a certain moment strength. The joint moment occurred at each joint as a result of lifting a load was divided by the strength of the joint to form a joint moment strength ratio. The sum of joint moment strength ratios of all the joints was considered to be an indicator of the body's total effort to lift a load. If each individual joint moment during lifting a load is calculated, the moment should not be greater than the moment strength of that joint. Therefore, joint moment strength ratio (joint moment/joint strength), similar to the load/capacity ratio, can be used for each joint to evaluate joint stress, and the sum of individual joint strength ratio reflects the total body joint stress, which should correlate with the above-mentioned load/capacity ratios to a certain degree.

The objective of the study was to develop a field biomechanical evaluation method based on the sum of joint moment strength ratios. The method is expected to be used to evaluate the whole-body physical load for awkward manual lifting postures and tasks in the field environment. The method was applied in a field environment with relatively simple equipment and procedure.

Method

Field tasks

The manual lifting tasks evaluated in the study were selected from the truck loading jobs in the warehousing and delivery service industry, including the shipping service, mail service, industrial warehouse, physical distribution center, moving service, furniture warehouse, home appliances store, and the waste disposal service. The jobs covered a wide range of different manual lifting tasks in the warehousing and delivery industry. The common characteristic of these jobs is that manual lifting is performed as part of the loading and unloading tasks. The entire job may contain carrying objects, pushing carts, and other handling and processing of the items. The overall period of handling may be less than one hour. Usually after finishing with the loading, the worker drives the truck to its destination for another loading or unloading. Table 1 is a summary of the jobs considered in the study. All the tasks analyzed in the study were lifting tasks occurred while objects were being loaded into the trucks. While many of their jobs dealt with regular-sized well-packed cartons, some dealt with large and irregular objects such as furniture and home appliances (air conditioners, TV sets, …, etc.). Some of the participants handled flour or rice sacks and liquid barrels. The workers in the waste disposal service followed a trash collection truck and collected plastic trash bags placed in the sidewalks of residential areas then loaded them into the truck. Since the tasks under evaluation were the real-world jobs, they might not be symmetrical throughout the lift. Some of them contained one-handed lifting and might be asymmetrical at one time or another during the lift. Both sides of the joints might have different postures and share different load. Three-dimensional dynamic biomechanical analysis would be very difficult to implement in a variety of these field environments. Thus, a simplified biomechanical model was developed for the study.

Participants

To get a pool of collaborating companies for the study, solicitation for cooperation was first given to the nearby companies in an industrial site. The intent and objective of the study were conveyed to the managers of each interested company. In each of the collaborating companies, volunteers were then solicited for participation in the study. The result was a total of 38 participants from the collaborating companies. The participants were all employees performing manual lifting tasks in their daily jobs. The managers and employees were given a small gift for their participation in the study. All of the participants hand-lifted objects in their jobs without using any particular handling devices or lifting aids. The participants' mean height was 169.45 cm (152–174), mean weight was 66.05 kg (46–81), and mean age

Table 1. Description of the tasks under study

Job category	No. of study (participant)	Description	Handled objects	Posture and motion
Shipping	4	Loading objects from pallet on floor into truck	Large corrugated cardboard cartons, Flour/Rice sacks	Standing, bending, 2-handed lifting
Mail delivery	2	Loading objects from sorting conveyor into truck	Small packages	Standing, one-handed lifting
Industrial warehouses	5	Loading objects from pallet on floor into truck	Large corrugated cardboard cartons, Beer/Drink packs, Oil/Liquid Barrels	Standing, bending, 2-handed lifting
Physical distribution centers	3	Loading objects from deck into truck	Cartons, Drink packs	Standing, 2-handed lifting
Moving services	4	Loading objects from floor into truck	Large baskets with assorted objects, Cartons, Furniture, TV set	Standing, 2-handed lifting
Furniture warehouses	4	Loading objects from floor into truck	Furniture	Standing, 2-handed lifting
Home appliances centers	3	Loading objects from floor into truck	Appliances in cartons (computer, monitor, air conditioner)	Standing, 2-handed lifting
Waste disposal service	1	Loading objects from floor into truck	Plastic trash bags	Standing, Bending, one-handed lifting

was 31.19 (22–47) yr old. Only one was female.

Apparatus and procedure

Portable video cameras (Sony and Hitachi, video-8) were used for the recording of the manual truck loading tasks. Each task was filmed for a complete cycle between the object was lifted and placed in the target position. Whenever possible, the videotaping was performed so that the joint angles at both sides of the body in the sagittal plane could be completely included in the task cycle. The videotapes were replayed in the lab using a VCR. The joint angles were digitized using a two-dimensional motion analysis system (BTS Videotrack). Since each lifting task was different in duration, ten evenly spaced frames were digitized for each lifting cycle. From the data collected, we found that a lifting task would be completed within a few seconds, beyond that the operator would not be able to endure the heavy load too long. Ten evenly spaced frames would be able to sample enough static postural load covering most variations of the postures occurred in the task duration. Collecting more frames would have a higher chance of capturing more variations of postures, but would require a lot more efforts for data handling. Unless the lift is very long and has change postures drastically often during the lift, ten frames are usually sufficient to cover the lift.

Some of the tasks analyzed in the study contained body motions occurred not strictly along the sagittal plane at certain times of the lift, there might be projection errors in the estimation of the joint angles using the 2-d digitization system. For those tasks with apparent deviation from the sagittal plane, the joint angles were subjectively estimated in the digitization process. The degree of accuracy of angle estimation was further examined in the study with a lab experiment. A complete symmetrical lift was videotaped by two cameras with one filming at the sagittal plane and the other filming at 30 or 45 degree to the sagittal plane.

Three graduate students who helped digitize the videotapes were asked to estimate joint angles using the tapes filmed at 30 and 45 degrees. The estimation was then compared with the digitized angles from the sagittal plane. Table 2 shows the correlation and percent error between the estimation and the digitized angles. Both the estimations at 45 degrees and 30 degrees show high accuracy with the actual sagittal plane angles, with the 45-degree estimation having better accuracy. It seems that people are better at estimation at canonical orientations (perpendicular or 45-degree) than the others. This comparison shows that the angles estimated for those movements and postures not strictly in the sagittal plane can still be acquired with fairly good accuracy. For the purpose of the study, the use of the estimated angles for the nine-link model and the NIOSH equation was considered to be acceptable.

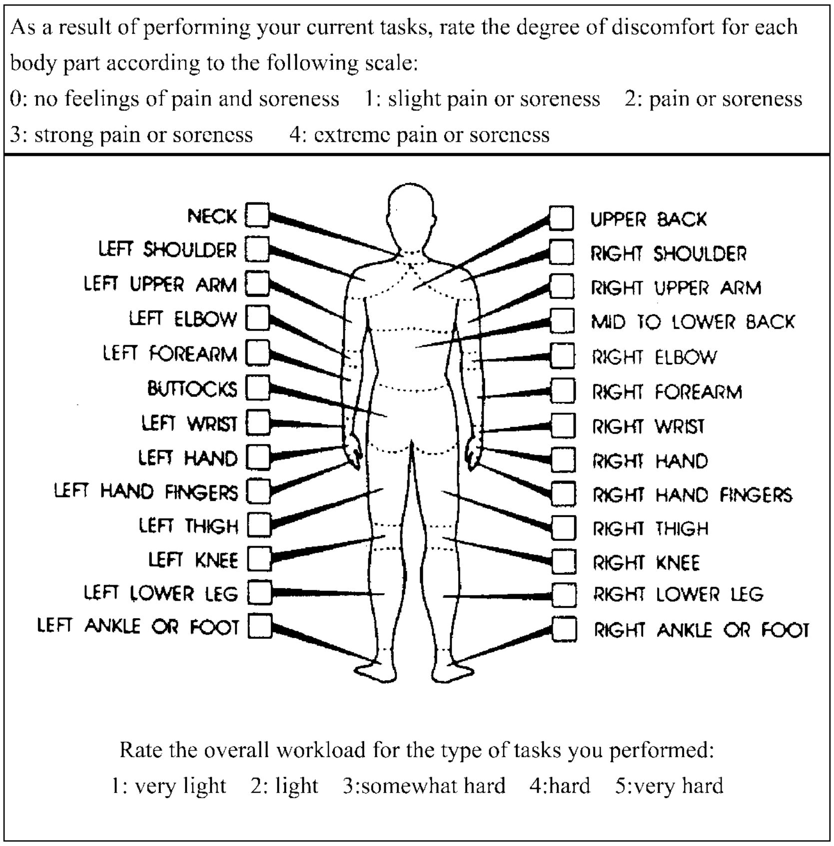
Table 2. Angle estimation error of the three evaluators (S1, S2, S3): correlation and percent error between the estimation at 30 or 45 degree and the digitized angle in the sagittal plane

Corr. /%error	S1	S2	S3	Avg
30 deg	0.96/10.6%	0.95/11.1%	0.95/12.3%	0.95/11.4%
45 deg	0.99/4.3%	0.99/4.9%	0.99/4.0%	0.99/4.4%
Avg	0.98/7.5%	0.98/8.1%	0.98/8.1%	0.98/7.9%

A questionnaire was given to each participant as shown in Fig. 1. The questionnaire contains a body discomfort chart and an overall workload assessment scale. The participant was asked to rate the degree of discomfort for each listed body part as a result of performing the type of tasks being studied. The degree of discomfort is a five-point scale going from no feeling of pain or soreness (0) to extreme pain or soreness (4). After the rating of discomfort, the participant was asked to rate the overall workload for the type of tasks being studied. The workload scale is also a five-point scale with one being very light and five being very hard.

Biomechanical model

A biomechanical model based on whole-body joint moment ratio was developed for the study. The model is an adaptation from the objective function of the lifting motion



As a result of performing your current tasks, rate the degree of discomfort for each body part according to the following scale:
0: no feelings of pain and soreness 1: slight pain or soreness 2: pain or soreness
3: strong pain or soreness 4: extreme pain or soreness

Rate the overall workload for the type of tasks you performed:
1: very light 2: light 3:somewhat hard 4:hard 5:very hard

Fig. 1. The body discomfort and overall workload questionnaire.
The discomfort chart is adapted from Sauter *et al.*[15]

optimization model in Lee[16)], Hsiang and Ayoub[13)], and Lin *et al.*[14)]. The objective function is shown in Equation 1.

$$\int_{t=0}^{T}\sum_{j=1}^{5}\left(\frac{Mj\,(t)}{Sj\,(t)}\right)^{2} dt \quad \cdots\cdots\cdots (1)$$

where

M_j=the magnitude of the moment about joint j

S_j=the static moment strength of joint j

T=total lifting time.

In the optimization model, only five joints, the elbow, shoulder, hip, knee, and ankle, were considered because it was a planar symmetrical model. As can be seen, the objective function is a time integral of the total joint loadings (ratios of actual moment vs. capacity moment) for the five joints. The joint moment strength ratio is based on the ergonomic concept of physical workload versus the maximal capacity. By minimizing the objective function, assuming that the body would minimize the joint effort in lifting, motion trajectories were predicted with good accuracy[13, 14)]. The objective function was adapted for the asymmetrical truck loading tasks in the present study.

The computation of the variables in Equation 1 requires the complete displacement time data to be digitized for all the joints. For the model to be easy-to-use and for the purpose of field evaluation, the digitization and computation process must be simple, however, the degree of accuracy in accounting for the lifting workload must be reasonably good. In order to simplify the complex digitization procedure, one adaptation was to use the static moments instead of dynamic moments in the equation. Static moments can be calculated using the postures obtained at each single video frames. Most tasks under study were the handling of large or heavy objects, therefore, the resulting lifting motion was in general at fairly low speed, making the use of static joint moments to account for joint loading a reasonable approach.

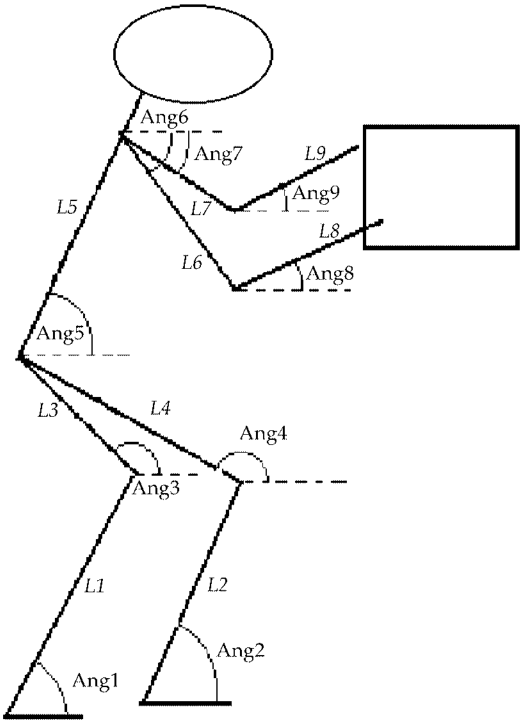


Fig. 2. The nine-link whole body model.
Joint moments are calculated at the elbows, shoulder, hip, knees, and ankles.

Since the model in Equation 1 is planar and considers only the five joints of the body, it was further adapted for a nine-link body segment model as shown in Fig. 2. The human body is considered as nine connected rigid links, the left and right lower legs, upper legs, upper arms, forearms, and the trunk. The joint angles (elbows, shoulders, trunk, knees, and ankles) as shown in the figure were digitized or estimated from the videotapes. When the weight of the load imposed at the hand is known, the joint moments at the elbows, shoulder, hip, knees, and ankles can be calculated based on link static equilibrium. The anthropometric proportional segment mass and length as ratios of body weight and height were used as compiled in Winter[17)]. The study further assumed that the load was shared evenly at both hands if the load was handled with two hands. The moment calculation was carried out from the hand to the ankle. The two sides of the joint moment were joined at the shoulder and then evenly split at the hip down.

The developed biomechanical model is presented in Equation 2.

$$MR=\frac{1}{10}\sum_{i=1}^{10}\sum_{j=1}^{8}\frac{M_{ij}}{S_{ij}} \quad \cdots\cdots\cdots (2)$$

where

M_{ij} = the static moment at joint j at frame i

S_{ij} = the static moment strength of joint j at frame i

As described earlier, the lifting motion was digitized at ten evenly spaced time frames. The calculation of joint moments was based on the posture at each frozen time frame using static equilibrium. Stobbe's[18)] static joint moment strength predicting equations were used for the calculation of S_{ij}. The Stobbe's equations are a series of regression equations in which joint moment capability is predicted by joint angles. These equations can also be found in Chaffin[21)]. The moment ratio (MR) is the ten frame average of the sum of the total joint moment ratios for the eight joints, representing cumulative muscular effort for the lifting motion. Equation 2 was used to evaluate the lifting tasks in the selected truck loading jobs in the study.

NIOSH lifting index

For comparison with the proposed moment ratio (MR), the NIOSH lifting index (LI)[10)] was calculated for each task. The recommended weight limit (RWL)[10)] is a multiplication of a load constant by six multipliers which consider six important variables of lifting stress, including the horizontal multiplier (HM), vertical multiplier (VM), distance multiplier (DM), asymmetry multiplier (AM), frequency multiplier (FM), and coupling multiplier (CM). The lifting index (LI) is the ratio of actual weight lifted to the RWL. Since the evaluation in the study was biomechanical in nature, further, the estimation of lifting frequency for the short period of loading tasks described in the study might not be accurate, the frequency multiplier was not considered in the RWL calculation, that is, the FM was assumed as one.

Results

The moment ratio (MR) as in Equation 2 was calculated for each task evaluated. The lifting index (LI) was also calculated and plotted with the moment ratio (MR) as shown in the top of Fig. 3. The NIOSH lifting index (LI) correlates with MR very well. Of the 38 tasks evaluated, 61% had the lifting index (LI) over 1.0, the theoretical risk threshold, and 16% were over 3.0. The moment ratio (MR) when divided by the joint number (MR/8) indicates an average overall ratio, which if beyond 1.0 means that the task is on average beyond the body's maximum moment strength. Of the 38 tasks evaluated, 24% had the average MR over 1.0.

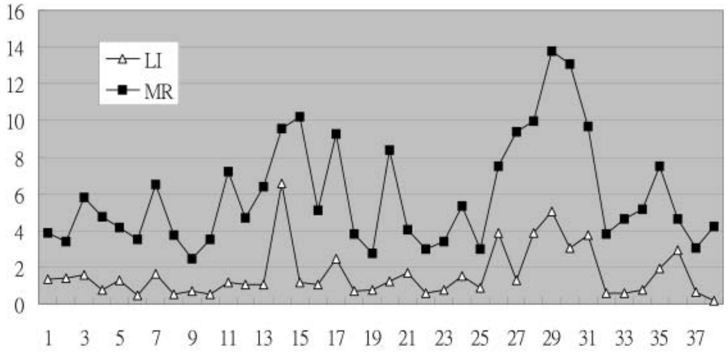
The ratings of discomfort for each body part as shown in Fig. 1 were totaled. The sum of the discomfort ratings reflects total body discomfort. The total discomfort (Discomfort) and overall workload (Workload) ratings are plotted in the bottom of Fig. 3. Looking at the four variables altogether, a degree of consistency exists. Note that the workload rating was limited to five, causing the workload plot to level from task 23 to 31, however, this leveling was not seen for the other three variables.

Pearson's correlation was further calculated as presented in Table 3. Results of the two-tailed tests to examine whether the correlation is zero are also shown in the Table. The correlation between the moment ratio (MR) and the NIOSH lifting index (LI) is 0.716 ($p<0.001$), the highest among the variable pairs. The correlation between MR and the total discomfort rating (Discomfort) is 0.533 ($p<0.001$). The correlation between MR and the overall workload rating (Workload) is unfortunately not significant. However, Workload correlates with LI and Discomfort significantly.

Discussion

It is interesting to find that the NIOSH lifting index (LI) and the total joint moment loading (MR) was well correlated. Both the two are based on the concept that the ratio between the actual load and the capacity of the body can be used to indicate whether the person is overloaded. The NIOSH recommended weight limit (RWL) equation is based on extensive studies from psychophysical, biomechanical, and physiological research on human safe limits in performing lifting tasks[10)]. According to the applications manual for the revised NIOSH lifting equation, the recommended weight limit (RWL) is a weight limit under which nearly all healthy workers could perform over a substantial period of time without increasing the risk of low-back pain[10)]. The lifting index (LI), the ratio between the actual load and RWL, indicates how much the actual load is in relation to the safe load of the task if it is to be performed for a substantial period of time. The moment ratio (MR) developed in the study, on the other hand, compares the actual joint moment with the predicted maximum static joint moment, which is obviously not a "safe" limit but a maximum capacity limit. Unlike the lifting index (LI), the moment ratio (MR) is pure biomechanical and provides a biomechanical index for whole-body joint stress. Although the LI and MR are two variables of different nature, the study showed that they followed a certain consistency in predicting the physical stress as a result of performing lifting tasks. The correlation also supports the biomechanical aspect of the NIOSH lifting index as a whole-body workload assessment tool, in addition to its usual emphasis on the low-back injury prevention capability. It must be noted that in the calculation of the lifting index (LI), the study had assumed that the frequency multiplier (FM) to be one so that the effect of lifting frequency in reducing the RWL was not considered. The determination of the lifting index (LI) in this way seems to reflect its biomechanical characteristic more and therefore correlates with the moment ratio (MR) significantly in the study.

Although the NIOSH lift index (LI) or the recommended weight limit (RWL) may be used as a specialized risk assessment tool, it has been noted that limitations exist in



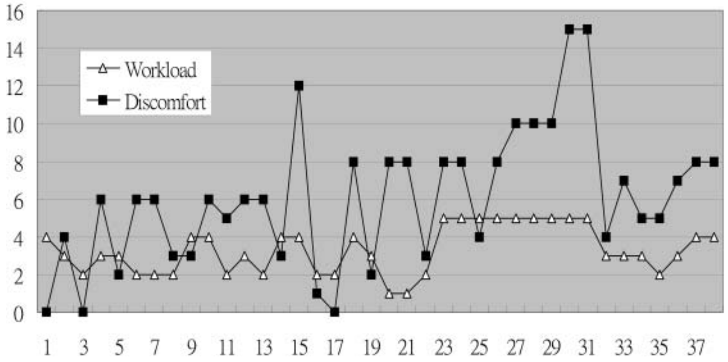


Fig. 3. The moment ratio (MR), lifting index (LI), total discomfort rating (Discomfort), and overall workload rating (Workload) for the 38 evaluated tasks.

Table 3. Pearson's correlation of the evaluated variables

	MR	LI	Discomfort
LI	0.716***		
Discomfort	0.533***	0.264	
Workload	0.272	0.343*	0.497**

*Test that the correlation=0, $p<0.05$, $^{**}p<0.01$, $^{***}p<0.001$.

using the NIOSH lifting equation[19]. For example, the NIOSH lifting equation was not designed to predict a safe limit for one-handed lifting and lifting in a constrained work space. In the on-site jobs such as the tasks under study, one-handed lifting sometimes occurred and tasks were often confined in a limited space in which the operator had to assume asymmetrical and awkward joint postures. In addition, for infrequent, non-repetitive, and heavy lifting tasks mixed in other light material handling tasks, the concern may not be physiological but biomechanical for the lifting task itself. The moment ratio (MR) of the study provides a simple biomechanical assessment to the physical stress for all the body joints in these situations. The study shows that the method can be used where the NIOSH equation although is easy to use but might not be suitable, for example, for one-handed lifting or confined space and awkward posture. In these situations, 3-D biomechanical models are often used but they take too much effort to develop and require expensive motion analysis system with many cameras which may not be easy to install in the lifting task sites described in this paper.

It is worth noting that although LI and MR are correlated, there are discrepancies between them as shown in Fig. 3. Particularly number 15 and 27, where LI's are low but MR's are high. By further examining the videotapes of the two cases, we found that some extreme postures had occurred during the lifting period. In one case the load was upon one hand only for a certain amount of time. The moment calculations reflect this extreme posture effect. The calculation of the NIOSH weight limit however cannot account for this. If this unbalanced posture is accounted for, the recommended weight limit would have been much higher.

The moment ratio (MR) also has a degree of positive correlation (0.533) with the total discomfort rating. However, when asked about their overall workload, the rating did not appear to be correlated with MR (only 0.272). The lower correlation between the moment ratio and the workload rating was partly because of the resolution of the rating scale. With only five levels of rating, many high-demand tasks such as those from task 23 to 31 were rated up to the fifth level, causing the plot to level off at this region (Fig. 3). The Borg's RPE (rating of perceived exertion)[20] was not used in the study because it was felt that the scale might have too many levels for the on-site operators to use correctly. The lower correlation could also be attributed to the fact that the evaluation of an overall workload might be easily contaminated with the manual handling tasks other than the lifting task itself. On the other hand, the sum of total discomfort resulted in higher correlation with the moment ratio because it was a direct rating from each body part, similar to the sum of each joint loading in the moment ratio calculation. Nonetheless, the overall workload rating was correlated with the NIOSH lifting index and the total discomfort rating to a certain degree. The proposed method is still at its early stage in which we tried to test the idea of moment ratio as a whole-body workload index. For the moment, we only compare it with the available NIOSH LI index. In the future, research will be needed to determine the relationship of MR and compression on the spine. Also, the upper limit of MR must be determined for a safe lifting workload.

Conclusions

The moment ratio (MR) used in the study may not reflect the actual joint loading as accurately as a dynamic model, however, the procedure and equipment requirement to carry out the analysis is much easier than a dynamic model for field evaluation. The study demonstrated that the biomechanical analysis can be completed with a portable video camera and a simple static nine-link biomechanical model. The physical joint stress appeared to correlate well with the NIOSH lifting index. The biomechanical model and calculation procedure can be programmed into an automated procedure, which would increase the ease of application in the future for the field user.

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