BIOMECHANICAL ANALYSIS OF LOW-BACK LOAD DURING MATERIALS HANDLING AND ITS WHOLE-SHIFT MONITORING WITHIN THE *DORTMUND LUMBAR LOAD STUDY - DOLLY*

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In the so-called Dortmund Lumbar Load Study (DOLLY), the load on the lumbar spine was quantitatively monitored for complete shifts in diverse fields, i.e. for the materials handling tasks in construction and metal-processing industries as well as in a meat-processing factory and for dustbin removal. Video recording of 8 shifts was performed, actual posture was described and the action forces applied at the hands were determined for each work situation. Based on the respective data for posture and handforces, lumbar load was calculated applying the 3D biomechanical model *The Dortmunder* for each working situation, in total between approx. 4 and 22 thousands per shift. Shift-monitored temporal profiles for several load indicators - trunk flexion and torsional moments, compression and shear forces with respect to the lumbosacral joint - describe the load on the lumbar spine. Comprehensive results with regard to posture, handforces and lumbar load are available. Several load indices regarding load level, duration and the cumulative effects were defined and applied for assessing the analysed jobs.

In relation to recommended limits for the maximal disc compression, lumbar load is exceeded in numerous situations during a shift, in particular, with regard to persons of higher age. In a "dose model" developed in this study, the cumulative effect of single-task exposures was considered by superproportional weighting of the compressive force with respect to the corresponding duration of a working task, based on the higher injury potential of high loads compared to - although longer effective - low loads.

INTRODUCTION

High load on the lumbar spine may result from manual materials handling. Activities such as lifting, carrying, pushing and pulling of objects are regarded as a possible causation for mechanically induced musculoskeletal disorders in the lower back (e.g. Frymoyer et al. 1980, Luttmann et al. 1988, Riihimäki et al. 1989, Andersson 1991, Burdorf 1992, Brinckmann et al. 1998, Norman et al. 1998). Knowledge of lumbar load is therefore needed in order to evaluate the health risk during occupational materials handling and, from the preventive point of view, to enable the avoidance of working tasks resulting in too high lumbar load. Commonly, lumbar load is investigated with respect to short activity sections or to specified load-handling types. In contrast, the aim of the so-called Dortmund Lumbar Load Study - *DOLLY* (Jäger et al. 1998, 2000) was to describe quantitatively the lumbar exposure during total shifts for jobs associated with manual materials handling. Consequently, cumulative-load indices had to be "created" and were quantified for the working shifts under study in order to support the discussions on intensity, on duration of lumbar load during work, on adequate measures of lumbar load and on respective limits.

FIELDS OF INVESTIGATION

The load on the lumbar spine was determined in four occupational fields combined with manual materials handling activities and, in consequence, representing work of lumbar-load relevance. The jobs and working sites under study in *DOLLY* were selected with the assistance of workmen's compensation companies, the respective industry and factory or public utility. For each of the occupational fields - surface construction, metal-processing industry, meat-processing factory, refuse collection - the work of two persons during complete shifts was analyzed with regard to posture, action forces, and lumbar load. In total, the activities of eight persons, equivalent to eight shifts, were investigated.

The tasks in surface construction referred mainly to bricklaying when building 1-family or appartment houses; during the one shift bricks of approx. 8 kg were manipulated, during the other shift various bricks weighing from 3 kg to 19 kg were layed. The metal-processing work in both shifts under study represented tasks at a drop hammer when manufacturing piston-rods of about $1^1/_2$ kg for cars; the objects were handled with a blacksmith's tongs of about the same weight. The two shifts in the meat processing jobs differed to a considerable extent: During the one day, sausages were hung up on rods by means of a loop at a sausage's end. The loaded rods of a weight varying between approx. 14 and 29 kg were hung up into wheeled racks, so-called smoke house wagons, which were pushed or pulled to the smoke house for further processing. The main task in the other shift was the placing of big sized sausages or hams, weighing approx. 10 kg, into slicing machines.

The 4th field in *DOLLY* referred to the removal of residual garbage in the one shift or paper disposal in the other; the workers mainly performed movements of containers of different volumes (40-240 l) and weights (up to 97 kg) between their common place during the week and the dustcart, i.e. picking up a bin at the pavement, transferring it to the back side of the truck, operating some levers for mechanized lifting and tilting it, and - after emptying - lowering the bin and bringing it back.

TASK EVALUATION

Whole-shift video documentations of the working activities were performed on the shop-floor in agreement with the respective working person. Whereas the workplaces on the building sites, at the drop hammer and during meat processing were stationary, the mobile workplace of the dustmen had to be pursued in order to perform the video recording. In this special case, the camera was mounted to the handlebars of a bicycle. This part of work description was accompanied by recording the weight of the handled objects or the corresponding action forces applied at the hands: Samples of bricks, forgings and tongs as well as sausages and hams were weighed, whereas the weight of each dustbin was determined individually before emptying and recorded in a hand protocol. Marking each bin made identification possible in the subsequent evaluation of video recordings in the laboratory.

The work's documentation on the shop floor by video recording was evaluated in the following with regard to body posture and action forces exerted with the arms using a specifically developed coding system. Each "working situation" interpreted as being relevant to spinal load was analyzed on hand of a video frame - considering also the neighbouring frames for evaluating postural changes during a movement - when either the load weighed at least half a kilogram or the trunk was distinctly inclined, twisted or bent laterally. Excepting absence or pauses, a basic reference posture was presumed, i.e. standing upright with the arms hanging down and no load in the hands for all other situations.

Posture and handforces were characterized on the basis of a detailed coding system sketched in Table 1. Each body-segment's position was classified according to its spatial location, and the action forces were considered seperately for both hands in terms of amplitude and direction. Each working situation was represented by a 21-digit code string with 10 digits regarding posture and 11 digits for force description. Each digit may represent up to 10 "expressions". For example, the classification of the sagittal trunk inclination (digit no. 1) was performed in steps of 15°, where 7 classes are attributed between "upright 0°" and "far forward inclined/held horizontally 90°". Furthermore, trunk postures with the upper body inclined slightly backwards (set to -15°) or extremely forward (105°) were also considered. In consequence, a trunk inclination shown in a video frame was attached to one of the 9 classes in total. On the basis of the digits nos. 2 to 4, trunk posture was described in more detail with respect to spinal curvature.

Distincted into right or left, the positions of the arms were described by pairs of code digits (see nos. 5/6 and 7/8). First, 10 different "typical" configurations of upper arm and forearm were differentiated, e.g. arm completely hanging or upper arm hanging with the forearm being horizontal. Secondly, the spatial position of this configuration with respect to the shoulder sagittal plane was classified, i.e. whether the arm was inner-rotated, held sagittally, or more or less outer-rotated. Following this procedure, about 60 different arm postures resulted for the right or left side, each. A total of about 70 millions of different codes were principally possible when characterizing a video recorded "real" posture considering only all body segments and their position in space, i.e. besides the variety of action force amplitudes and directions.

Table 1. Codifying system for a classified description of the spatial position or orientation of the body segments and action forces with respect to each of the thousands of working situations during each shifts analyzed in the *DOLLY*.

digit	topic	explanation	expressions
	posture description		
1	trunk inclination	sagittal pelvic tilt incl. spinal flexion	9
2	spinal curvature	sagittal plane	4
3	trunk's lateral flexion	lateral spine flexion and lateral tilt of shoulder axis	3
4	trunk torsion	spinal torsion & shoulder axis rotation	3
5	left arm	lateral view of upper-and-forearm configuration	10
6		position in space	8
7	right arm	lateral view of upper-and-forearm configuration	10
8		position in space	8
9	head position	in relation to trunk's longitudinal axis	4
10	legs	configuration of feet, shanks & thighs	10
	action-force description		
11-12	left-arm action force	sagittal-plane component	8
		coronal-plane component	8
13-14	right-arm action force	sagittal-plane component	8
		coronal-plane component	8
15	handling type	uni- / bi-manual, 2 objects etc.	4
16-18	left action force	amplitude: 3 digits in N	-
19-21	right action force	amplitude: 3 digits in N	-

The action forces are described by the respective intensity (digit nos. 16-18, 19-21) and by their directions. An additional code digit (no. 15) was provided to differentiate, for example, load manipulation performed bi-manually from manipulation with one hand. - Force direction, seperately for the right and left arm, was classified in correspondence to

- the anatomical axes (i.e. force exertion to anterior / posterior, to the left / right, upwards / downwards - 6 directions in total),
- the anatomical planes (e.g. force exertion in the sagittal plane into the anterior upward direction, or into the posterior downward direction; alternatively sagittal / frontal / transversal planes with 4 quadrants each - 12 directions in total),
- the spatial octants (e.g. force exertion into the anterior right upward direction, or into posterior left downward direction - 8 directions in total).

If, for example, an object is held in the right hand, the action force required for holding points up vertically; the corresponding direction was described by a vector with a sagittal or coronal component (digits 13/14), since the vector would be localized in the intersection of sagittal and coronal planes. When pushing forward, the action force direction would be characterized solely by a horizontal sagittal component. Oblique pushing to the lateral front, however, contains a sagittal as well as a coronal component. In consequence, a "real" force direction, derived from the video frames, was attached to one of 26 force direction classes.

In addition, alphanumerical symbols for encoding the time (6 digits for h/min/s) and the situation type (1 symbol)

enables identification of a certain situation. Utilizing this procedure, the shifts analyzed in *DOLLY* resulted in approx. 4 to 22 thousands of code strings describing the working conditions with respect to posture and action forces.

DETERMINATION OF LUMBAR LOAD

The load on the lumbar spine was quantified for all working situations using the data for body posture and action forces - after decoding of the posture-and-handforce code strings mentioned in the previous chapter - with the help of a modified version of the previously developed 3-D dynamic tool *The Dortmunder* (Jäger et al. 1991). However, the effects of dynamics due to acceleration during the movements of body and load were neglected in this study because of the high expense for a detailed posture description during total shifts. Furthermore, records for lumbar load during the course of a shift were established for several lumbar-load indicators. The skeletal structure of the human body is simulated by 30 segments, two further segments may simulate handled objects, e.g. the blacksmith's tongs and a handled object. The muscular structure in the lumbar region is modelled by 5 muscle equivalents representing the erector spinae, the oblique abdominals and the rectus abdominal muscles. [Actual modelling consideres 9 equivalents according to 14 muscle cords.] The effects of intra-abdominal pressure in supporting the trunk are considered using a modified version of the model of Chaffin (1969). Body height and weight reflect the individual properties of the working persons, whereas standard body proportions were assumed.

LUMBAR-LOAD MONITORING

Figure 1 exemplarily shows the time courses of four lumbar-load indicators for the morning half shift during the work of dustbin removal. This time period of about $4^1/_2$ hours reflects a sequence of about 9 thousand working situations. The continuous sections of the time courses result from connecting consecutive values, the interruptions from regular pauses or parapauses.

Within the complete shift, the dustman emptied a total of 1007 dustbins with residual garbage. The mean weight was 20 kg, the 10th and 90th percentile amounted to 11 or 33 kg, respectively, the maximum was 97 kg. When a dustbin was lifted, for example into the claw levers at the backside of the dustcart, the action-force direction would have been assumed pointing vertically. When pulling or pushing the dustbins, in most cases furnished with wheels, they were moved over firm paths. In general, horizontal push-or-pull forces of 13% of the weight were assumed resulting from preliminary measurements on manipulating about 50 dustbins.

With respect to the lumbosacral disc (L5-S1), force curves - resolved in components due to the vectorial character - are demonstrated as typical indicators of lumbar load. As figure 1 shows, roughly shaped curves with many and distinct peaks result from the considerably varying conditions during the handling of dustbins. The forces assume positive values, excepting lateral shear, due to weight effects of the upper body segments (superior to L5-S1) and the handled objects as well as due to back-muscle activities. Lateral shear, to the left as well as to the right, occurs at postures with the trunk laterally inclined or in situations with pulling or pushing sideways. The bottom trace represents the total force at L5-S1 disc, resulting from the vectorial addition of the compressive and shear force components at any point in time.

OVEREXERTION RISK

For the evaluation of lumbar load, recommendations on the maximum lumbar disc compression were introduced in the literature. The National Institute for Occupational Safety and Health has provided in the Work Practices Guide for Manual Lifting or in its derivates (NIOSH 1981, Waters et al. 1993) a biomechanical criterion of 3.4 kN for lumbosacral compressive force based on ultimate compressive strength of lumbar autopsy material. Due to several discrepancies between NIOSH's explanations and the sources (Jäger and Luttmann 1999), comparable strength data evaluation was performed on an approx. 30 times larger sample. Limits for maximum lumbar-disc compression were recommended considering the empirically identified dependencies of strength on age and gender (Jäger and Luttmann 1997). With respect to males, the *Dortmund Recommendations* amount to 6 kN for younger, 4.1 kN for middle-aged and 2.3 kN for older adults (20 / 40 / 60 yrs. of age). This range also covers the recommendation of 3.9 kN provided by Mital et al. (1993).

Subsequently, the calculated compressive force values of each working situation was compared with the recommended limits, and the respective number of limit exceedings during a shift was determined. The NIOSH-limit is surpassed during all shifts, excepting one shift in the drop forge so that - after NIOSH - the respective tasks would require a redesign. The respective amount of limit exceedings assuming different ages of the working person according to the *Dortmund Recommendations* increases distinctly with age: For young male adults the frequency of hyperlimit situations amounts up to 10 per shift, for a middle-aged man up to about 300 per

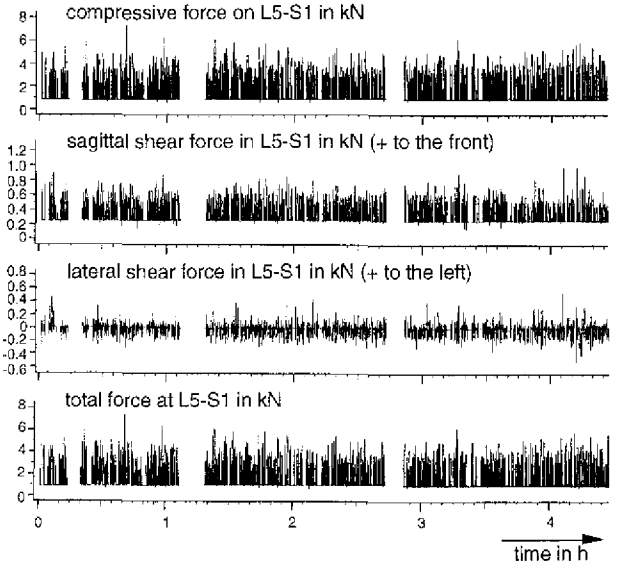

Figure 1. Time courses for lumbar-load indicators regarding half a shift of dustbin removal analyzed in *DOLLY*.

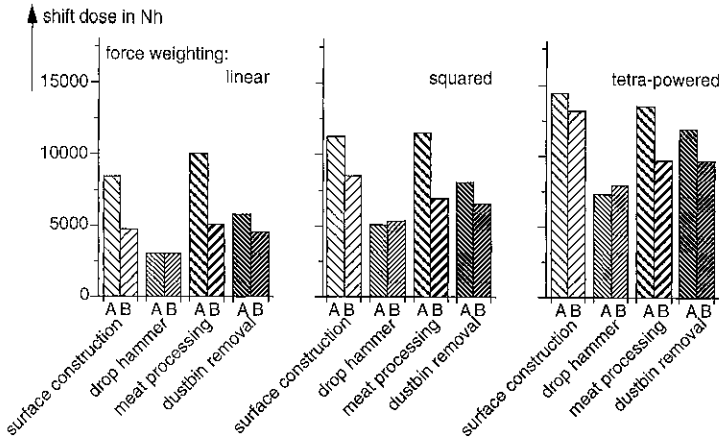

Figure 2. Cumulated shift dose of L5-S1 compression for the 2 shifts (A/B) in 4 occupational fields analyzed in *DOLLY*.

shift and for older ones up to 3000 per shift - depending on the field. In consequence, the investigated tasks should not be carried out by older persons or the work content has to be appropriately re-designed.

CUMULATIVE LUMBAR LOAD

Considering exposure duration in addition to load level (cf. Kumar 1990, Norman et al. 1998), integrational measures in the form of cumulative doses were determined for the 8 shifts analyzed in *DOLLY*. In figure 2, the results for the cumulation over the shifts applying various dose models are demonstrated. For the left-hand diagram, the lumbar-disc compressive force was multiplied with the respective exposure time, and such products were summed up for all tasks of a shift ("linear" dose model). According to the higher overexertion potential of high forces in relation to lower ones, superproportional weighting of the force in relation to time was performed for derivation of the results shown in the middle and right-hand diagrams ("squared"/"tetra-powered"). Independently of force weighting, the lowest dose values were found for the drop hammer tasks. Highest doses result from bricklying and meat processing. The interrelation between the fields and shifts reflects, inter alia, the considerable content of high compression-force values in construction B and both dustbin-removal shifts: Assuming a linear model, the respective dose values differ evidently from the highest doses (construction A, meat A), whereas they are in the same order of magnitude using the 4th power in force weighting.

In conclusion, evaluating posture and action forces and subsequent biomechanical model calculations permits a whole-shift monitoring of lumbar load providing a comprehensive basis for the assessment of occupational load handling jobs with respect to the overexertion risk. The lumbar load exceeds diverse recommended limits provided in literature on maximum disc compression regarding refuse collection, surface construction and industrial meat processing in numerous working situations per shift. Such tasks should not be performed by older persons, or redesign of workplace or work flow should guarantee ergonomic conditions. In the assessment of the cumulative lumbar load using integrative dose models, disc compression should be considered with higher weight than the respective exposure duration, owing to the particular overload effect of high forces.

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