Risks of Occupational Vibration Exposures

VIBRISKS

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Title: Prediction of spinal stress in drivers from field measurements

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SUMMARY

A procedure was developed to assess the health risk related to whole-body vibration (WBV) based on the results of model calculations and using the prediction of cumulative fatigue failure of vertebral endplates caused by compression as criterium. The procedure permits the consideration of individual exposure conditions, posture and personal characteristics which are reflected by different finite element models described under workpackage 6.1. A Matlab-program identifies the peak-to-peak compressive forces in the predicted time series and calculates a risk factor. The user can (i) chose an appropriate combination of body mass, body height and body mass index (BMI), (ii) select one of five different postures, (iii) make predictions for a variable percentage of the exposed driver population as basis for political decisions, (iv) select different assumptions with respect to the consideration of the size of the lumbar endplate areas and variability of spinal strength, (v) predict the spinal stress and health risk for different segments of the lumbar spine, and (iv) calculate the health risk in dependence on age and duration of exposure. Conditions with a high health risk can be identified by model-based stress predictions. Predictions of intra-spinal stress and risk assessments were performed for 36 whole-body field measurements of vibration exposures obtained in WP5. The results indicate an underestimation of the health risk by the limit value set in the DIRECTIVE 2002/44/EC for many real exposure conditions. The reliable protection of workers' health suggests an urgent revision of this limit. Keeping to the action value does probably not exclude a potential health risk in all cases. Model calculations suggest significant synergistic detrimental effects of a high body mass and/or low ultimate compressive strength of lumbar vertebrae. The results could be used to amend or revise current international standards ISO 2631-1 and ISO 2631-5. Further research is required in order to assess a possible health risk caused by repetitive shear and torsion.

CONTENTS

1 Introduction – Development of a method for analysis and risk assessment

The prediction of spinal stress is a prerequisite for a quantitative assessment of the health risk of the lumbar spine. Repetitive peak compressive forces are assumed to be responsible for fatigue failure of vertebral endplates (Sandover, 1998; Seidel et al., 1997, 1998). Up to now, the detrimental effect of shear forces cannot be quantified. The processing of predicted compressive forces in the time domain enables the calculation of a dose measure characterising the probability of fatigue failure. One procedure for the quantification of health risk described in ISO 2631-5 (2004) is based on the erroneous assumption that three compressive force components exist arising independently and separately from spinal accelerations in x-, y-, and z-axis, and that the peak values of these components can be used to calculate a dose that characterises the compressive stress. This procedure ignores the fact that only one time series of compressive force exists as a result of the superposition of different components. Hence, any sufficient dose of peak values can be based on one time series only and not on peak values of several non-existing components. The origin of this error is the approach described by Morrison et al. (1997). The models used in ISO 2631-5 (2004) and described by Seidel et al. (1998) cannot be considered as verified (cf. Seidel 2005 for details). Further aspects of a critical analysis and discussion of the results (Morrison et al. 1997) underlying ISO 2631-5, their interpretation and implementation in Morrison et al. (1997) have been recently published (Seidel 2004). The possible underestimation of health risk (cf. Seidel 2004, 2005) deserves special attention. Variable postures, anthropometric characteristics, spinal geometry, and individual spinal tolerance were identified as important factors that co-determine the effects of occupational WBV on health. A re-analysis of the paper by Michel et al. (1993) led to the conclusion that the exponent derived from this study (Seidel et al. 1998) should not be used for the dose calculation, because the pronounced non-linearity of the stress-strain relationship – not obvious from the paper by Michel et al. (1993) – does not permit the calculation of a correct equivalent stress.

The European Directive (2002) states an extremely high limit value for whole-body vibration (WBV) in z-direction without any limitation of an energy-equivalent evaluation. The consequence is a very dubious assessment of health effects, especially for WBV containing high peak values and/or short daily exposure times (cf. Griffin, 2004).)

Task 6.2 of the VIBRISKS-project requires estimates of the predicted stress from vibration measurements made in WP5 by the application of a mathematical model, considering different postures and personal characteristics. The stress predictions should be suited to identify the health risk due to whole-body vibration with respect to health. Details of the model, the consideration of different postures and personal characteristics are described in the Annex to the report of WP6, Task 6.1. This Annex concentrates on the application of the model and the method to assess the health risk. All parameters and equations are given which are necessary for such assessment based on the peak-to-peak intra-spinal dynamic and posture-related static compressive forces. The assessment procedure could be implemented in a spreadsheet-program. Partner FIOSH has developed a user-friendly MatLab-program that uses the predicted forces as input and calculates a parameter for the risk assessment according to a new approach. Details are described in the following sections.

The existing methods for the quantification of health risk caused by WBV (ISO 2631-5, 2004; Seidel et al., 1998) require time series of internal forces acting on lumbar vertebral endplates. The models used in ISO 2631-5 (2004) and described by Seidel et al. (1998) cannot be considered as verified (cf. Seidel 2005 for details).

1.1 Approach

The following assessment of health effects of random whole-body vibration exposure containing high transients exhibits some similarity to the approach implemented in ISO 2631-5 concerning the calculation of a dose of repetitive stress equal to an equivalent static stress. It uses subsequent peak-to-peak compressive forces acting on the lumbar discs, i.e. increasing (from plus to minus) and decreasing (from minus to plus) dynamic amplitudes are counted. *(Note: This procedure is similar to the "mean crossing peak counting" (Buxbaum 1992, p. 16)).* Hence, peaks below the static stress are included, and the number of peak-to-peak values is twice as much compared with a counting method that would consider either upwards or downwards directed peaks only. In order to be comparable with results from laboratory tests on fatigue failure counting full sinusoidal cycles and the usual lifetime prediction methodology in mechanics (Nijssen et al., 2004), both, each peak-to-peak amplitude, and the number of peak-to-peak values calculated for one day of exposure or longer, were divided by 2. *(Note: Alternatively, only the downwards directed peak-to-peak values (from plus to minus, i.e., increasing compression) might be counted. The authors are not aware of any argument that speaks in favour for a certain counting method.)* The condition to count peak-to-peak amplitudes only between zero-crossings eliminates smaller peak-to-peak amplitudes that exist between two subsequent zero-crossings, i.e., either above or below the static internal load.

1.2 Advantages – comparison with ISO 2631-5

The FE-model (cf. Annex on WP6, Task 6.1) is to a considerable extent verified, more reliable, and variable with respect to individual characteristics than the method underlying ISO 2631-5, thus providing a well-suited instrument for stress predictions. Different FE-models reflect representative anthropometric characteristics and postures of European drivers. Due to their close relation to real human anatomy, the FE-models enable a prediction of forces acting on all lumbar levels. The consequences of the variability caused by posture and anatomy are illustrated by the different static forces caused by various postures and anthropometric characteristics (Figure 1, Table 1). The maximum forces can reach the triple of the minimal ones! The possibility to consider the individual posture and anatomy by an assignment to different model groups and classes, respectively, improves the validity of stress predictions and risk assessments for single cases.

Since the internal dynamic forces acting on the discs are predicted by transfer functions derived from FE-model calculations, these forces can also be used by the approach for the direct calculation of the daily equivalent static compression dose. The FE-model calculations provide the compressive force as a result of a combined acceleration input in x, y and z-axis at four contact areas and summarising of the compressive force components in the time domain. This methods avoids a fundamental error implemented in the procedure described by ISO 2631-5 (2004). In this standard, three different dose values of peak compressive stress components resulting from spine accelerations in x-, y, and z-axis are summed up, thus ignoring the fact that such peak values do not exist in reality. Actually peak values of only one time series of compressive force exist, and the effect of the components by x-, y- and z-accelerations on this compression depends on their mutual time-relations. In a random multi-axis vibration environment the peaks of the components do not occur simultaneously, hence, the accelerations of different axes can have mutually amplifying or diminishing effects on the compressive force.

Unlike ISO 2631-5 (2004), the FIOSH-approach considers additionally significant variables like posture, body mass and body height, body mass index (BMI), disc area, disc level. Combinations of body mass, body height and BMI were chosen in order to provide representative characteristics of European drivers. The procedure can be used to judge the effects of the biological variability or posture. It offers the possibility to predict the health risk for different shares of the exposed population as a contribution to subsequent decisions on tolerated risks.

There are further differences between the FIOSH-approach and the method described by ISO 2631-5 (2004). A variable static stress is predicted instead of the “constant c representing the static stress due to gravitational force” in ISO 2631-5, equation A.3. Another consequence is the variable dynamic stress predicted for different anthropometric characteristics. The FIOSH-approach also offers the possibility to use different exponents for the dose calculations. Two alternatives, instead of only one, are offered for the calculation of the age-dependent ultimate strength, additionally the user can decide, if a risk assessment for 50 or 95 percent of the general population is required.

1.3 Limitations

Present limitations of the FE-models concern their linearity, simplified modelling of soft tissue at the input areas, missing consideration of twisting, and limited verification for horizontal and rotational inputs.

The procedures for assessment of health risk do not intend to provide a quantitative risk assessment for internal stresses caused by shear forces, bending and torsion, because reliable strength data for such stresses, especially for dynamic repetitive loads are not available. One might consider peak-to-peak shear forces exceeding 30 percent of the provisionally estimated final strength limits of such loads as potentially harmful (cf. Morrison et al. Part 5, p. 65 after Begemann et al 1994 2700 N ± 400 N for shear, Seidel et al. 1995 after Farfan (1979) maximum 1250 N shear for the disk alone). Recent data by Cripton et al. (1995) suggest an ultimate shear strength of lumbar functional spinal units between 1300 and 2900 N. Bending moments and torsion are generally not considered.

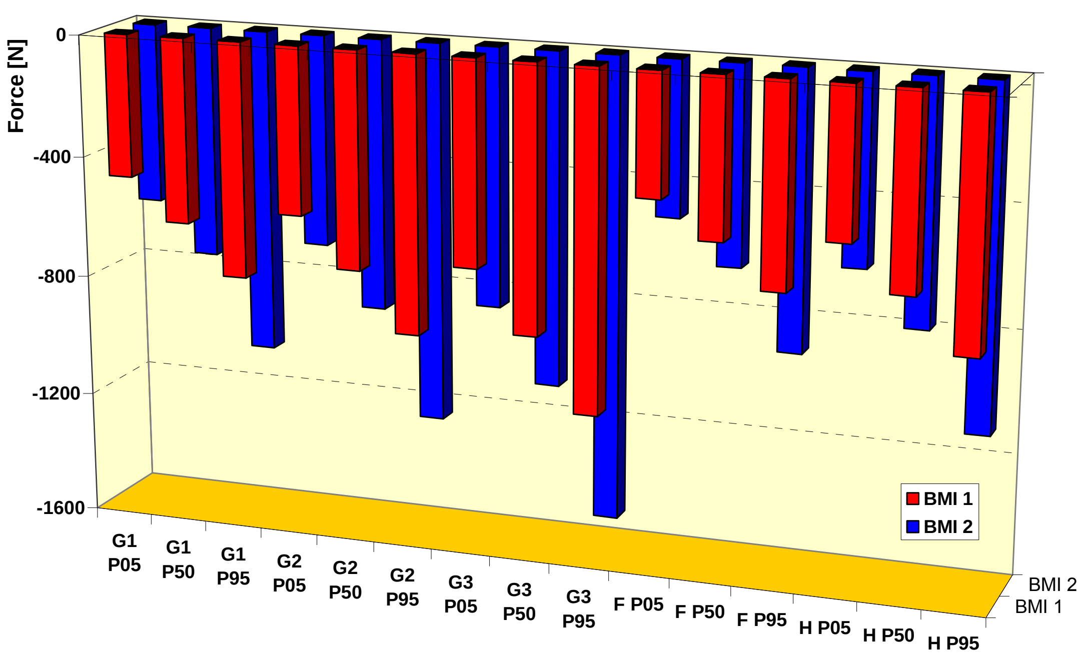

Figure 1. Static compressive forces (in N) predicted for the level L4/L5 caused by different postures (G1…G3, F-forwarder, H-harvester) and anthropometric characteristics of different percentiles (P) of European drivers with a body mass index ≤ 2.6122 g/cm^2 (BMI 1) or > 2.6122 g/cm^2 (BMI 2).

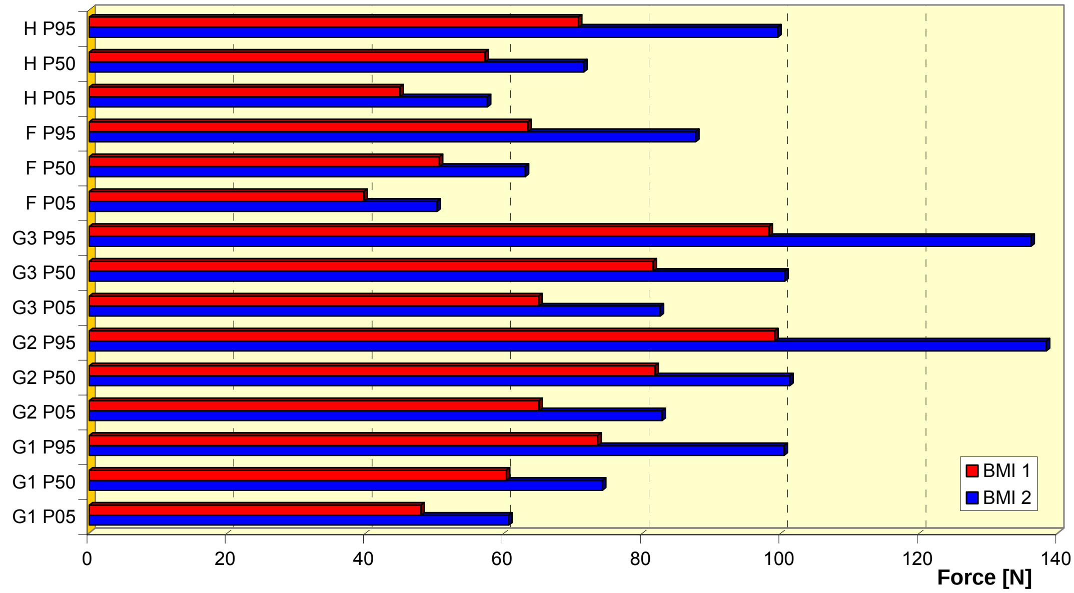

Figure 2. Static shear forces (in N) predicted for the level L4/L5 caused by different postures (G1…G3, F-forwarder, H-harvester) and anthropometric characteristics of different percentiles (P) of European drivers with a body mass index ≤ 2.6122 g/cm^2 (BMI 1) or > 2.6122 g/cm^2 (BMI 2).

2 Methods

2.1 Calculation of intraspinal compressive and shear forces

The following data are required before each calculation:

- Accelerations as input to the program for the calculation of intraspinal forces acting on 6 levels *l* (from T12/L1 to L5/S1) – see separate instruction in Annex to the Work Package 6, Task 6.1. The data file of accelerations shall consist of 4 columns (time, acceleration in x-, y-, z-dicrection) for each measurement point and contain no more than 140000 values in each columns. The signs of the acceleration shall correspond to ISO 2631-1, i.e., positive signs for ventrally directed acceleration in x-axis, acceleration to the left side in y-axis, and cranially directed acceleration in z-axis. Since the sign of measured data depends on the whole measurement chain, an experimental testing with documentation of signs in all directions is recommended.

- Selection of one of the five model groups describing the posture of the driver as characterised by different angles between body parts (cf. Annex to the Report on Work Package 6, Task 6.1).

- Class of anthropometric characteristics. At first, the BMI-group shall be determined in order to assign the subject to a group with BMI ≤ or > 2.61224 [g/cm^2]). Based on the best fitting combination of body height and body mass for this BMI, the corresponding percentile of body mass - 5th, 25th, 50th, 75th, or 95th percentile – shall be selected, cf. Annex to the Report on Work Package 6, Task 6.1.

Calculation of the dynamic internal forces in the spine by 'MAKE.SPF'

- Run of model calculation 'MAKE.SPF'

  Within the MatLab Software the user routine 'MAKE.SPF' can be started. A user window will appear (cf. Annex to Report on Work Package 6, Task 6.1). The following model settings have to be chosen, example given in brackets.

  Model posture: (example forwarder)

  Percentile: (example P05)

  BMI: (example ≤ 2.61224 g/cm^2)

  There is the possibility to insert comments into the file header.

  It is recommended to set up an output directory (suited for a series of results). For an easy handling of the results, the output file name should reflect the model settings (e.g. f1Lp05bmi1 for 'Forwarder 1, loading 5th percentile, BMI ≤ 0.2661 g/cm^2).

  After a mouse click on one of the inputs the corresponding data file of the accelerations can be opened.

  The calculation can be started (click on 'Start'). The results will be stored in the directory chosen before.

2.2 Calculation of the risk factor

2.2.1 Symbols, abbreviations and subscripts

A area of the endplates at the lumbar level l = 1…6 and for one of three categories (c) (in cm^2)

b age at which the exposure starts, can vary between 20 and 65 (years) without decimals

c abbreviation - category of the size of the endplate at level l, details are given for categories small, medium, and large and for all levels l in Table 2.

Cstat absolute value of the static compressive force due to posture and gravity (in Newton) acting on the lumbar level l

Cdyn dynamic peak-to-peak values of the compressive force (in Newton) due to vibration acting on the lumbar level l

exp exponent for the calculation of compressive dose

i counter of the years of exposure

j subscript - exposure condition

k counter of the Cdyn during t_{mj} *(Note: The maximum number of k = s will be determined automatically by the MatLab-program.)*

l abbreviation - lumbar level (1 – T12/L1, 2 – L1/L2, 3 – L2/L3, 4 - L3/L4, 5 – L4/L5, 6 – L5/S1)

nd number of days with exposure j per year

p abbreviation - percent of the population for which the calculation is intended, details are given for 50 or 95 percent

Pdyn dynamic peak-to-peak compressive stress (in MPa) acting on level l

Pstat static compressive stress (in MPa) acting on level l

q maximum number of years i of total exposure

r maximum number of exposure conditions j per day

R risk factor calculated by FIOSH-Approach, corresponds to the equivalent normalised static compressive stress that would cause failure if the value 1 is reached or exceeded

S_u ultimate (u) strength of the lumbar endplates for a person of age (b + i) years (in MPa) predicted for up to a certain percentage (p) of the population, details are given for p = 50 and p = 95 percent

S_{ed} daily dynamic compression dose for the lumbar level l

S_j dynamic compression dose for the measurement period of exposure j

t_{dj} duration of the daily exposure to condition j

t_{mj} period over which the exposure j has been measured

u abbreviation - designating the kind of calculation of the ultimate strength depending on age. u = 1 means application of Equation 1 for the prediction of ultimate static strength, u = 2 means application of Equation 2 for the prediction of ultimate static strength

2.2.2 FIOSH-Approach of risk assessment - equations

Transformation. Transformation of $Cdyn_l$ and $Cstat_l$ into dynamic compressive stress $Pdyn_l$ and static compressive stress $Pstat_l$ according to

Pdyn [MPa] = *Cdyn* [N]/(*A* [cm^2] * 100) (1)

and

Pstat [MPa] = *Cstat* [N]/(*A* [cm^2] * 100) (2).

Internal cyclic stress. All peak-to-peak values are related to the disc area A_l of the lumbar level l.

$$\mathrm{Pdyn} = \frac{\mathrm{Cdyn}}{\mathrm{A} \ * 100} [\mathrm{MPa}] \tag{3}$$

*Calculation of the compressive stress dose $S_{l,j}$ for the exposure j and disc level l*

$$S_j = \left[\sum_{k=1}^{s} Pdyn_k^{\exp} \right]^{1/\exp} \tag{4}$$

(Note: S_j is calculated for the period over which the exposure j has been measured. The result depends on the disc level l and c.)

*Calculation of the daily compression dose S_{ed} for disc level l*

$$S_{ed} = \left[\sum_{j=1}^{r} S_j^{\exp} \frac{t_{dj}}{t_{mj} * 2} \right]^{1/\exp} \tag{5}$$

where

j is the exposure condition j

t_{dj} is the duration of the daily exposure to condition *j*

t_{mj} is the period over which S_j has been calculated based on the measurement

Note: The reason for factor "2" in the divisor of equation (6) is given in Chapter 1.1.1. The result depends on the disc level l and c.

Notes:

- *This daily compression dose does not consider the extent of the simultaneously acting $Pstat_l$ that could be taken into account, e.g., by Goodman's law (Seidel et al. 1998). The static compressive stress is considered in the calculation of the Risk factor R (Equation 6).*
- *A simple assessment of adverse health effect at lifetime exposure based on this dose will cause misjudgements due to the missing consideration of the individual age and individual $Pstat_l$.*

<u>Calculation of the Risk factor R (or 'equivalent static compressive stress') for disc level l</u>

(Cf. equation A.3 of ISO 2631-5)

$$R = \left[\sum_{i=1}^{q} \left(\frac{S_{ed} * nd^{1/\exp}}{S_{ui} - Pstat} \right)^{\exp} \right]^{1/\exp} \qquad (6)$$

Note: The result depends on the disc level l, c, p, and v.

nd is the number of exposure days per year

i is the year counter

Pstat is a constant representing the static compressive stress acting on disk level *l* during a certain posture (*Note: Instead of one constant value for all conditions in ISO 2631-5, this procedure uses specific values that depend on anthropometric characteristics [BMI, body mass, body height], disk level l, posture and the decision on the category c of the size of the endplate.*)

S_{ui} is the ultimate (subscript u) strength of the lumbar spine for a person of age (*b* + *i*) years that can be predicted by two different regression equations (equations 1 or 2) and considering the share of the population p that shall be covered by the prediction (50 or 95 percent, subscript p), *b* is the age at which the exposure starts

exp is the exponent chosen by the user, default is 6

Notes:

- *R is a quantity that predicts the risk of fatigue failure of the vertebral endplate due to repeated compressions, if it reaches or exceeds the value 1. It can also be designated as 'equivalent static compressive stress', because it is equivalent to the static compressive stress that would cause failure, if the value 1 is reached.*
- *Equation (6) considers the simultaneously acting static stress.*
- *In vitro data suggest that S_{ui} does not depend on gender and/or disk level.*
- *The S_{ui} predicted by equations 1 and 2 provide average values that are valid for about 50 percent of the population. If one wants to consider 95 percent of the population, these values should be reduced by about 1.3 MPa (Equation 1) or 1.5 MPa (Equation 2).*
- *Unlike S_e, the risk factor R considers the decreasing strength with increasing age also for the assessment of the effects of repetitive dynamic loads due to the kind of divisor*

2.2.3 Input variables to the MatLab-program for risk assessment

The user will be asked to accept default values or to change them by typing in the following variables in the MatLab program. The input data will be documented together with the result of the calculation.

1) *Ultimate strength.* Equation (1) or (2). Which equation for ultimate static strength? There are two possibilities described by Seidel et al. (1998) with equations (1) and (2) for p = 50 percent of the population. Equation 1: S_{u1} [MPa] = -0.037747 (b) + 5.106713 **or** Equation 2: S_{u2} [MPa] = -0.067184 (b) + 6.765024. Both equations are based on experimental in vitro data. Equation (1) leads to somewhat lower values at young age and is less dependent on age (b) given in years. Equation (2) is based on additional experimental data with compressive load applied to differently flexed vertebral segments with a high load rate of 3 kN/s (cf. Seidel et al. 1998). The authors recommend to use Equation 2, because its results agree better with recent data obtained for specimens of young males (unpublished predictions of ultimate strength based on measurements of the bone mineral density and endplate area of functional spinal units described by Huber et al., 2005).

2) *Percentage of population p.* p = 50 or 95 percent. Which share of the exposed male population (abbreviation p) shall be covered by the risk prediction? 50 or 95 percent? If 50 percent shall be covered, the results of the regression

equations according to the formulae (1) and (2) are used as they are. If 95 percent shall be covered, i.e., a very conservative assessment is intended, the predicted ultimate static strength values will be reduced by 1.3 or 1.5 MPa, respectively, i.e. Equation 1 modified: S_u [MPa] = -0.037747 (b) + 5.106713 – 1.3 **or** Equation 2 modified: S_u [MPa] = -0.067184 (b) + 6.765024 – 1.5. The authors recommend to use 50 percent, because the reduction for 95 percent does not seem to be appropriate for the working male population. Such reduction might be justified for single cases with supposed reduced individual tolerance.

3) *Disc level l.* Selection of the lumbar level (abbreviation l, T12/L1…L5/S1) for which the calculation shall be performed. *(Note: T12/L1 should be considered with caution, cf. Annex to Report on WP 6, Task 6.1.)*

4) age of the subject at the last year of exposure in years without decimals

5) *Exponent for the calculation of the cumulative fatigue failure* exp. Default is 6, other possibilities are, e.g., 4, 5, 7 and 8. The authors recommend 6. This factor agreed best with results of in vitro experiments (Huber et al., 2005).

6) j number of exposures condition, i. e. numbers j = 1 or 2 …or …r. Important note: The combination of different exposure conditions is performed in the last steps of calculation.

7) nd number of days with exposure j per year. According to the number of exposure conditions (cf. j) up to r numbers will be asked for.

8) ny number of exposure years, maximum quantity of ny = q. The calculation will be performed for the years ago, i. e., if the age of a person is 45 and 20 years of exposure are used as input, the risk will be calculated for an exposure between the age of 25 and 45 years

9) r - maximum number of exposure conditions j per day

10) t_{dj} - duration of the daily exposure to condition j; should be given in seconds (range up to 36,000)

11) t_{mj} - period over which the exposure j has been measured; should be given in seconds

12) Cstat - static compressive force due to posture and gravity (in Newton) acting on the lumber level l. The user is asked to look into Table 1 and to select the value depending on posture, BMI, percentile of body mass and body height, disc level.

It should be considered that the absolute value of the compressive force should be typed in, i. e. the value without the minus sign.

13) *Size of endplate area.* A - area of the endplates at the lumbar level l = 1…6 chosen for one of three categories (small, medium, large) (in cm^2). The user can take a number from Table 2 (or any other source). Range 13 …20, one decimal. A value of 16 cm^2 is recommended for routine calculations as sufficient approximation valid for all lumbar levels. The data reported by Pöpplau (2006) can be considered as the most precise and reliable ones. Small endplate areas mean a higher risk, large ones a smaller risk. Small, medium and large areas were derived from data of the normal population. *(Note: At present, contradictory results exist with respect to the possibility to predict individual areas from anthropometric parameters by regression equations (Colombini et al. 1989, Turk and Celan 2004, Pöpplau 2006) The authors cannot recommend such prediction, because the largest and most reliable study by Pöpplau (2006) did not indicate any significant correlation between diameters of large joints and the size of lumbar endplate areas. Body mass did also not correlate with the endplate areas).*

The following instructions were used as input with the program 'riscm3t.m' for the calculation of the data reported in the results section:

Input parameters:

Lumbar level (1,2,3,4,5 or 6 (see text)) : 5

Equation 1 or 2 : 2

50 or 95 percent(for ultimate strength) : 50

age of the the subject in years (without decimals) : 65

number of exposure years : 45

exponent for the calculation in Approach 2 (e.g. 6,4,5,7 or 8) : 6

static compressive (see text) in Newton : (according to Table 1)

area of the endplates : 16

number of days with exposure per year : 240

How many exposure conditions ? : 1

Input for exposure : 1

duration of the daily exposure to exposure in seconds : 14400

period over which the exposure has been measured in seconds : 140

mfm = (selection of a file name containing the result of model calculation, i.e. F1TnoCp05bmi1_time.asc)

Table 1. Static compressive (Z) and shear forces in the sagittal plane (X) at 6 lumbar disc levels calculated by FE-models adjusted to representative combinations of postures, body mass index (BMI) and percentiles (according to body mass) of the population of European drivers.

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 1	BMI ≤ 2.61224	P05	1 - T12/L1	-63.508	-431.68
Group 1	BMI ≤ 2.61224	P05	2 - L1/L2	-65.845	-455.63
Group 1	BMI ≤ 2.61224	P05	3 - L2/L3	-58.902	-475.75
Group 1	BMI ≤ 2.61224	P05	4 - L3/L4	-25.381	-479.42
Group 1	BMI ≤ 2.61224	P05	5 - L4/L5	47.919	-469.07
Group 1	BMI ≤ 2.61224	P05	6 - L5/S1	144.14	-422.79
Group 1	BMI ≤ 2.61224	P25	1 - T12/L1	-71.516	-482.2
Group 1	BMI ≤ 2.61224	P25	2 - L1/L2	-73.913	-509.43
Group 1	BMI ≤ 2.61224	P25	3 - L2/L3	-66.043	-532.15
Group 1	BMI ≤ 2.61224	P25	4 - L3/L4	-28.738	-536.44
Group 1	BMI ≤ 2.61224	P25	5 - L4/L5	53.116	-525.26
Group 1	BMI ≤ 2.61224	P25	6 - L5/S1	160.8	-473.92
Group 1	BMI ≤ 2.61224	P50	1 - T12/L1	-82.835	-556.53
Group 1	BMI ≤ 2.61224	P50	2 - L1/L2	-85.35	-588.64
Group 1	BMI ≤ 2.61224	P50	3 - L2/L3	-76.367	-615.46
Group 1	BMI ≤ 2.61224	P50	4 - L3/L4	-33.818	-620.75
Group 1	BMI ≤ 2.61224	P50	5 - L4/L5	60.254	-608.02
Group 1	BMI ≤ 2.61224	P50	6 - L5/S1	184.94	-549.58
Group 1	BMI ≤ 2.61224	P75	1 - T12/L1	-94.73	-636.1
Group 1	BMI ≤ 2.61224	P75	2 - L1/L2	-97.171	-671.54

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 1	BMI ≤ 2.61224	P75	3 - L2/L3	-86.993	-702.39
Group 1	BMI ≤ 2.61224	P75	4 - L3/L4	-39.265	-708.57
Group 1	BMI ≤ 2.61224	P75	5 - L4/L5	67.267	-694.58
Group 1	BMI ≤ 2.61224	P75	6 - L5/S1	209.72	-628.78
Group 1	BMI ≤ 2.61224	P95	1 - T12/L1	-105.3	-705.83
Group 1	BMI ≤ 2.61224	P95	2 - L1/L2	-107.65	-745.87
Group 1	BMI ≤ 2.61224	P95	3 - L2/L3	-96.624	-781.87
Group 1	BMI ≤ 2.61224	P95	4 - L3/L4	-44.208	-787.82
Group 1	BMI ≤ 2.61224	P95	5 - L4/L5	73.474	-772.85
Group 1	BMI ≤ 2.61224	P95	6 - L5/S1	231.99	-700.27
Group 1	BMI > 2.61224	P05	1 - T12/L1	-79.692	-540.27
Group 1	BMI > 2.61224	P05	2 - L1/L2	-82.611	-570.79
Group 1	BMI > 2.61224	P05	3 - L2/L3	-73.855	-597.37
Group 1	BMI > 2.61224	P05	4 - L3/L4	-31.603	-602.63
Group 1	BMI > 2.61224	P05	5 - L4/L5	60.58	-590.1
Group 1	BMI > 2.61224	P05	6 - L5/S1	181.13	-532.51
Group 1	BMI > 2.61224	P25	1 - T12/L1	-89.985	-605.97
Group 1	BMI > 2.61224	P25	2 - L1/L2	-92.833	-640.91
Group 1	BMI > 2.61224	P25	3 - L2/L3	-83.095	-670.82
Group 1	BMI > 2.61224	P25	4 - L3/L4	-36.338	-676.99
Group 1	BMI > 2.61224	P25	5 - L4/L5	66.497	-663.33
Group 1	BMI > 2.61224	P25	6 - L5/S1	202.13	-599.41
Group 1	BMI > 2.61224	P50	1 - T12/L1	-103.77	-690.06
Group 1	BMI > 2.61224	P50	2 - L1/L2	-106.51	-731.02
Group 1	BMI > 2.61224	P50	3 - L2/L3	-95.207	-766.01
Group 1	BMI > 2.61224	P50	4 - L3/L4	-42.46	-772.63
Group 1	BMI > 2.61224	P50	5 - L4/L5	74.161	-757.64

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 1	BMI > 2.61224	P50	6 - L5/S1	229.14	-685.64
Group 1	BMI > 2.61224	P75	1 - T12/L1	-122.53	-806.12
Group 1	BMI > 2.61224	P75	2 - L1/L2	-125.16	-855.2
Group 1	BMI > 2.61224	P75	3 - L2/L3	-111.72	-895.5
Group 1	BMI > 2.61224	P75	4 - L3/L4	-50.514	-904.71
Group 1	BMI > 2.61224	P75	5 - L4/L5	85.387	-887.22
Group 1	BMI > 2.61224	P75	6 - L5/S1	266.79	-803.98
Group 1	BMI > 2.61224	P95	1 - T12/L1	-148.53	-959.09
Group 1	BMI > 2.61224	P95	2 - L1/L2	-150.87	-1019.9
Group 1	BMI > 2.61224	P95	3 - L2/L3	-134.11	-1068
Group 1	BMI > 2.61224	P95	4 - L3/L4	-61.292	-1079.6
Group 1	BMI > 2.61224	P95	5 - L4/L5	100.41	-1060.4
Group 1	BMI > 2.61224	P95	6 - L5/S1	316.87	-961.59
Group 2	BMI ≤ 2.61224	P05	1 - T12/L1	-63.879	-502.33
Group 2	BMI ≤ 2.61224	P05	2 - L1/L2	-67.845	-533.16
Group 2	BMI ≤ 2.61224	P05	3 - L2/L3	-61.101	-558.63
Group 2	BMI ≤ 2.61224	P05	4 - L3/L4	-22.609	-563.14
Group 2	BMI ≤ 2.61224	P05	5 - L4/L5	64.973	-550.62
Group 2	BMI ≤ 2.61224	P05	6 - L5/S1	180.25	-493.76
Group 2	BMI ≤ 2.61224	P25	1 - T12/L1	-70.957	-562.05
Group 2	BMI ≤ 2.61224	P25	2 - L1/L2	-75.44	-596.45
Group 2	BMI ≤ 2.61224	P25	3 - L2/L3	-68.141	-625.15
Group 2	BMI ≤ 2.61224	P25	4 - L3/L4	-25.585	-630.46
Group 2	BMI ≤ 2.61224	P25	5 - L4/L5	72.102	-616.7
Group 2	BMI ≤ 2.61224	P25	6 - L5/S1	201.11	-553.45
Group 2	BMI ≤ 2.61224	P50	1 - T12/L1	-80.342	-649.31
Group 2	BMI ≤ 2.61224	P50	2 - L1/L2	-85.873	-690.25

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 2	BMI ≤ 2.61224	P50	3 - L2/L3	-78.158	-723.7
Group 2	BMI ≤ 2.61224	P50	4 - L3/L4	-30.237	-729.81
Group 2	BMI ≤ 2.61224	P50	5 - L4/L5	81.74	-714.33
Group 2	BMI ≤ 2.61224	P50	6 - L5/S1	231.15	-642.05
Group 2	BMI ≤ 2.61224	P75	1 - T12/L1	-89.79	-742.46
Group 2	BMI ≤ 2.61224	P75	2 - L1/L2	-96.166	-788.3
Group 2	BMI ≤ 2.61224	P75	3 - L2/L3	-88.424	-827.43
Group 2	BMI ≤ 2.61224	P75	4 - L3/L4	-35.425	-833.76
Group 2	BMI ≤ 2.61224	P75	5 - L4/L5	91.009	-816.7
Group 2	BMI ≤ 2.61224	P75	6 - L5/S1	261.82	-735.1
Group 2	BMI ≤ 2.61224	P95	1 - T12/L1	-97.8	-825.38
Group 2	BMI ≤ 2.61224	P95	2 - L1/L2	-105.18	-877.04
Group 2	BMI ≤ 2.61224	P95	3 - L2/L3	-97.374	-919.92
Group 2	BMI ≤ 2.61224	P95	4 - L3/L4	-40.166	-927.29
Group 2	BMI ≤ 2.61224	P95	5 - L4/L5	99.051	-908.84
Group 2	BMI ≤ 2.61224	P95	6 - L5/S1	289.11	-819.06
Group 2	BMI > 2.61224	P05	1 - T12/L1	-77.939	-628.92
Group 2	BMI > 2.61224	P05	2 - L1/L2	-83.61	-669
Group 2	BMI > 2.61224	P05	3 - L2/L3	-75.579	-701.93
Group 2	BMI > 2.61224	P05	4 - L3/L4	-27.273	-708.37
Group 2	BMI > 2.61224	P05	5 - L4/L5	82.772	-693.09
Group 2	BMI > 2.61224	P05	6 - L5/S1	227.16	-621.37
Group 2	BMI > 2.61224	P25	1 - T12/L1	-86.181	-705.75
Group 2	BMI > 2.61224	P25	2 - L1/L2	-92.709	-751.89
Group 2	BMI > 2.61224	P25	3 - L2/L3	-84.344	-787.93
Group 2	BMI > 2.61224	P25	4 - L3/L4	-31.673	-795.76
Group 2	BMI > 2.61224	P25	5 - L4/L5	90.719	-779

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 2	BMI > 2.61224	P25	6 - L5/S1	253.15	-699.71
Group 2	BMI > 2.61224	P50	1 - T12/L1	-96.697	-806.08
Group 2	BMI > 2.61224	P50	2 - L1/L2	-104.37	-859
Group 2	BMI > 2.61224	P50	3 - L2/L3	-95.666	-900.71
Group 2	BMI > 2.61224	P50	4 - L3/L4	-37.214	-909.08
Group 2	BMI > 2.61224	P50	5 - L4/L5	101.2	-890.61
Group 2	BMI > 2.61224	P50	6 - L5/S1	286.96	-801.11
Group 2	BMI > 2.61224	P75	1 - T12/L1	-110.25	-943.77
Group 2	BMI > 2.61224	P75	2 - L1/L2	-119.54	-1004.9
Group 2	BMI > 2.61224	P75	3 - L2/L3	-110.58	-1055.1
Group 2	BMI > 2.61224	P75	4 - L3/L4	-43.775	-1064.3
Group 2	BMI > 2.61224	P75	5 - L4/L5	116.84	-1043.2
Group 2	BMI > 2.61224	P75	6 - L5/S1	334.16	-939.54
Group 2	BMI > 2.61224	P95	1 - T12/L1	-127.27	-1124
Group 2	BMI > 2.61224	P95	2 - L1/L2	-139.06	-1197.2
Group 2	BMI > 2.61224	P95	3 - L2/L3	-129.45	-1256.6
Group 2	BMI > 2.61224	P95	4 - L3/L4	-51.642	-1268.3
Group 2	BMI > 2.61224	P95	5 - L4/L5	138.3	-1243.4
Group 2	BMI > 2.61224	P95	6 - L5/S1	396.84	-1121
Group 3	BMI ≤ 2.61224	P05	1 - T12/L1	-28.055	-596.56
Group 3	BMI ≤ 2.61224	P05	2 - L1/L2	-48.081	-642.9
Group 3	BMI ≤ 2.61224	P05	3 - L2/L3	-56.681	-681.54
Group 3	BMI ≤ 2.61224	P05	4 - L3/L4	-25.282	-689.18
Group 3	BMI ≤ 2.61224	P05	5 - L4/L5	64.92	-673.57
Group 3	BMI ≤ 2.61224	P05	6 - L5/S1	187.67	-604.93
Group 3	BMI ≤ 2.61224	P25	1 - T12/L1	-31.034	-668.7
Group 3	BMI ≤ 2.61224	P25	2 - L1/L2	-53.478	-720.33

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 3	BMI ≤ 2.61224	P25	3 - L2/L3	-63.366	-763.98
Group 3	BMI ≤ 2.61224	P25	4 - L3/L4	-28.691	-772.54
Group 3	BMI ≤ 2.61224	P25	5 - L4/L5	72.048	-755.67
Group 3	BMI ≤ 2.61224	P25	6 - L5/S1	209.54	-679.06
Group 3	BMI ≤ 2.61224	P50	1 - T12/L1	-34.244	-770.99
Group 3	BMI ≤ 2.61224	P50	2 - L1/L2	-60.759	-834.25
Group 3	BMI ≤ 2.61224	P50	3 - L2/L3	-72.872	-884.51
Group 3	BMI ≤ 2.61224	P50	4 - L3/L4	-34.034	-894.67
Group 3	BMI ≤ 2.61224	P50	5 - L4/L5	81.45	-875.68
Group 3	BMI ≤ 2.61224	P50	6 - L5/S1	240.67	-787.91
Group 3	BMI ≤ 2.61224	P75	1 - T12/L1	-37.308	-883.11
Group 3	BMI ≤ 2.61224	P75	2 - L1/L2	-67.8	-952.21
Group 3	BMI ≤ 2.61224	P75	3 - L2/L3	-82.625	-1009.4
Group 3	BMI ≤ 2.61224	P75	4 - L3/L4	-40.026	-1021.9
Group 3	BMI ≤ 2.61224	P75	5 - L4/L5	90.401	-1000.7
Group 3	BMI ≤ 2.61224	P75	6 - L5/S1	272.26	-901.83
Group 3	BMI ≤ 2.61224	P95	1 - T12/L1	-39.357	-980.22
Group 3	BMI ≤ 2.61224	P95	2 - L1/L2	-73.765	-1059.6
Group 3	BMI ≤ 2.61224	P95	3 - L2/L3	-91.357	-1124.1
Group 3	BMI ≤ 2.61224	P95	4 - L3/L4	-45.544	-1137.5
Group 3	BMI ≤ 2.61224	P95	5 - L4/L5	98.213	-1114.4
Group 3	BMI ≤ 2.61224	P95	6 - L5/S1	300.59	-1005.3
Group 3	BMI > 2.61224	P05	1 - T12/L1	-33.957	-748.76
Group 3	BMI > 2.61224	P05	2 - L1/L2	-59.246	-807.49
Group 3	BMI > 2.61224	P05	3 - L2/L3	-70.196	-857.59
Group 3	BMI > 2.61224	P05	4 - L3/L4	-30.83	-867.97
Group 3	BMI > 2.61224	P05	5 - L4/L5	82.489	-848.9

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Group 3	BMI > 2.61224	P05	6 - L5/S1	236.46	-762.55
Group 3	BMI > 2.61224	P25	1 - T12/L1	-36.74	-839.21
Group 3	BMI > 2.61224	P25	2 - L1/L2	-65.504	-907.4
Group 3	BMI > 2.61224	P25	3 - L2/L3	-78.672	-964.11
Group 3	BMI > 2.61224	P25	4 - L3/L4	-35.843	-975.34
Group 3	BMI > 2.61224	P25	5 - L4/L5	90.324	-954.55
Group 3	BMI > 2.61224	P25	6 - L5/S1	263.37	-858.72
Group 3	BMI > 2.61224	P50	1 - T12/L1	-40.596	-961.41
Group 3	BMI > 2.61224	P50	2 - L1/L2	-73.58	-1036.5
Group 3	BMI > 2.61224	P50	3 - L2/L3	-89.466	-1101.3
Group 3	BMI > 2.61224	P50	4 - L3/L4	-42.217	-1114.9
Group 3	BMI > 2.61224	P50	5 - L4/L5	100.51	-1091.6
Group 3	BMI > 2.61224	P50	6 - L5/S1	298.38	-983.16
Group 3	BMI > 2.61224	P75	1 - T12/L1	-45.321	-1120.4
Group 3	BMI > 2.61224	P75	2 - L1/L2	-84.226	-1212.3
Group 3	BMI > 2.61224	P75	3 - L2/L3	-103.48	-1286.7
Group 3	BMI > 2.61224	P75	4 - L3/L4	-49.733	-1302.9
Group 3	BMI > 2.61224	P75	5 - L4/L5	115.76	-1276.6
Group 3	BMI > 2.61224	P75	6 - L5/S1	346.79	-1150.8
Group 3	BMI > 2.61224	P95	1 - T12/L1	-52.822	-1331.1
Group 3	BMI > 2.61224	P95	2 - L1/L2	-98.781	-1438.1
Group 3	BMI > 2.61224	P95	3 - L2/L3	-121.88	-1527.9
Group 3	BMI > 2.61224	P95	4 - L3/L4	-59.127	-1546.7
Group 3	BMI > 2.61224	P95	5 - L4/L5	136.09	-1514.8
Group 3	BMI > 2.61224	P95	6 - L5/S1	410.18	-1368.9
Forwarder	BMI ≤ 2.61224	P05	1 - T12/L1	-67.707	-380.46
Forwarder	BMI ≤ 2.61224	P05	2 - L1/L2	-65.848	-396.57

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Forwarder	BMI ≤ 2.61224	P05	3 - L2/L3	-56.985	-409.78
Forwarder	BMI ≤ 2.61224	P05	4 - L3/L4	-26.049	-411.22
Forwarder	BMI ≤ 2.61224	P05	5 - L4/L5	39.641	-402.08
Forwarder	BMI ≤ 2.61224	P05	6 - L5/S1	125.59	-363.53
Forwarder	BMI ≤ 2.61224	P25	1 - T12/L1	-75.576	-424.29
Forwarder	BMI ≤ 2.61224	P25	2 - L1/L2	-73.367	-442.73
Forwarder	BMI ≤ 2.61224	P25	3 - L2/L3	-63.432	-457.47
Forwarder	BMI ≤ 2.61224	P25	4 - L3/L4	-29.131	-459.4
Forwarder	BMI ≤ 2.61224	P25	5 - L4/L5	44.054	-449.52
Forwarder	BMI ≤ 2.61224	P25	6 - L5/S1	140.08	-406.67
Forwarder	BMI ≤ 2.61224	P50	1 - T12/L1	-86.148	-490.29
Forwarder	BMI ≤ 2.61224	P50	2 - L1/L2	-83.473	-511.57
Forwarder	BMI ≤ 2.61224	P50	3 - L2/L3	-72.336	-529.14
Forwarder	BMI ≤ 2.61224	P50	4 - L3/L4	-33.382	-531.45
Forwarder	BMI ≤ 2.61224	P50	5 - L4/L5	50.588	-520.27
Forwarder	BMI ≤ 2.61224	P50	6 - L5/S1	161.62	-471.25
Forwarder	BMI ≤ 2.61224	P75	1 - T12/L1	-96.564	-559.65
Forwarder	BMI ≤ 2.61224	P75	2 - L1/L2	-93.431	-584.44
Forwarder	BMI ≤ 2.61224	P75	3 - L2/L3	-81.124	-604.77
Forwarder	BMI ≤ 2.61224	P75	4 - L3/L4	-37.598	-606.98
Forwarder	BMI ≤ 2.61224	P75	5 - L4/L5	57.287	-594.4
Forwarder	BMI ≤ 2.61224	P75	6 - L5/S1	184.1	-539.23
Forwarder	BMI ≤ 2.61224	P95	1 - T12/L1	-105.8	-622.4
Forwarder	BMI ≤ 2.61224	P95	2 - L1/L2	-102.1	-649.67
Forwarder	BMI ≤ 2.61224	P95	3 - L2/L3	-88.807	-673.21
Forwarder	BMI ≤ 2.61224	P95	4 - L3/L4	-41.315	-674.74
Forwarder	BMI ≤ 2.61224	P95	5 - L4/L5	63.339	-661.26

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Forwarder	BMI ≤ 2.61224	P95	6 - L5/S1	204.28	-600.23
Forwarder	BMI > 2.61224	P05	1 - T12/L1	-84.128	-475.03
Forwarder	BMI > 2.61224	P05	2 - L1/L2	-82.151	-496.1
Forwarder	BMI > 2.61224	P05	3 - L2/L3	-71.255	-513.94
Forwarder	BMI > 2.61224	P05	4 - L3/L4	-32.318	-516.61
Forwarder	BMI > 2.61224	P05	5 - L4/L5	50.254	-505.8
Forwarder	BMI > 2.61224	P05	6 - L5/S1	157.94	-457.51
Forwarder	BMI > 2.61224	P25	1 - T12/L1	-93.437	-533.18
Forwarder	BMI > 2.61224	P25	2 - L1/L2	-90.969	-557.02
Forwarder	BMI > 2.61224	P25	3 - L2/L3	-78.921	-576.78
Forwarder	BMI > 2.61224	P25	4 - L3/L4	-36.141	-579.79
Forwarder	BMI > 2.61224	P25	5 - L4/L5	55.736	-567.89
Forwarder	BMI > 2.61224	P25	6 - L5/S1	176.68	-514.31
Forwarder	BMI > 2.61224	P50	1 - T12/L1	-105.66	-607.72
Forwarder	BMI > 2.61224	P50	2 - L1/L2	-102.63	-636.75
Forwarder	BMI > 2.61224	P50	3 - L2/L3	-88.896	-657.76
Forwarder	BMI > 2.61224	P50	4 - L3/L4	-41.025	-661.55
Forwarder	BMI > 2.61224	P50	5 - L4/L5	62.956	-648.34
Forwarder	BMI > 2.61224	P50	6 - L5/S1	201.03	-587.93
Forwarder	BMI > 2.61224	P75	1 - T12/L1	-121.98	-709.18
Forwarder	BMI > 2.61224	P75	2 - L1/L2	-118.4	-743.67
Forwarder	BMI > 2.61224	P75	3 - L2/L3	-102.8	-770.46
Forwarder	BMI > 2.61224	P75	4 - L3/L4	-47.552	-774.8
Forwarder	BMI > 2.61224	P75	5 - L4/L5	73.442	-758.89
Forwarder	BMI > 2.61224	P75	6 - L5/S1	234.91	-689.25
Forwarder	BMI > 2.61224	P95	1 - T12/L1	-144.14	-845.92
Forwarder	BMI > 2.61224	P95	2 - L1/L2	-139.75	-887.68

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Forwarder	BMI > 2.61224	P95	3 - L2/L3	-121.26	-918.21
Forwarder	BMI > 2.61224	P95	4 - L3/L4	-56.068	-925.07
Forwarder	BMI > 2.61224	P95	5 - L4/L5	87.601	-906.61
Forwarder	BMI > 2.61224	P95	6 - L5/S1	280.28	-824.5
Harvester	BMI ≤ 2.61224	P05	1 - T12/L1	-55.57	-451.45
Harvester	BMI ≤ 2.61224	P05	2 - L1/L2	-62.325	-476.26
Harvester	BMI ≤ 2.61224	P05	3 - L2/L3	-59.776	-497.07
Harvester	BMI ≤ 2.61224	P05	4 - L3/L4	-28.311	-500.66
Harvester	BMI ≤ 2.61224	P05	5 - L4/L5	44.849	-490.09
Harvester	BMI ≤ 2.61224	P05	6 - L5/S1	142.04	-443.14
Harvester	BMI ≤ 2.61224	P25	1 - T12/L1	-61.736	-504.72
Harvester	BMI ≤ 2.61224	P25	2 - L1/L2	-69.292	-532.91
Harvester	BMI ≤ 2.61224	P25	3 - L2/L3	-66.516	-556.3
Harvester	BMI ≤ 2.61224	P25	4 - L3/L4	-31.598	-560.55
Harvester	BMI ≤ 2.61224	P25	5 - L4/L5	50.023	-549.04
Harvester	BMI ≤ 2.61224	P25	6 - L5/S1	158.83	-496.85
Harvester	BMI ≤ 2.61224	P50	1 - T12/L1	-69.72	-583.19
Harvester	BMI ≤ 2.61224	P50	2 - L1/L2	-78.548	-616.26
Harvester	BMI ≤ 2.61224	P50	3 - L2/L3	-75.774	-643.85
Harvester	BMI ≤ 2.61224	P50	4 - L3/L4	-36.358	-648.8
Harvester	BMI ≤ 2.61224	P50	5 - L4/L5	57.191	-635.74
Harvester	BMI ≤ 2.61224	P50	6 - L5/S1	183.12	-576.09
Harvester	BMI ≤ 2.61224	P75	1 - T12/L1	-77.455	-665.59
Harvester	BMI ≤ 2.61224	P75	2 - L1/L2	-87.594	-704.36
Harvester	BMI ≤ 2.61224	P75	3 - L2/L3	-85.084	-735.44
Harvester	BMI ≤ 2.61224	P75	4 - L3/L4	-41.321	-740.9
Harvester	BMI ≤ 2.61224	P75	5 - L4/L5	64.324	-726.4

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Harvester	BMI ≤ 2.61224	P75	6 - L5/S1	208.13	-658.91
Harvester	BMI ≤ 2.61224	P95	1 - T12/L1	-84.035	-740.48
Harvester	BMI ≤ 2.61224	P95	2 - L1/L2	-95.341	-783.17
Harvester	BMI ≤ 2.61224	P95	3 - L2/L3	-93.129	-817.49
Harvester	BMI ≤ 2.61224	P95	4 - L3/L4	-45.728	-824.26
Harvester	BMI ≤ 2.61224	P95	5 - L4/L5	70.659	-808.28
Harvester	BMI ≤ 2.61224	P95	6 - L5/S1	230.5	-734.03
Harvester	BMI > 2.61224	P05	1 - T12/L1	-68.649	-565.36
Harvester	BMI > 2.61224	P05	2 - L1/L2	-77.325	-596.71
Harvester	BMI > 2.61224	P05	3 - L2/L3	-74.289	-624.26
Harvester	BMI > 2.61224	P05	4 - L3/L4	-34.645	-629.73
Harvester	BMI > 2.61224	P05	5 - L4/L5	57.498	-616.93
Harvester	BMI > 2.61224	P05	6 - L5/S1	179.52	-557.96
Harvester	BMI > 2.61224	P25	1 - T12/L1	-75.376	-633.57
Harvester	BMI > 2.61224	P25	2 - L1/L2	-85.336	-671.01
Harvester	BMI > 2.61224	P25	3 - L2/L3	-82.403	-701.85
Harvester	BMI > 2.61224	P25	4 - L3/L4	-38.944	-707.62
Harvester	BMI > 2.61224	P25	5 - L4/L5	63.577	-693.57
Harvester	BMI > 2.61224	P25	6 - L5/S1	200.72	-628.08
Harvester	BMI > 2.61224	P50	1 - T12/L1	-84.608	-724.51
Harvester	BMI > 2.61224	P50	2 - L1/L2	-95.772	-766.34
Harvester	BMI > 2.61224	P50	3 - L2/L3	-92.868	-801.31
Harvester	BMI > 2.61224	P50	4 - L3/L4	-44.394	-807.79
Harvester	BMI > 2.61224	P50	5 - L4/L5	71.426	-792.29
Harvester	BMI > 2.61224	P50	6 - L5/S1	228.13	-718.47
Harvester	BMI > 2.61224	P75	1 - T12/L1	-96.501	-847.34
Harvester	BMI > 2.61224	P75	2 - L1/L2	-109.83	-897.62

Posture	BMI	Per-centile	Disc level	Static Force X [N]	Static Force Z [N]
Harvester	BMI > 2.61224	P75	3 - L2/L3	-106.91	-937.67
Harvester	BMI > 2.61224	P75	4 - L3/L4	-51.429	-946.63
Harvester	BMI > 2.61224	P75	5 - L4/L5	83.268	-928.51
Harvester	BMI > 2.61224	P75	6 - L5/S1	266.59	-842.77
Harvester	BMI > 2.61224	P95	1 - T12/L1	-112.06	-1011.3
Harvester	BMI > 2.61224	P95	2 - L1/L2	-128.16	-1069.7
Harvester	BMI > 2.61224	P95	3 - L2/L3	-125.48	-1119.8
Harvester	BMI > 2.61224	P95	4 - L3/L4	-60.295	-1130
Harvester	BMI > 2.61224	P95	5 - L4/L5	99.452	-1109.3
Harvester	BMI > 2.61224	P95	6 - L5/S1	318.15	-1007.2

2.2.4 Comments on data of endplate areas

An input of the disc area is not required for ISO 2631-5, because it assumes a constant area for all calculations. Since the normal variability, e.g. at the cranial endplate of L4, can be considerable (from 12 to 22 cm^2), the disc area as variable is of major significance for the prediction of the normal variability of strength. Hence, the large extent of the normal variability of A_l justifies the consideration of this factor in a more sophisticated assessment method. The table is for male persons only. The smaller areas reported by Pöpplau (2006) may be caused by the young age of these specimens (33,2 ±5,8 years) and the very precise measurement method. Other authors included osteophytes into the area of endplates, and this might explain the increase of area with increasing age. The mean age of specimens in the paper by Brinckmann et al. (1989) was 48.2 ± 15.7 years across all endplate levels, and in the paper by Brinckmann et al. (1988) 50.2 ± 17.7 years across all endplate levels. The estimation of the standard deviation within one lumbar level was elaborated based on data by Pöpplau (2006). The data by Jäger (2001) might also be used for the derivation of a mean value for the disc level L3/L4 and of the average change of the area with other disc levels. Data from Brinckmann et al. (1988, 1989) and other sources (Singer et al. 1995) could be used to get estimates for a change in dependence on disc level, including the extent of reduction at L5/S1. The precise data by Pöpplau (2006) contradict a systematic trend. Since there is probably no correlation with body mass or body height (Pöpplau 2006), an assumption concerning the endplate area shall be made independently of these characteristics.

Small and large values were not estimated based on the Jäger data (2001), because Jäger

Table 2. Size of lumbar endplate areas at different lumbar levels; cr. – cranial, ca. – caudal.

Scaling and data source	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Proposal for application "medium"	*14.6*	*15.2*	*15.8*	*15.9*	*16.0*	*15.5*
Proposal for application "small"	*13.1*	*13.7*	*14.2*	*14.0*	*14.0*	*14.6*
Proposal for application "large"	*16.0*	*16.7*	*17.4*	*17.8*	*17.8*	*17.4*
Small cr. (Pöpplau 2006)	-	-	13.8[1]	13.8[1]	14.1[1]	-
Small ca. (Pöppllau 2006)	-	-	-	14.2[1]	14.0[1]	13.2[1]
Small (Brinckmann et al. 1989)[2]	11.7	13.3	14.8	-	15.6	-
Medium cr. (Pöpplau 2006)	-	-	15.6[3]	15.8[3]	16.1[3]	-
Medium ca. (Pöpplau 2006)	-	-	-	16.0[3]	15.8[3]	15.1[4]
Medium (Jäger 2001)[5]	15.5	16.2	16.9	17.6	18.3[6]	17.6[7]
Medium (Brinckmann et al. 1988)[8]	14.3		17.2	-	17.5	-
Medium (Brinckmann et al. 1989)[9]	14.6	16.23	17.7	-	18.5	-
Large cr. (Pöpplau 2006)	-	-	17.4[10]	17.8[10]	18.1[10]	-
Large ca. (Pöpplau 2006)	-	-	-	17.8[10]	17.6[10]	17.0[11]
Large (Brinckmann et al. 1989)[12]	17.5	19.1	20.6	-	21.4	-

(2001) did not provide the standard deviation within one disc level. The proposals for practical applications were based mainly on data by Pöpplau (2006). Data by Brinckmann et al. (1988, 1989) could be used to reflect the condition at a higher age near 53 years. Disc area A_l (in cm^2)

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[1] Mean value reduced by one standard deviation, n = 53
[2] Calculated by subtracting an average SD of 2.9 cm^2 to the medium values. The average SD within one disc level of data Brinckmann et al. 1988 amounted to 3.5 cm^2. For disc level L3/L4 n= 5
[3] Mean value, n = 53
[4] Mean value, n=46
[5] No precise lumbar level indicated. In spite of different samples for endplate areas and lumbar level in the original paper, the average lumbar level near L3/L4 was used in this table. The number of specimen per disc level is unknown. The decrease of higher disc levels and increase with lower disc levels was estimated according to Jäger (2001) as 0.7 cm^2/lumbar disc level.
[6] The increase of the endplate area was estimated according to Jäger (2001) as 0.7 cm^2/lumbar disc level. (Disc level is not identical with lumbar height of Jäger, the latter assigning 2 numbers to one disc level.)
[7] The decrease was roughly estimated according to Singer et al. (1995). Singer published mean values of 10 males and 8 females, mean increase per level 46.1 mm^2, but decrease from L4/L5 to L5/S1. These authors examined the "midvertebral body cross sectional area" and not the endplate area.
[8] Mean values of upper and lower endplates, measurements from photos, max. n per disc level 16
[9] as footnote for Brinckmann 1988, but max. n per disc level 15
[10] Mean value increased by one standard deviation, n = 53
[11] Mean value increased by one standard deviation, n = 46
[12] Calculated by adding an average SD of 2.9 cm^2 within each disc level to the medium values. The average SD within one disc level of data Brinckmann et al. 1988 amounted to 3.5 cm^2. For disc level L3/L4 n= 3

of the lumbar disk level *l* for which the calculation is wanted, can be differentiated by small, medium, large. The small and large areas were calculated by subtracting and adding either one standard deviation (data by Pöpplau, 2006) or about 10 percent of the mean.

3 Results of analysis and risk assessment

3.1 Compressive stress

The spinal forces were calculated for five forwarders (f), five harvesters (h), four forklifts (FL), two wheel loaders (WL), and one truck excavator (TE). For the calculations the models of the 5th percentile and the BMI ≤ 2.6 (cf. Annex to Report on Work Package 6, Task 6.1) as well as

Table 3. Conditions for which dynamic compressive stress was calculated

Model/ posture	Type of machine	Input accelerations	Working task
Group 1	Forklift 1	p_1.asc	Carrara port
	Forklift 2	pts5_02.asc	loading, transport
	Forklift 3	via_l05	loading, transport, marble slides
	Forklift 4	pml_03_load	loading, paper mills
	Forklift 4	pml_03_mov	moving, paper mills
Group 2	Wheel loader 1	c_5.asc	Marble block moving
	Wheel loader 2	via_c01.asc	Excavation wastes, quarry roads
Group 3	Truck excavator	c_3.asc	Marble block excavation
Forwarder	Forwarder 1-5	Loading	Transporting timber
		Transport no Cargo	Transporting timber
		transport with Cargo	Transporting timber
		Unloading	Transporting timber
Harvester	Harvester 1-5	Felling	Felling trees
		Transport	Felling trees

of the 95th percentile and the BMI > 2.6 (cf. Report on Work Package 6, Task 6.1 and Appendix) were used to get results standing for the maximum range of the spinal stress associated with the stature of the drivers. For the calculation of forces the first 140000 values (2.33 minutes) of the acceleration signals were used. This limitation was due to the limited capacity of a normal computer. Longer signals could be computed after reducing the sampling frequency.

In Table 3 the conditions are summarized for which altogether 72 calculations were performed. The results were static (cf. Table 1) and dynamic spinal forces in three directions (x, y, z) at six spinal level (L5/S1 – T12/L1). As described in Chapter 1 in detail, the peak-to-peak values were fundamental parameters for the assessment of the health risks. Based on the dynamic share of calculated forces, i.e. the mean value of the time series equals zero, subsequent peak-to-peak values were determined for all spinal levels. To characterise the forces and make the peak-to-peak values comparable within and between the conditions tested, the following parameters of the peak-to-peak values were determined: their number, maxima, mean values, and the standard deviations. The results are shown in Figure 3 and Figure 4 for the data from partner UMUH and in Figure 5 and Figure 6 for the data from partner University Trieste.

Table 4 gives an overview about the working conditions with highest and lowest parameters of the peak-to-peak values of the compressive forces. The curves in Figure 7 illustrate the input accelerations and compressive forces for the exposure conditions with the maximum number of peak-to-peak values at the level T12/L1 and for the exposure condition with the highest peak-to-peak level of compression at the lumbar level L5/S1 under the exposure condition "F1 transport with cargo". During the latter, also the maximum mean value and maximum standard deviation of the peak-to-peak values were registered (cf. Table 4).

There are several trends obvious from Figure 3 – 6 and Table 4. The number of identified peak-to-peak values is on average decreasing from the cranial to the caudal part of the lumbar spine, although this trend cannot be observed in all cases, and the number of identified values also depends on the input acceleration (cf. Figure 3 and Figure 5). The average tendency might be linked with the simultaneous increase of the amplitudes of compressive stress that could cause an increased omitted counting of smaller peak-to-peak amplitudes between subsequent zero-crossings. The maximum predicted compression acting on L5/S1 is higher than that acting on L4/L5. Since the endplate area of L5/S1 is on average smaller than that of L4/L5, the highest risk of failure may be anticipated for this disc level. As expected, a higher body mass is linked with considerably higher compressive forces.

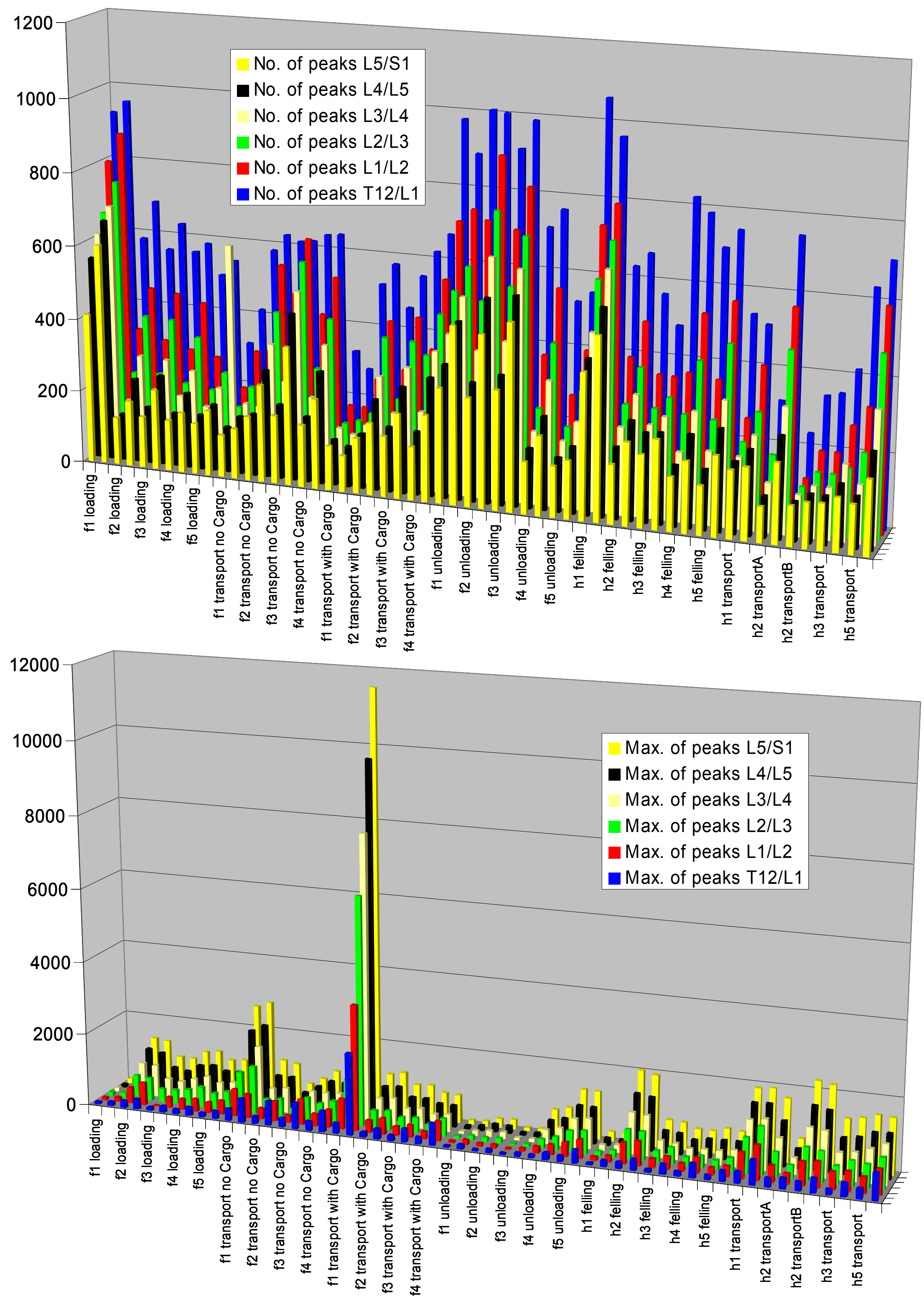
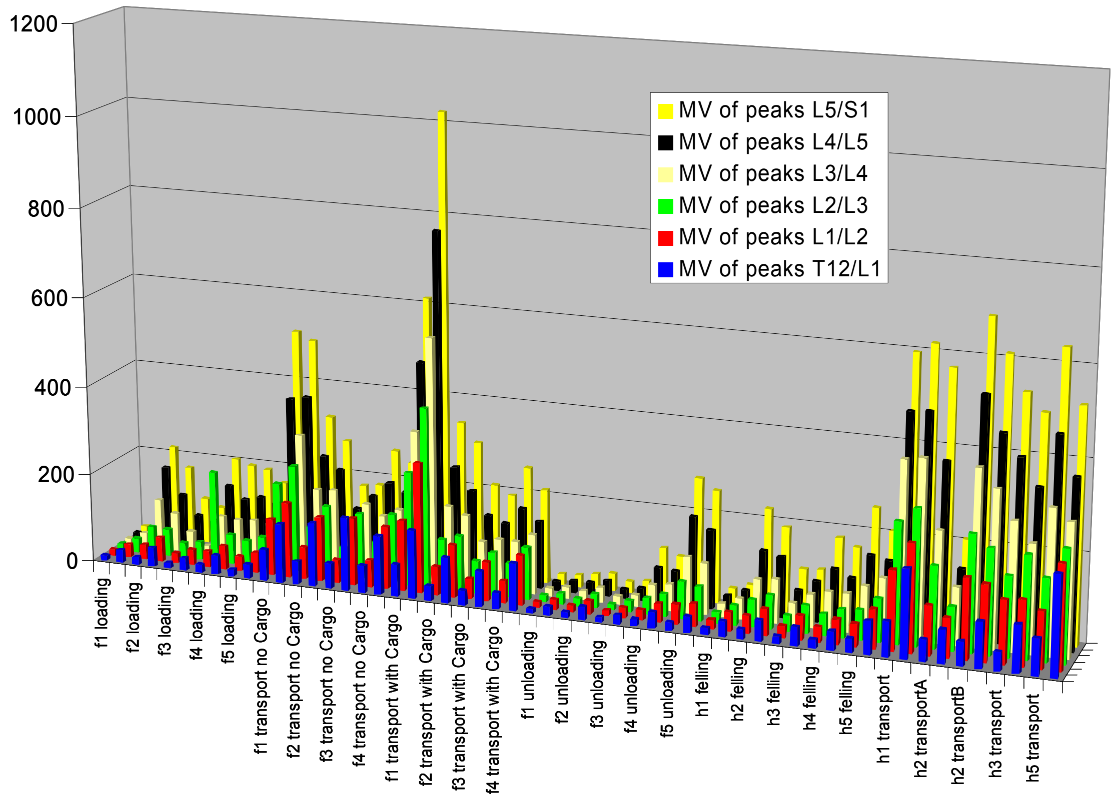


Figure 3. Number (top) and maxima (bottom)of peak-to-peak values of the compressive forces [N] calculated for different tasks of forestry machines (UMUH) and - alternately within each task - for statures p05bmi1 (left) and p95 bmi2 (right).



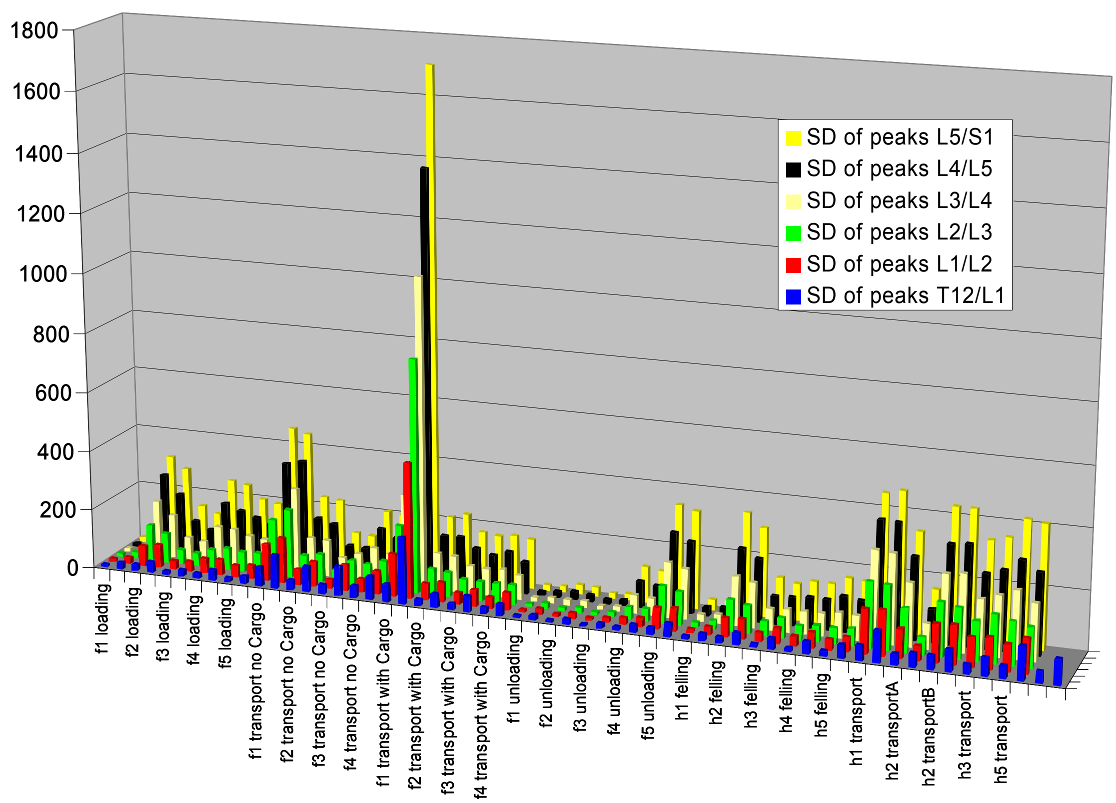


Figure 4. Mean values (top) and Standard deviations (bottom) of peak-to-peak values of the compressive forces [N] calculated for different tasks of forestry machines (UMUH) and - alternately within each task - for statures p05bmi1 (left) and p95 bmi2 (right).

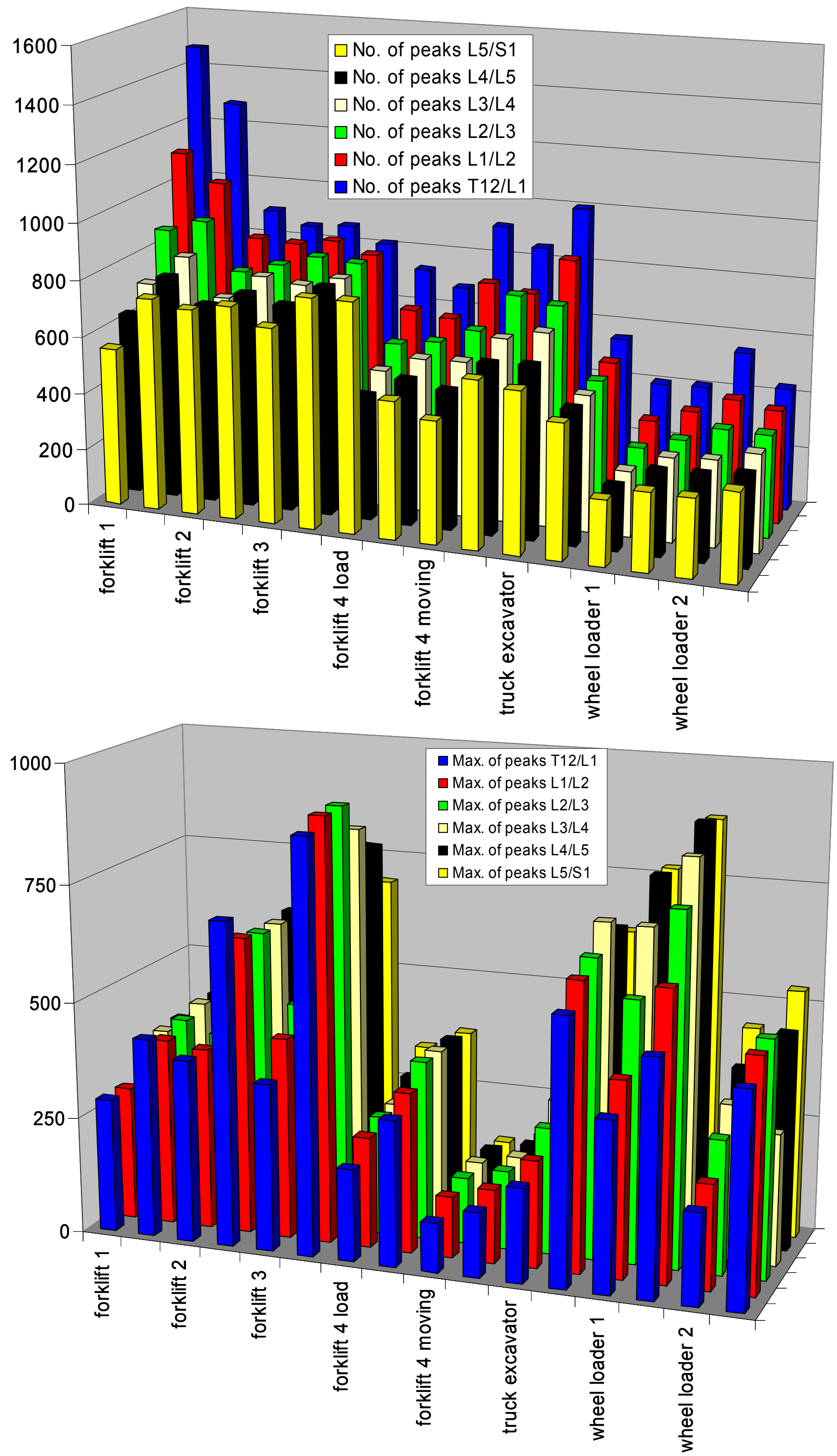
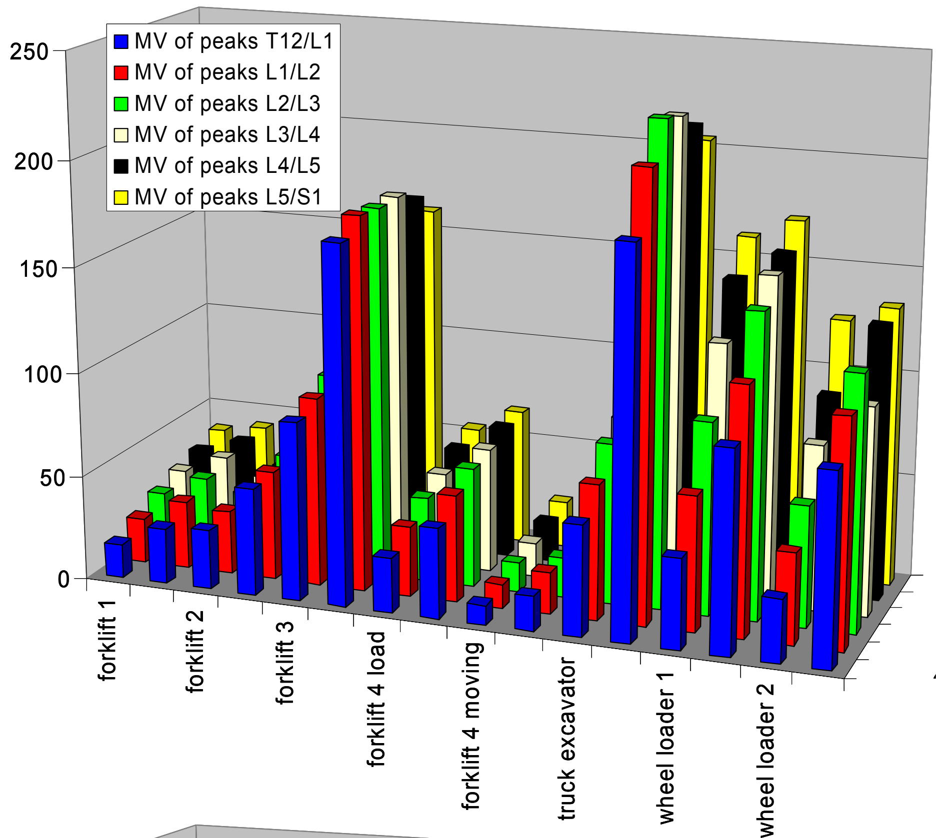


Figure 5. Number (top) and maxima (bottom) of peak-to-peak values of the compressive forces [N] calculated for fork lifts, wheel loaders and a truck excavator (Trieste), alternately within each machine for statures p05bmi1 (left) and p95 bmi2 (right).



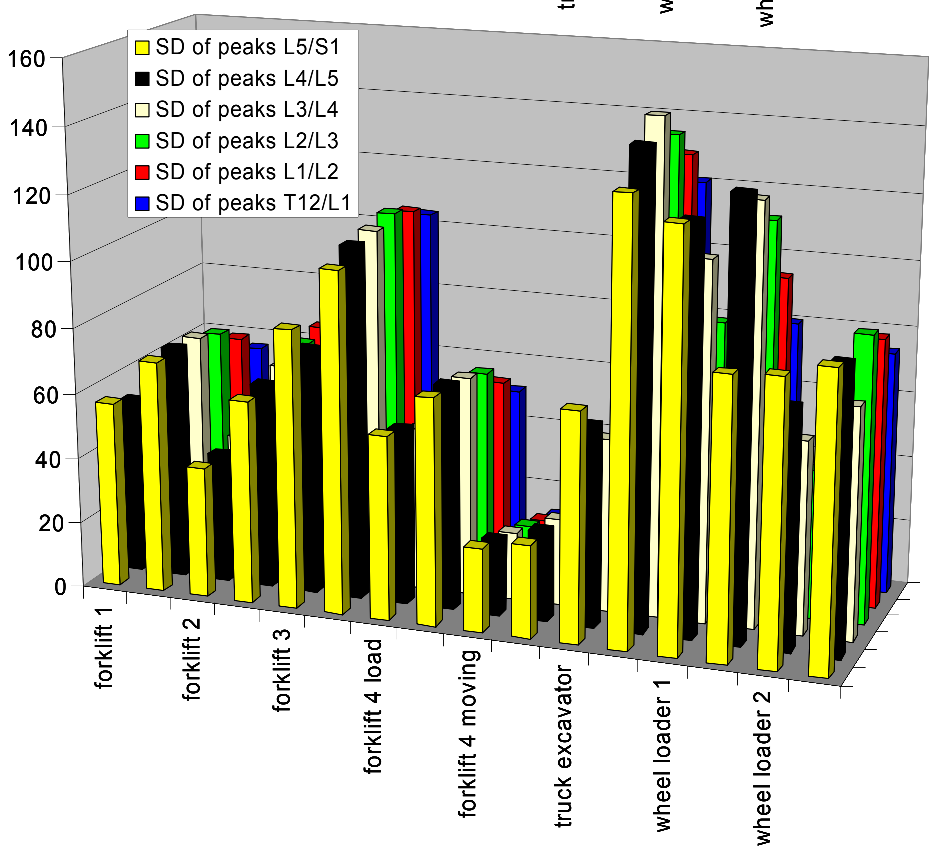


Figure 6. Mean values (top) and standard deviations (bottom) of peak-to-peak values of the compressive forces [N] calculated for fork lifts, wheel loader and a truck excavator, alternately within each machine for stature p05bmi1 (left) and p95bmi2 (right).

Table 4. Highest and lowest values of the parameters number (N), maximum (MAX), mean value (MV), and standard deviation (SD) of peak-to-peak compression values (ptpv) predicted for working tasks, posture/exposure condition, and anthropometric characteristics indicated below the numerals.

Disc level	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Highest values N	1475	1119	915	821	803	807
	FL1	FL1	FL1	FL1	FL 3	FL4 load
	p05 bmi1 mg1	p05 bmi1	p95 bmi2	p95 bmi2	p95 bmi2	p05 bmi1
Lowest values N	235	127	119	111	107	97
	h2 transportB	h2 transportB	h2 transportB	h2 transportB	h2 transportB	h2 transportA
	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1
Highest values Max	2251.83 N	3436.38 N	6273.68 N	7848.08 N	9729.03 N	11526.01 N
	f1 transport with	f1 transport with	f1 transport with	f1 transport with	f1 transport with	f1 transport with
	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2
Lowest values Max	37.8 N	25.11 N	49.53 N	64.44 N	75.57 N	92.23 N
	f2 loading	f3 loading	f3 unloading	f1 unloading	f1 loading	f3 unloading
	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1
Highest values MV	221.33 N	291.98 N	402.46 N	548.07 N	773.63 N	1023.49 N
	h5 transport	f1 transport with	f1 transport with	f1 transport with	f1 transport with	f1 transport with
	p95 bmi1	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2

Disc level	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Lowest values MV	9.35 N	11.53 N	14.18 N	15.39 N	15.76 N	19.44 N
	FL4, moving	FL4, moving	f4 moving	f1 loading	f1 loading	f1 loading
	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1
Highest values SD	223.56 N	456.32 N	784.04 N	1042.08 N	1382.69 N	1704.18 N
	f1 transport with	f1 transport with	f1 transport with	f1 transport with	f1 transport with	f1 transport with
	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2	Cargo, p95 bmi2
Lowest values SD	7.33 N	8.83 N	9.74 N	11.71 N	11.26 N	17.52 N
	f2 unloading	f3 unloading	f3 unloading	f1 transport no	f1 loading	f3 unloading
	p05 bmi1	p05 bmi1	p05 bmi1	Cargo, p95 bmi2	p05 bmi1	p05 bmi1

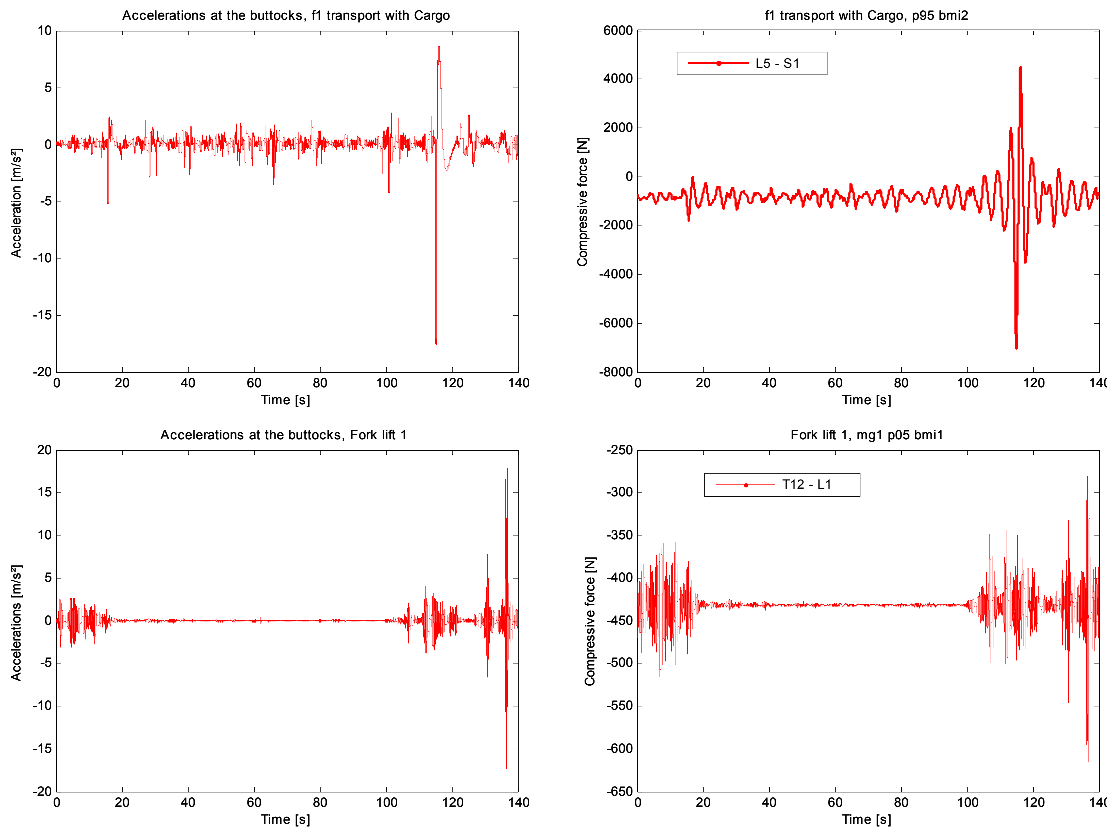


Figure 7. Input accelerations in z-axis (left) and the resulting compressive forces (sum of static and dynamic forces) with the maximum number of peak-to-peak values (bottom, right) and with the highest maximum peak-to-peak value (top, right). The insets designate the exposure condition/posture (cf. Table 3), the percentile of body mass (p), the body mass index (bmi) (cf. Annex to report on WP6, task 6.1) and the disc level.

3.2 Shear stress

Model calculations provide also the shear forces in x- and y-axis. At present, there are no reliable criteria that would enable an assessment of the health risk based on shear forces. Experimental in vitro data suggest the disc itself as the structure most vulnerable by shear forces.

3.2.1 Shear stress in x-direction

The shear forces acting on disc L5/S1 in the x-axis exemplify the possible significance of spinal stress related to posture and vibration. The static stress largely depends on the slope of the disc vs. the horizontal and the body mass located above the disc (cf. Table 1). The extent of the fore-and-aft shear force affecting the disc depends on the sign of that force. Positive shear forces (upper vertebra shifting forward) compress also the facet joints, hence, this spinal stress acts in part on the disc and partially on the facet joints. Figure 8 illustrates the large differences of predicted positive peak shear forces depending on the machine type, posture and exposure condition. The anthropometric differences have a minor effect in the selected examples.

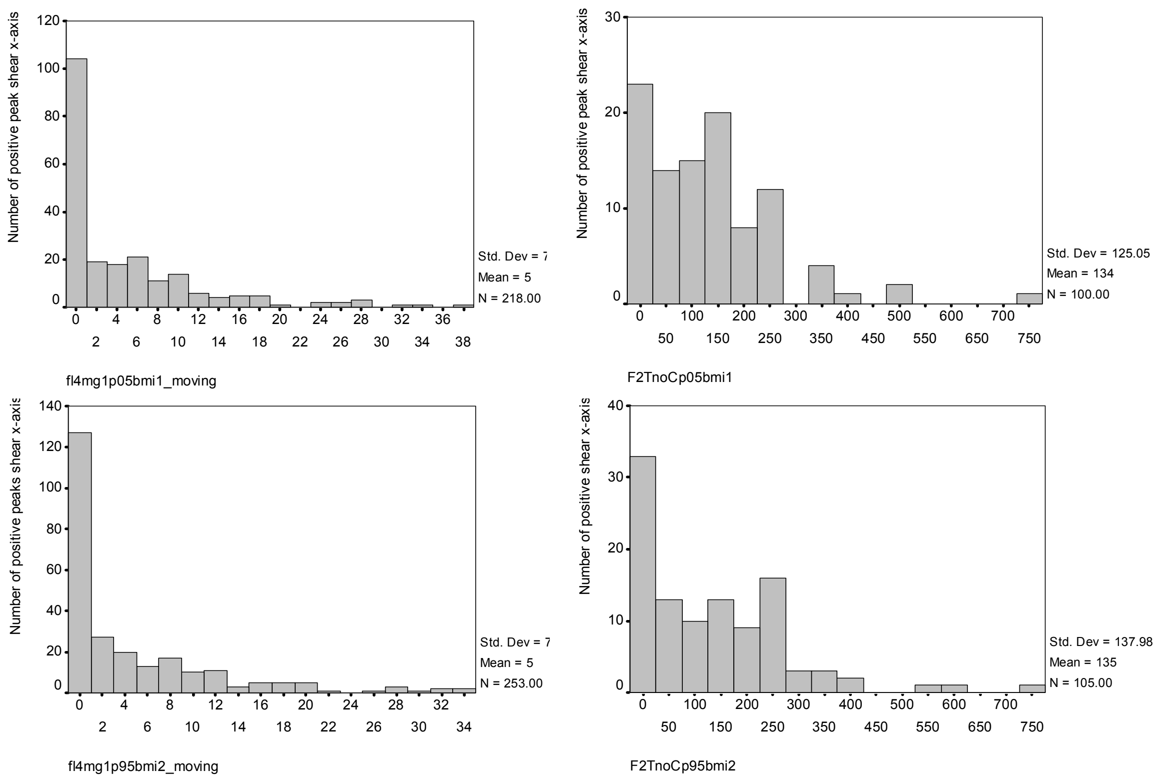


Figure 8. Histograms of peak dynamic positive (forwards) shear forces in [N] (x-axis) calculated for disc L5/S1 during exposures on forklift 4 moving paper mills (left) and on forwarder 2, transport no cargo (cf. Table 3) for a driver of the 5th percentile with a body mass index ≤ 2.61 g/cm^2 (top) (cf. Report on WP 6, Task 6.1) and driver of the 95th percentile with a body mass index > 2.61 g/cm^2 (bottom) (cf. Annex to Report on WP 6. Task 6.1)

The static shear forces in x-axis amount to 144.14 and 280.28 N for the driver (P05) of the forklift and that on the forwarder (P95) (cf. Table 1). These forces add to the dynamic peak forces shown in Figure 8, thus leading to maximum values of about 1 kN. Such loads could cause a damage to the isolated disc, but possibly not to the disc within an intact lumbar segment.

The curves in Figure 9 illustrate an example of the input acceleration and the related shear forces at six spinal levels. This condition delivered the highest positive peak values at T12/L1, the highest mean values at L5/S1, and highest standard deviation at T12/L1. A systematic examination of the parameters of the maximum values was performed, i.e. of the positive peaks of the time series of the shear forces in fore-and-aft direction, for the following parameters: the number of maximum values, the highest maximum values, the mean values and standard deviations of the positive peak shear forces were calculated.

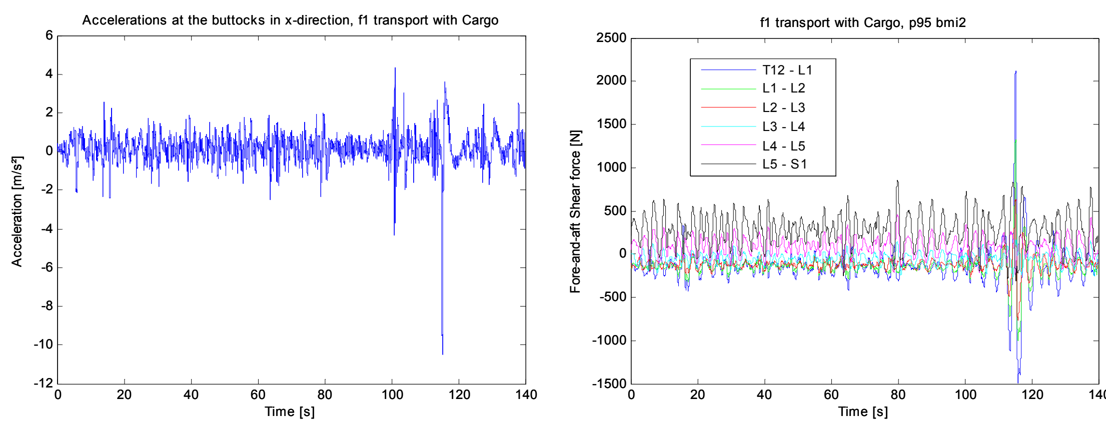
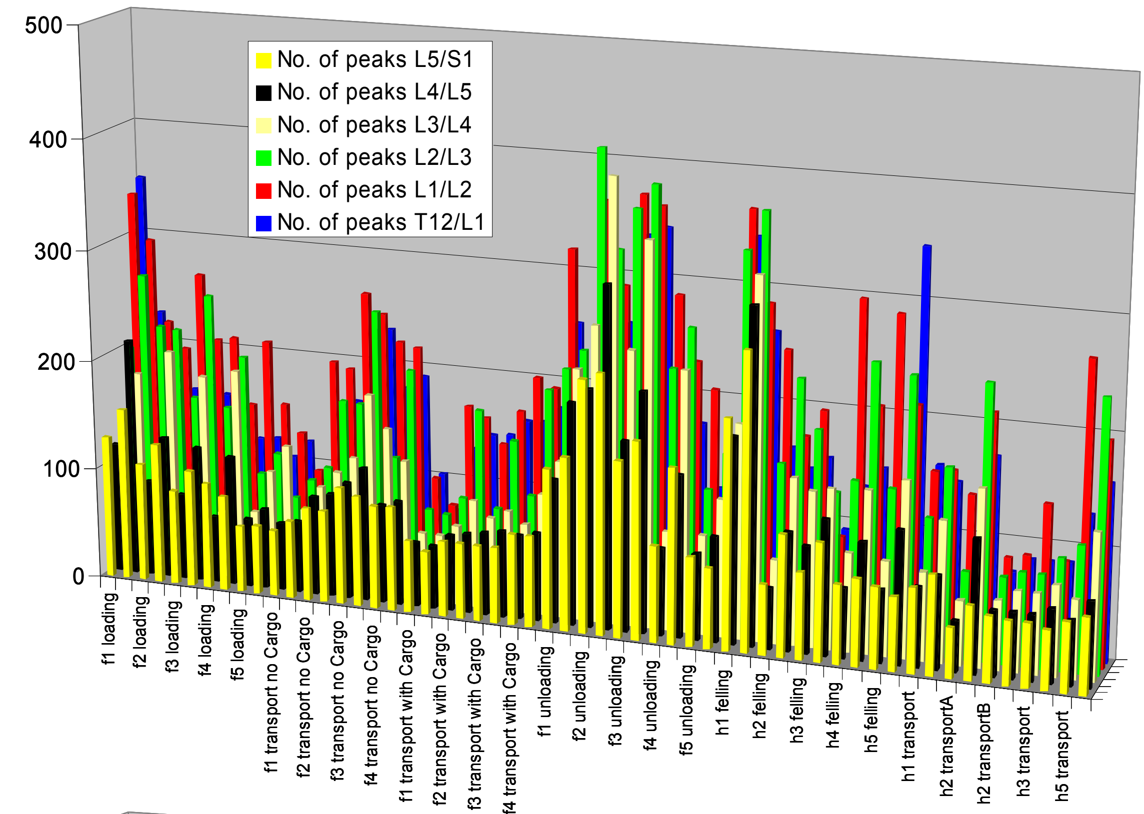


Figure 9. Input acceleration in the fore-and-aft direction measured at the seat (left) and the calculated fore-and-aft shear forces (sum of static and dynamic shares) at six spinal levels.

The results are shown in Figure 10 and Figure 11 for the data from partner UMUH and in Figure 12 and Figure 13 for the data from partner Trieste. The highest values were registered at the highest and lowest spinal level. Table 5 gives an overview about the working conditions with the highest and the smallest parameters of the positive peak values of the fore-and-aft shear forces.



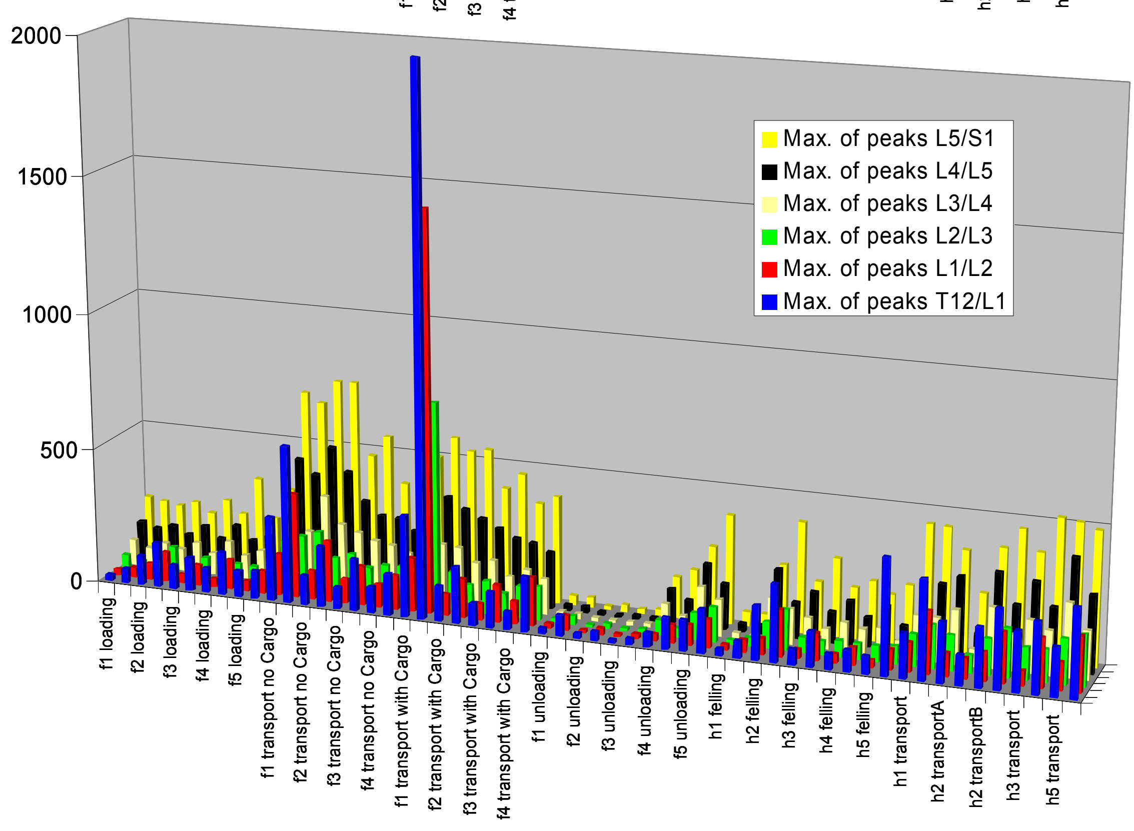
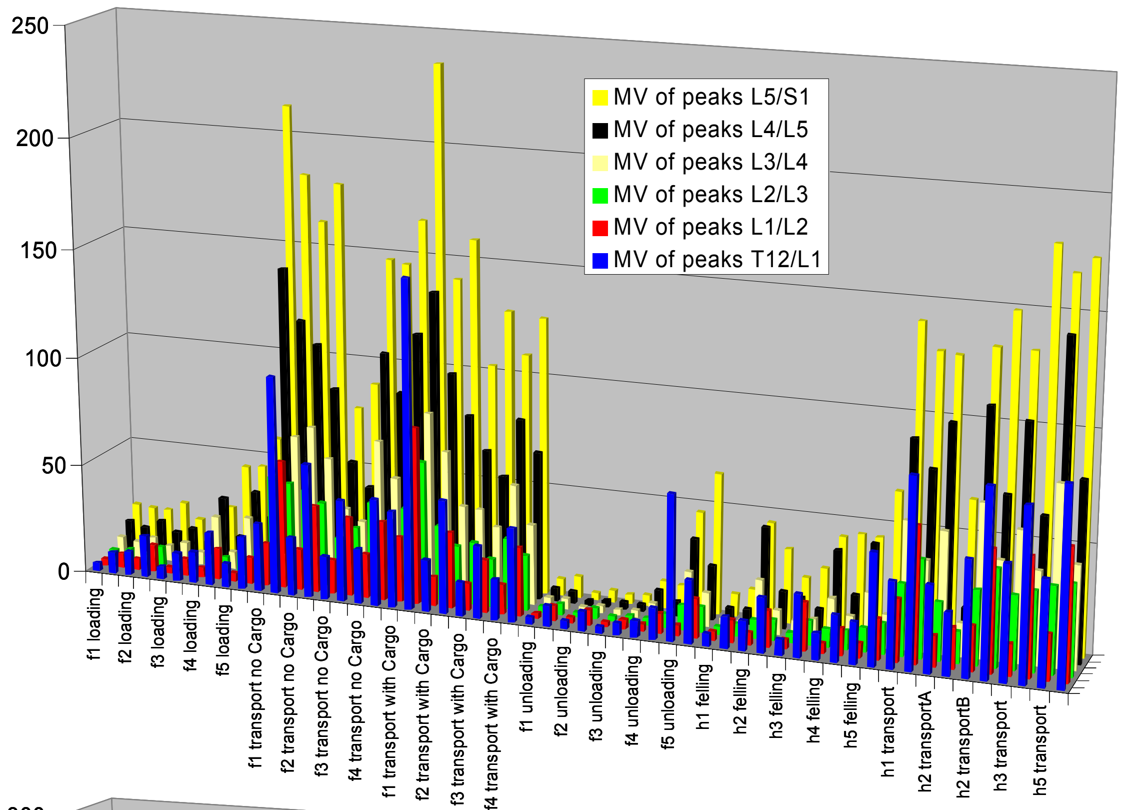


Figure 10. Number (top) and maxima (bottom) of the positive peak values of the fore-and-aft forces [N] calculated for different tasks of forestry machines (UMUH), alternately - within each task - for statures p05bmi1 (left) and p95bmi2 (right).



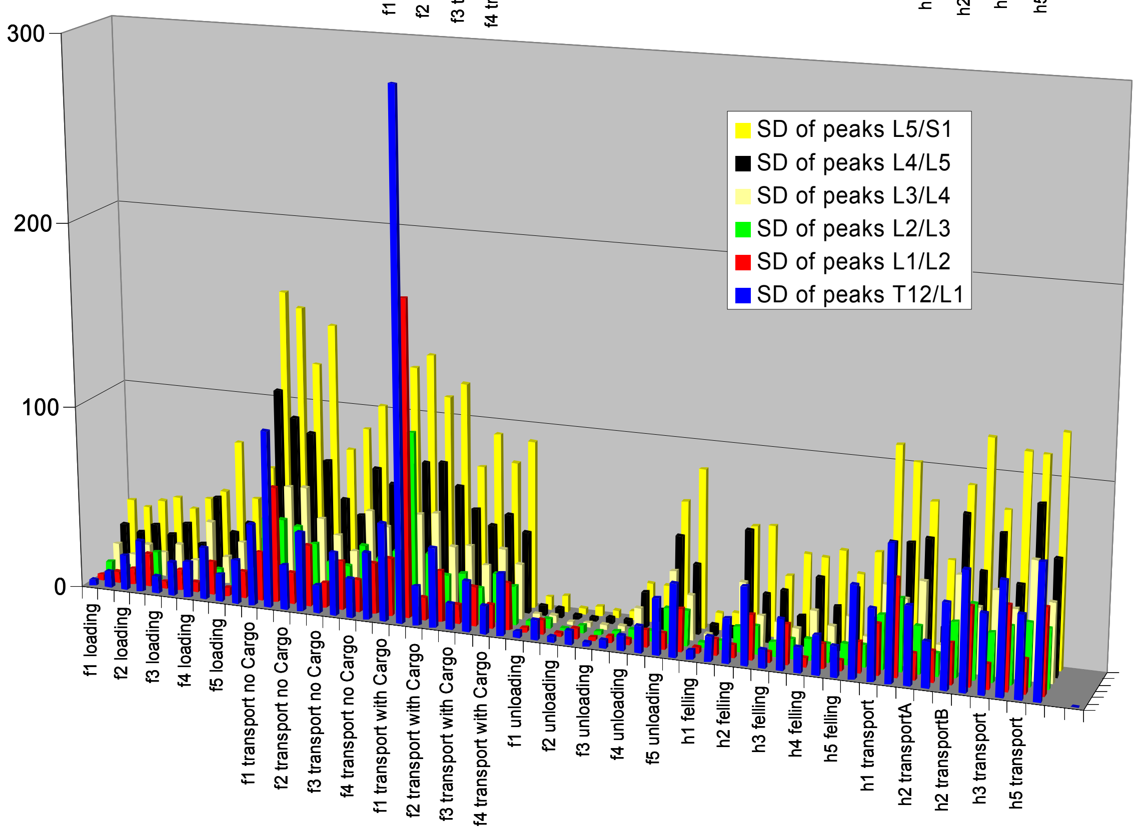
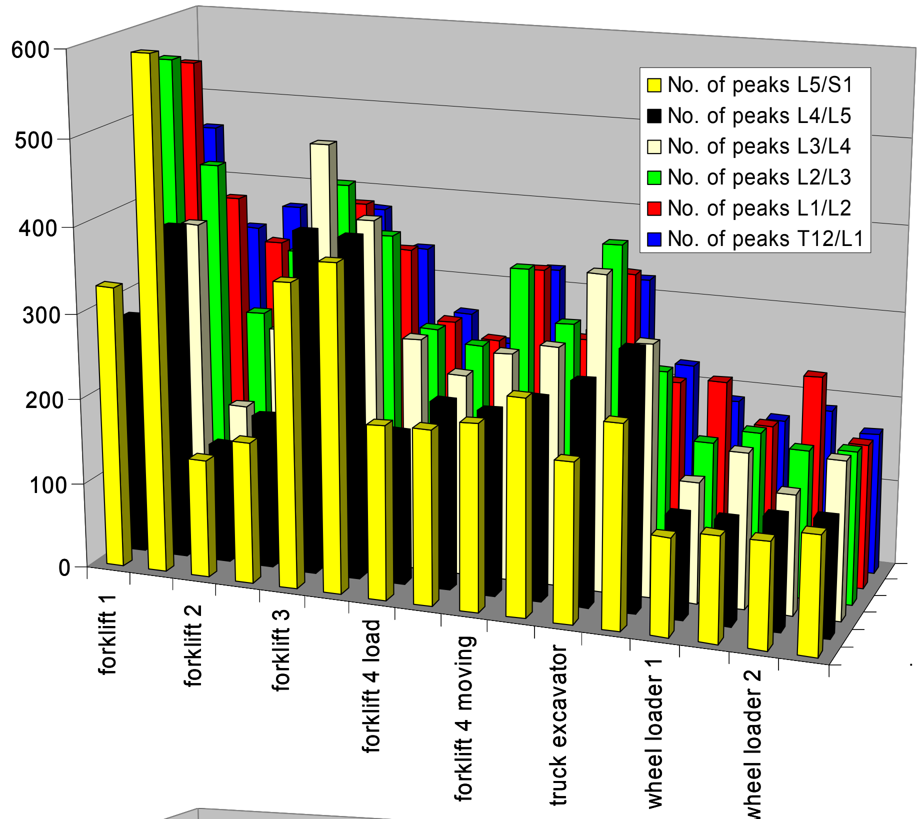


Figure 11. Mean values (top) and Standard deviations (bottom) of the positive peak values of the fore-and-aft forces [N] calculated for different tasks forestry machines (UMUH), alternately - within each task - for statures p05bmi1 (left) and p95bmi2 (right).



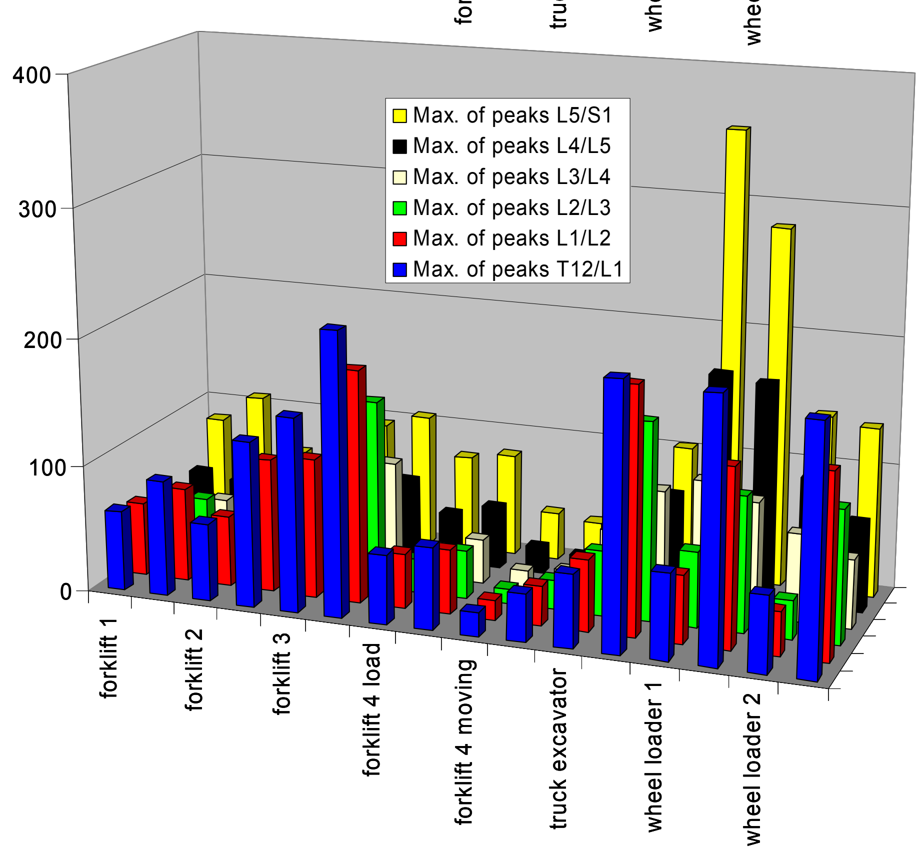


Figure 12. Number (top) and maxima (bottom) of positive peak values of the fore-and-aft shear forces [N] calculated for different tasks of fork lifts, wheel loaders and a truck excavator, alternately - within each combination of machine and task - for statures p05bmi1 (left) and p95bmi2 (right)

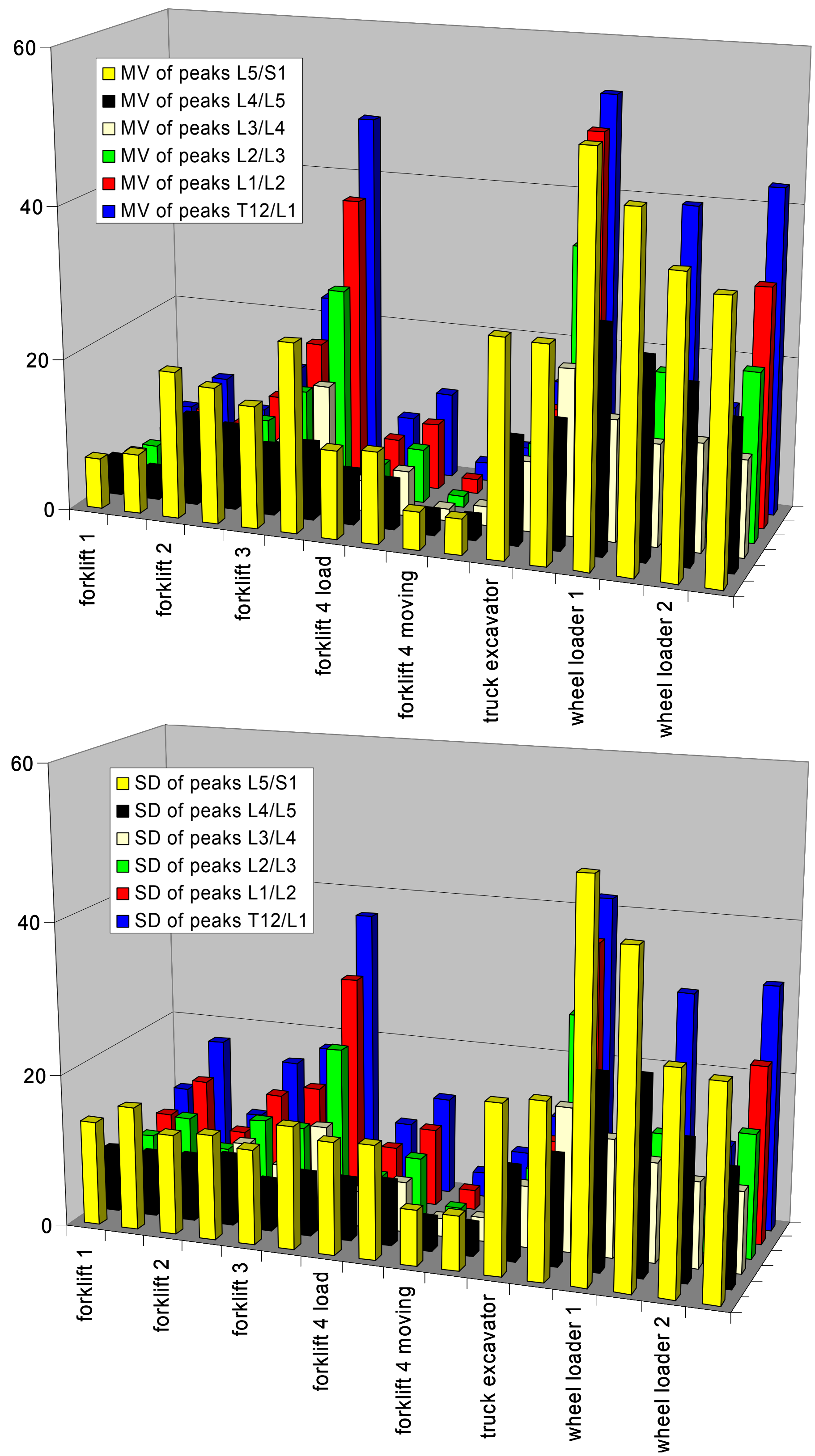


Figure 13. Mean values (top) and Standard deviations (bottom) in Newton of positive peak values of the fore-and-aft shear forces [N] calculated for different tasks of fork lifts, wheel loaders and a truck excavator, alternately for statures p05bmi1 (left) and p95bmi2 (right).

Table 5. Highest and lowest values of the parameters number (N), maximum (MAX), mean value (MV), and standard deviation (SD) of positive peak values of the predicted dynamic share of fore-and-aft shear forces for working tasks, posture/exposure condition, and anthropometric characteristics indicated below the numerals.

Shear forces fore/aft	**T12/L1**	**L1/L2**	**L2/L3**	**L3/L4**	**L4/L5**	**L5/S1**
Highest values N	461 FL1, p05, bmi1	548 FL1, p05, bmi1	562 FL1, p05, bmi1	487 FL3, p05, bmi1	399 FL3, p05, bmi1	598 FL1, P95, bmi2
Lowest values N	70 f1 transport with Cargo, p95 bmi2	80 f1 transport with Cargo, p95 bmi2	76 f1 transport with Cargo, p95 bmi2	58 h2 transport A p05 bmi1	46 h2 transport A p05 bmi1	45 h2 transport A p05 bmi1
Highest values Max	2261.30 N f1 transport with Cargo, p95 bmi2	1465.77 N f1 transport with Cargo, p95 bmi2	757.23 N f1 transport with	345.34 N Cargo, p95 bmi2 f2 transport with Cargo, p05 bmi1	510.13 N f2 transport with Cargo, p05 bmi1	740.99 N f2 transport with Cargo, p95 bmi2
Lowest values Max	11.83 f3 unloading p05 bmi1	10.33 f3 unloading p05 bmi1	8.23 f2 unloading p05 bmi1	10.37 f2 unloading p05 bmi1	9.57 f2 unloading p05 bmi1	13.97 f2 unloading p05 bmi1
Highest values MV	149.90 N f1 transport with Cargo, p95 bmi2	80.33 N f1 transport with Cargo, p95 bmi2	62.94 N f1 transport with Cargo, p95 bmi2	82.79 N f1 transport with Cargo, p95 bmi2	142.51 N h5 transport p05 bmi1	235.68 N f1 transport with Cargo, p95 bmi2

Shear forces fore/aft	**T12/L1**	**L1/L2**	**L2/L3**	**L3/L4**	**L4/L5**	**L5/S1**
Lowest values MV	2.40 N FL4 moving p05 bmi1	1.93 N FL4 moving p05 bmi1	1.46 N FL4 moving p05 bmi1	1.65 N FL4 moving p05 bmi1	2.30 N F2 unloading p05 bmi1	3.18 N F2 unloading p05 bmi1
Highest values SD	284.97 N f1 transport with Cargo, p95 bmi2	172.28 N f1 transport with Cargo, p95 bmi2	98.33 N f1 transport with Cargo, p95 bmi2	63.51 N h5 transport p05 bmi1	107.89 N f1 transport no Cargo, p05 bmi1	159.46 N f1 transport no Cargo, p05 bmi1
Lowest values SD	2.40 N f3 unloading p05 bmi1	1.99 N f3 unloading p05 bmi1	1.55 N f2 unloading p05 bmi1	1.78 N f2 unloading p05 bmi1	2.20 N f2 unloading p05 bmi1	2.96 N f2 unloading p05 bmi1

3.2.2 Shear stress in y-direction

The FE-model used is a lateral symmetric model and the interpretation of results should consider this limitation. The lateral forces reached remarkable magnitudes with peak values up to 1747 N. This extent should be a reason to consider the lateral forces, especially if they occur simultaneously with compressive and/or fore-and-aft shear forces. The curves in Figure 14 illustrate examples of the input acceleration at the buttocks and the related shear forces with the highest mean value and standard deviation of peak-to-peak values (Figure 14, top) and with the highest peak-to-peak values at six spinal levels (Figure 14, bottom). Table 6 gives an overview about the working conditions with the highest and smallest parameters of the peak-to-peak values of the lateral forces. The peak-to-peak values reached their maximum values at the spinal levels T12/L1 and L5/S1, but the lowest at L3/L4 (cf. Table 6, Figure 14).

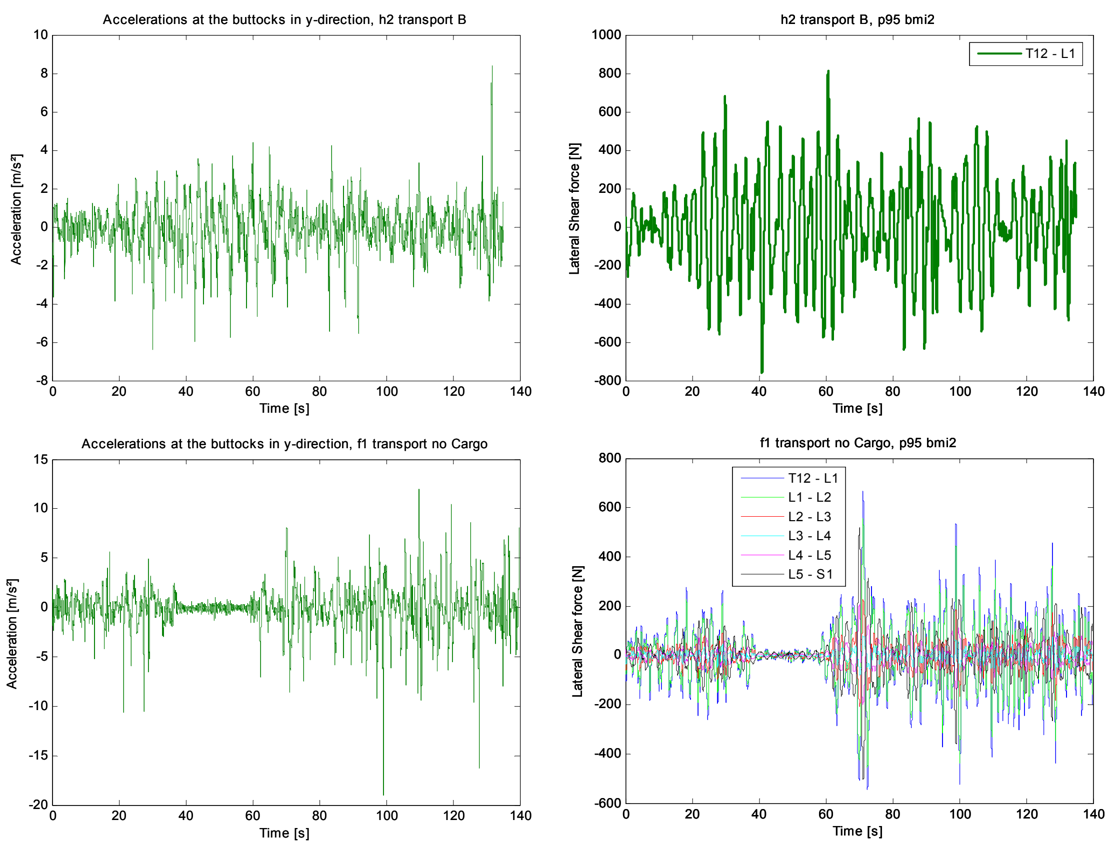
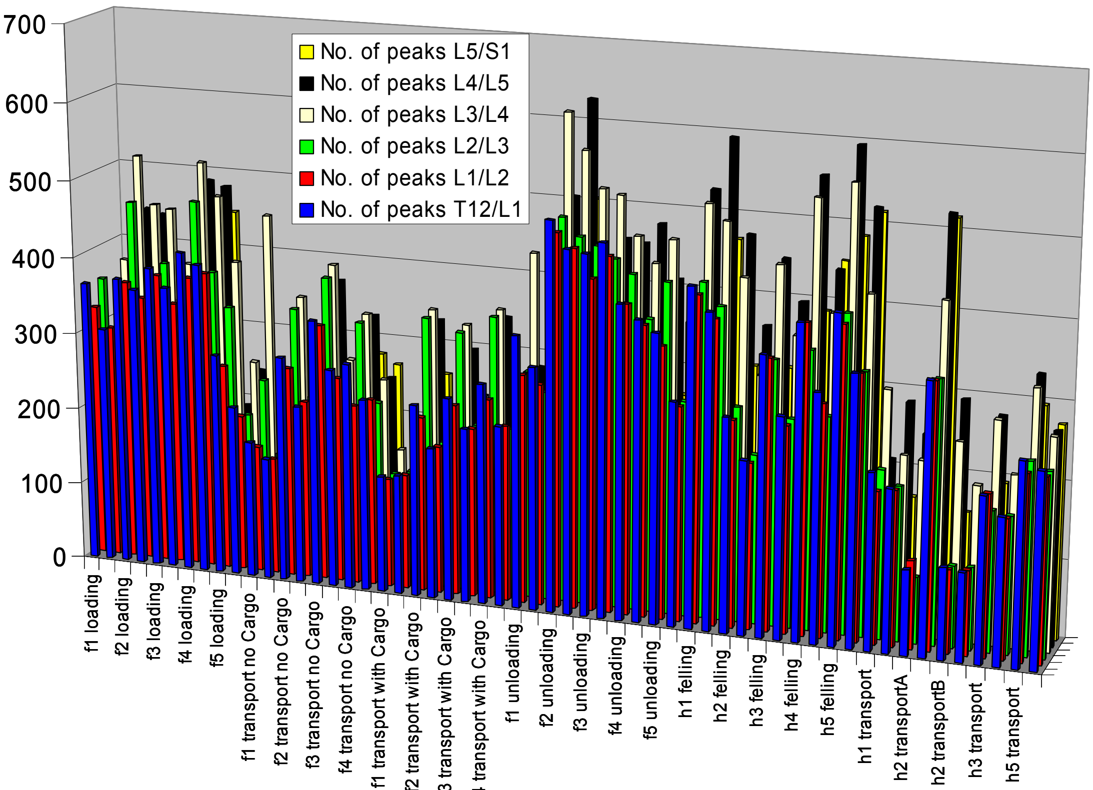


Figure 14. Input accelerations (left) and resulting lateral shear forces (right) with the highest mean value and standard deviation (top) and with the highest peak-to-peak values (bottom).

The results of the force calculations are summarized in Figure 15 and Figure 16 for the data from partner UMUH and in Figure 17 and Figure 18 for the data from partner Trieste. The forces were characterized by parameters of the peak-to-peak values in the way as for the compressive forces: number, maxima, mean values, and standard deviations.



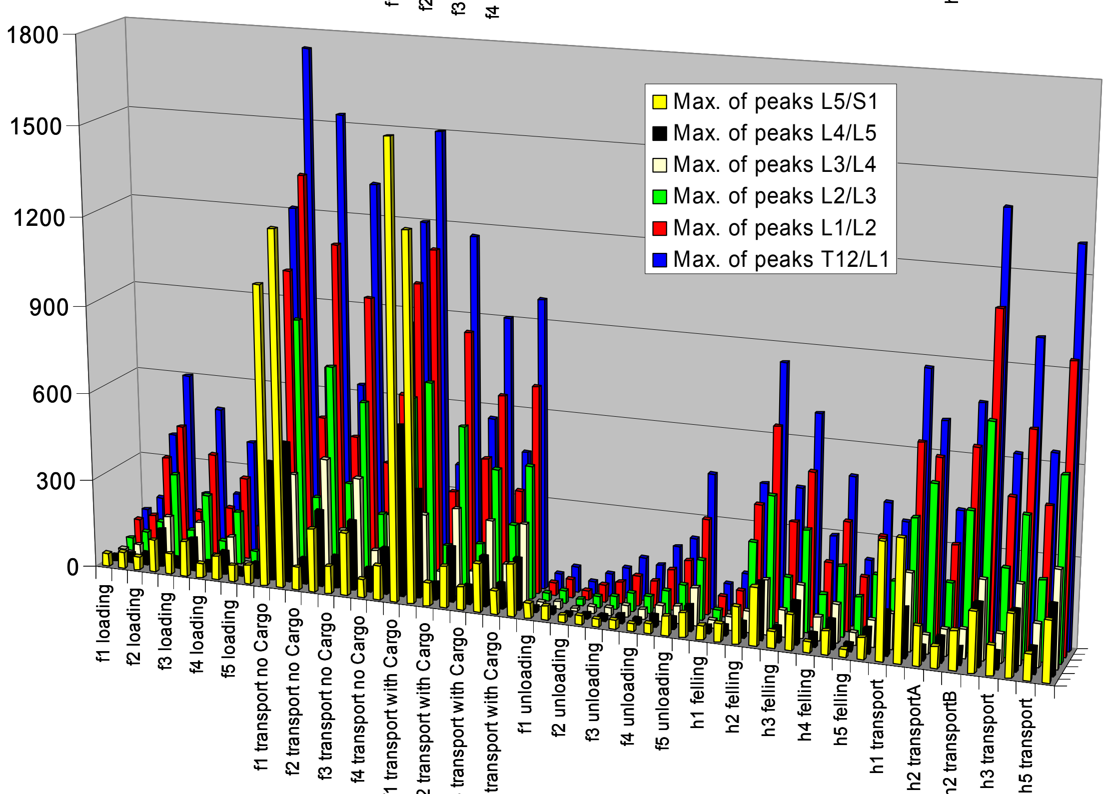
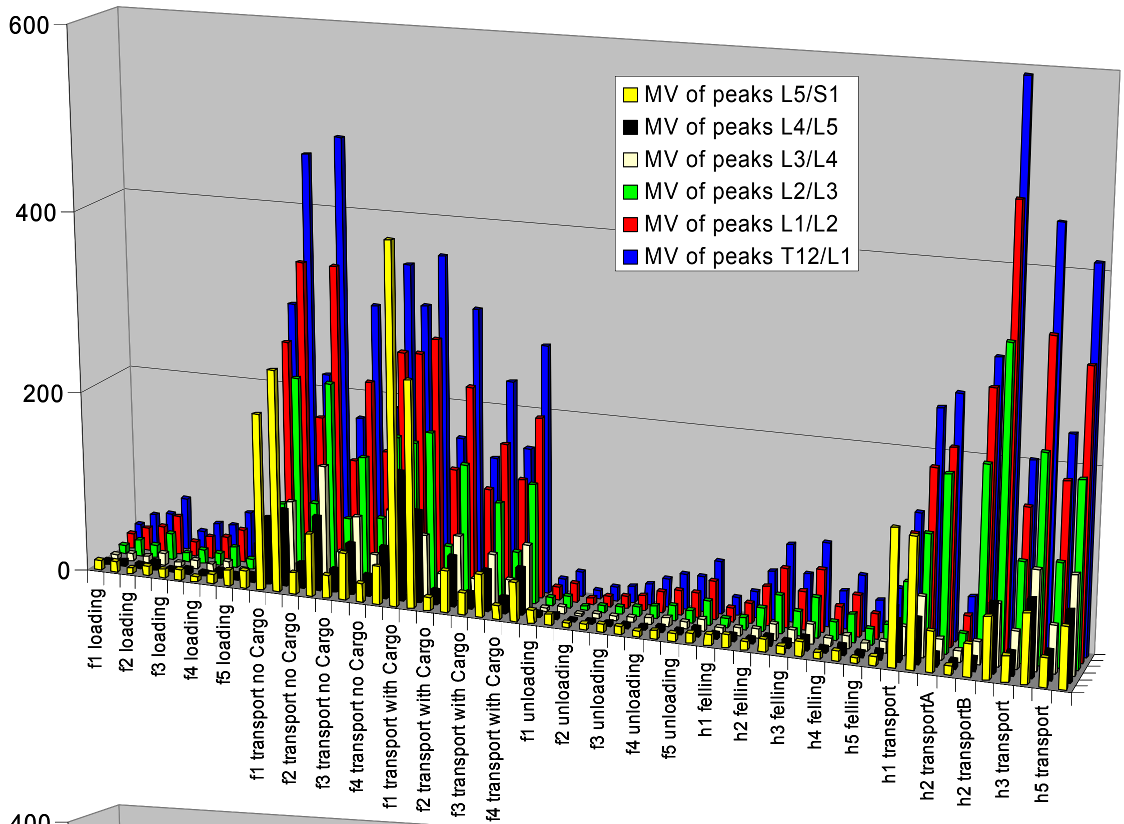


Figure 15. Number (top) and maxima (bottom) of the peak-to-peak values of the lateral shear forces [N] calculated for different tasks of forestry machines (UMUH), alternately - within each task - for statures p05bmi1 (left) and p95bmi2 (right).



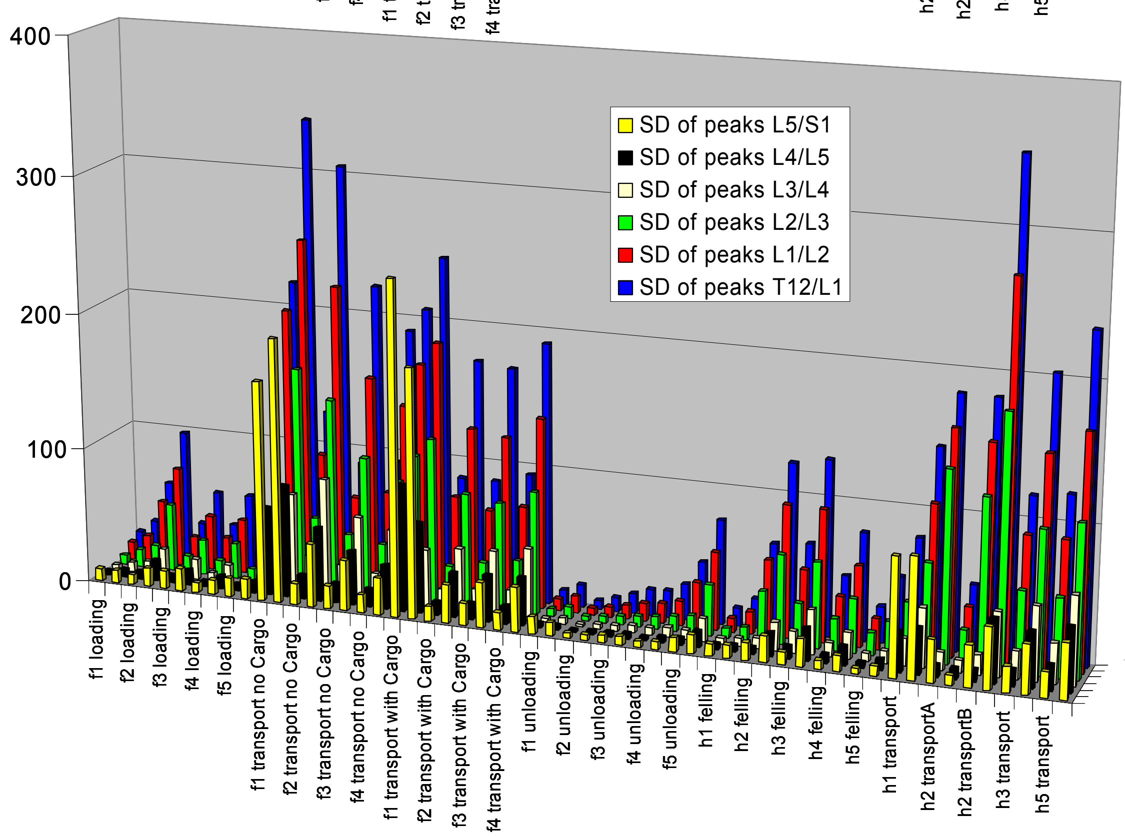
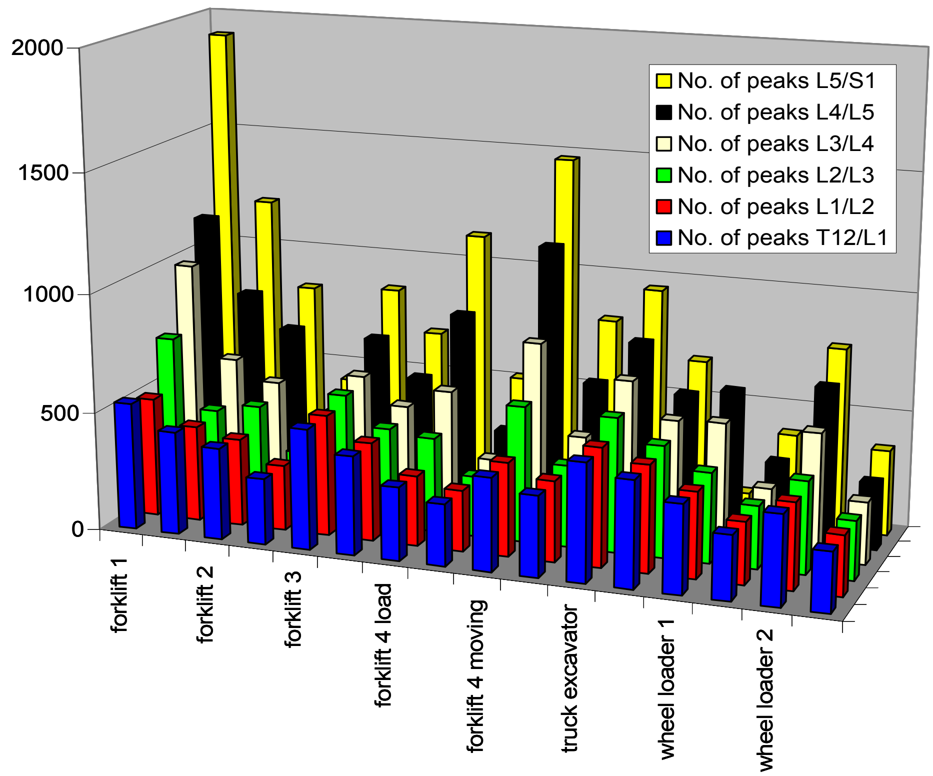


Figure 16. Mean values (top) and Standard deviations (SD, bottom) of the peak-to-peak values of the lateral shear forces [N] calculated for different tasks of forestry machines (UMUH), alternately - within each task - for statures p05bmi1 (left)and p95bmi2 (right).



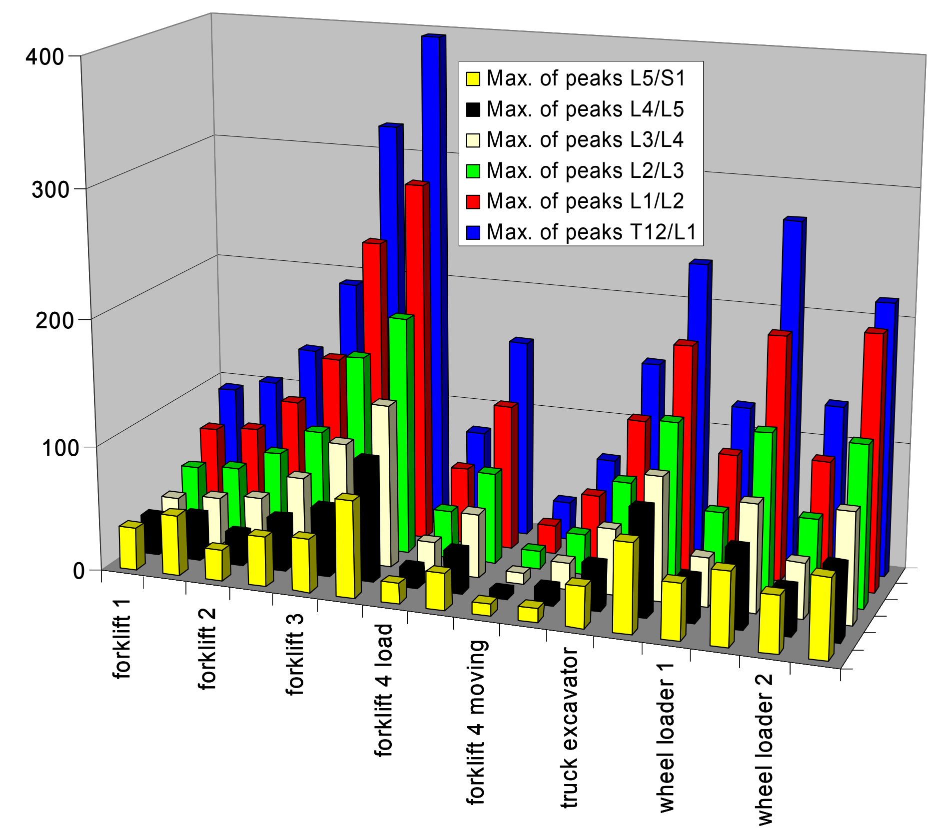
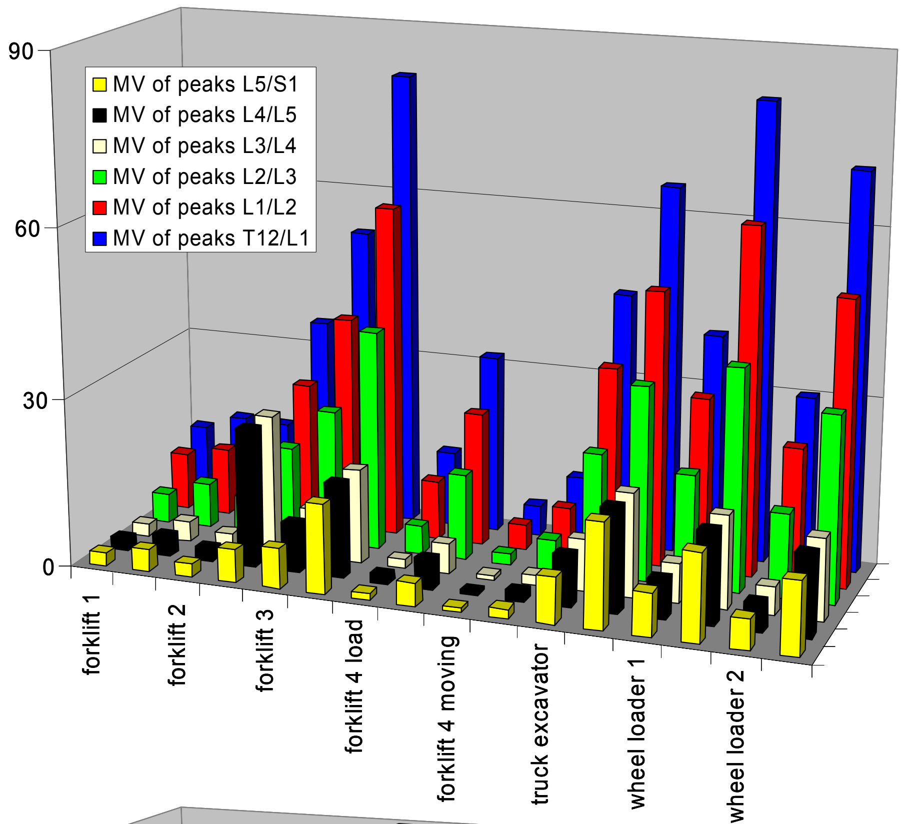


Figure 17. Number (top) and maxima (bottom) of peak-to-peak values of the lateral shear forces [N] calculated for different tasks of fork lifts, wheel loaders and a truck excavator. alternately - within each combination of machine and task - .for statures p05bmi1 (left) and p95bmi2 (right)



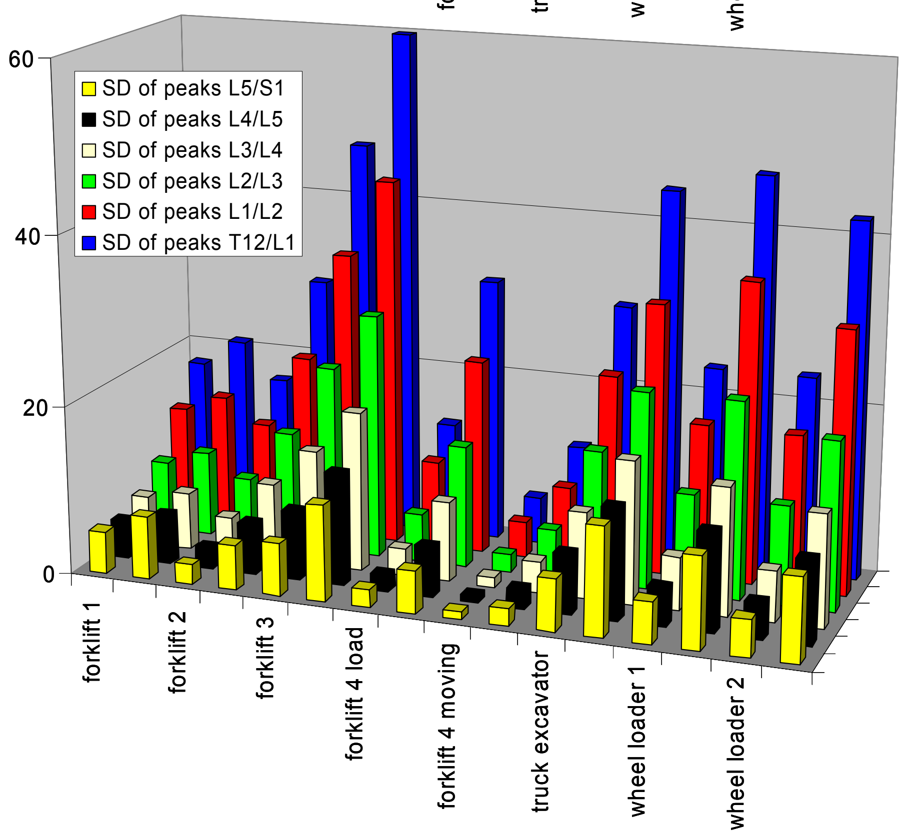


Figure 18. Mean values (top) and standard deviations (bottom) in Newton of peak-to-peak values of the lateral shear [N] calculated for different tasks of fork lifts, wheel loaders and a truck excavator, alternately - within each combination of machine and task - for statures p05bmi1 (left) and p95bmi2 (right).

Table 6. Highest and lowest values of the parameters number (N), maximum (MAX), mean value (MV), and standard deviation (SD) of positive peak values of the predicted dynamic share of lateral (y-axis) shear forces for working tasks, posture/exposure condition, and anthropometric characteristics indicated below the numerals.

Shear forces lateral	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
Highest values N	537 h2 transport A p05 bmi1	511 FL3, p05 bmi1	713 FL3, p05 bmi1	983 FL1, p05 bmi1	1145 FL1, FL4 moving p05 bmi1	1909 FL1, p05 bmi1
Lowest values N	109 FL1, p05 bmi1	107 h2 transport B p05 bmi1	85 h2 transport A p05 bmi1	128 f1 loading p05 bmi1	119 f1 transport with Cargo, p95 bmi2	101 h2 transport A p05 bmi1
Highest value Max	1742.77 N f1 transport no Cargo, p95 bmi2	1336.14 N f1 transport no Cargo, p95 bmi2	864.47 N f1 transport no Cargo, p95 bmi2	417.97 N f1 transport no Cargo, p95 bmi2	577.61 N f1 transport with Cargo, p05 bmi1	1539.64 N f1 transport with Cargo, p05 bmi1
Lowest value Max	30.20 N FL4 moving p05 bmi1	22.86 N FL4 moving p05 bmi1	13.69 N FL4 moving p05 bmi1	8.31 N FL4 moving p05 bmi1	6.82 N FL4 moving p05 bmi1	9.62 N FL4 moving p05 bmi1
Highest value MV	592.45 N h2 transport B p95 bmi2	472.47 N h2 transport B p95 bmi2	332.87 N h2 transport B p95 bmi2	132.48 N f2 transport no Cargo, p95 bmi2	142.79 N f1 transport with Cargo, p05 bmi1	396.95 N f1 transport with Cargo, p05 bmi1
Lowest value MV	5.38 N FL4 moving	4.38 N FL4 moving	1.85 N FL4 moving	0.73 N FL4 moving	0.73 N FL4 moving	0.84 N FL4 moving

Shear forces lateral	T12/L1	L1/L2	L2/L3	L3/L4	L4/L5	L5/S1
	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1	p05 bmi1
Highest value SD	350.79 N h2 transport B p95 bmi2	271.26 N h2 transport B p95 bmi2	181.97 N h2 transport B p95 bmi2	86.64 N f2 transport no Cargo, p95 bmi2	93.37 N f1 transport with Cargo, p05 bmi1	245.31 N f1 transport with Cargo, p05 bmi1
Lowest value SD	5.41 N FL4 moving p05 bmi1	4.20 N FL4 moving p05 bmi1	2.08 N FL4 moving p05 bmi1	1.21 N FL4 moving p05 bmi1	0.81 N FL4 moving p05 bmi1	0.90 N FL4 moving p05 bmi1

3.3 Combined compressive and fore-and-aft shear stress

The high fore-and-aft shear forces predicted for several exposure conditions should be considered in the future as an important possible damaging mechanism for the disc and the facet joints. The risk will be higher, if peak shear forces coincide with a reduced compression (below the static compression value) which causes a reduced stability of the lumbar spine. Figure 19 shows X-Y-plots of shear and compressive forces acting on two different lumbar levels during two segments of vibration exposure. Due to the nearly horizontal orientation of the disc L3/L4, shear forces are small (Figure 19, top). At L5/S1 considerably higher forces are predicted (Figure 19, bottom). There occur combinations of high positive shear forces between 800 and 1000 N with a remarkable decompression of the disc (200 – 400 N). At these moments, a lower stiffness of the lumbar spine can be assumed that coincides with large relative displacements, i. e. with a pronounced mechanical strain, between verrtebrae.

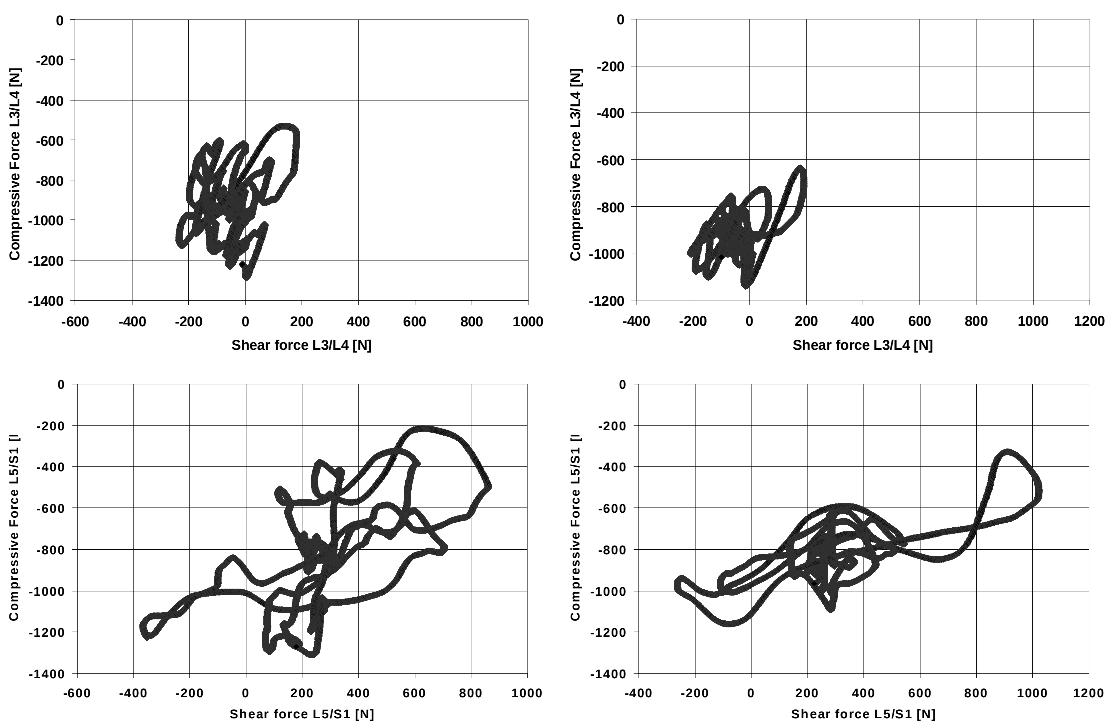


Figure 19. Bidimensional plots of predicted (driver with BMI2, body mass of P95) shear forces in x-direction and compressive forces acting on the disc L3/L4 (top) and L5/S1 (bottom) during two different segments (left and right) of the exposure "Forwarder1 Transport no Cargo" (cf. Table 3). Static and dynamic forces were summed up. Compression = negative sign, ventral shear of the upper vertebra = positive sign.

3.4 Results of risk assessment - Prediction of fatigue failure caused by repetitive compression

Calculations of the risk assessment were done with the newly developed method in order to provide suggestions concerning the comparison of different exposure conditions examined by the partners. For this purpose and a better comparison with ISO 2631-5 (2004), the following assumptions were made: age of the driver at the start of the exposure = 20 years, total duration of exposure = 45 years, days of exposure per year = 240, exposure duration per day = 14,400 s (4 hours), duration of measurement = 140 s (exceptions: H2transportA 110 s, H2transportB 135 s), area A of the endplates at the disc level L5/S1 = 16 cm^2. The static compressive forces due to posture were taken from Table 1. Generally, the regression Equation 2 was used for the prediction of ultimate strength covering 50 percent of the population. The lumbar level L4/L5 was selected considering the clinical relevance of degenerative changes at this spinal unit. In order to get an impression with respect to the significance of personal characteristics, the assessments of drivers belonging to the 5^{th} percentile of body mass with a BMI ≤ 2.61 g/cm^2) and of the 95^{th} percentile of body mass with a BMI > 2.61 g/cm^2 (cf. Annex to report on WP6, Task 6.1) were calculated for all exposure conditions. Table 7 shows the resulting risk factors R together with the A(8)-value and the factor R, the latter according to ISO 2631-5 calculated with the same time series after downsampling to 160 Hz and with the same assumptions concerning daily exposure time, age and total duration of exposure.

Additionally, calculations for the 50^{th} percentile of body mass with BMI ≤ 2.61 g/cm^2 and BMI > 2.61 g/cm^2 were performed for selected conditions and Swedish (cf. Table 8) and Italian machines (cf. Table 9) in order to provide hints for the interpretation of the epidemiologic studies, to compare these results with an assessment according to ISO 2631-1 (997), ISO 26331-5 (2004), and to get a feeling for further modifications of the input to risk assessment. The comparison of Table 9 with Table 10 illustrates the effect of reducing the ultimate strength in order to cover 95 instead of 50 percent of the general population. The Risk factors according to the FIOSH-approach rise sharply, thus indicating a health risk in a certain small portion of the exposed drivers at nearly all exposure conditions (Table 10), whereas a health risk is predicted in a larger portion of drivers for exceptional conditions only, if a normal average ultimate strength is assumed (Table 9).

Table 7 Risk assessment for the disc level L4/L5 at different exposure conditions (File name) after 45 years of exposure (between 20 and 65 years of age), 240 days per year. R - Risk factor according to FIOSH-approach, S_{ed} – daily compression dose according to FIOSH approach; P05 and P95 – for a driver with a body mass of the 5th and 95th percentile, respectively; bmi1 - body mass index ≤ 2.61224, bmi2 - body mass index > 2.61224. A(8) – daily exposure value in ms^{-2} r.m.s. according to Directive 2002/44/EC, R (ISO 2631-5) – factor calculated according to ISO 2631-5.

File name	R (p05 bmi1)	S_{ed} (p05 bmi)	R (p95 bmi2)	$S_{ed(}$ p95 bmi2)	A(8) (ISO 2631)	R (ISO 2631-5)
F1loading	0.1677	0.1048	0.3014	0.1646	0.2123	0.4200
F1transportNoCargo	2.1086	1.3184	2.5614	1.3988	1.3786	1.8924
F1transportWithCargo	8.9674	5.6071	11.1110	6.0678	1.0821	1.6597
F1unLoading	0.1383	0.0865	0.2178	0.1189	0.1414	0.2587
F2loading	1.3862	0.8668	1.4538	0.7939	0.2920	0.3925
F2transportNoCargo	1.4037	0.8777	1.7614	0.9619	1.0654	1.0785
F2transportWithCargo	1.1150	0.6972	1.3871	0.7575	0.6092	0.5487
F2unLoading	0.2351	0.1470	0.2729	0.1490	0.1585	0.2745
F3loading	0.7833	0.4897	0.8928	0.4875	0.1928	0.4420
F3transportNoCargo	0.7010	0.4383	1.2216	0.6671	0.9040	1.0372
F3transportWithCargo	0.8531	0.5334	1.0997	0.6006	0.6029	0.6459
F3unLoading	0.1020	0.0638	0.1744	0.0953	0.1703	0.3650
F4loading	1.0781	0.6741	1.3189	0.7203	0.2804	0.4010
F4transportNoCargo	1.0820	0.6766	1.6700	0.9120	0.9172	0.9207
F4transportWithCargo	0.8174	0.5110	1.1479	0.6278	0.7376	0.8464
F4unLoading	0.5931	0.3708	0.7521	0.4107	0.2112	0.3543
F5loading	0.9259	0.5790	0.9879	0.5395	0.1895	0.2694

File name	R (p05 bmi1)	S_{ed} (p05 bmi)	R (p95 bmi2)	$S_{ed(}$ p95 bmi2)	A(8) (ISO 2631)	R (ISO 2631-5)
F5unLoading	0.5599	0.3501	0.6945	0.3793	0.2329	0.3950
H1felling	0.2501	0.1530	0.3267	0.1678	0.2190	0.3446
H1transport	2.2359	1.3674	2.6169	1.3444	0.8477	0.8653
H2felling	1.7195	1.0516	1.8904	0.9712	0.2817	0.5982
H2transportA	1.6804	1.0277	2.0935	1.0755	0.6435	0.6106
H2transportB	2.0758	1.2696	2.4459	1.2566	0.6873	0.6525
H3felling	0.7129	0.4360	0.8932	0.4589	0.3715	0.4756
H3transport	1.4436	0.8829	1.7878	0.9185	0.6966	0.5468
H4felling	0.6604	0.4039	0.9477	0.4869	0.3179	0.4101
H5felling	0.6822	0.4172	0.8536	0.4386	0.3236	0.4596
H5transport	1.8346	1.1220	2.3349	1.1996	1.1570	1.0648
FL1	0.4161	0.2558	0.6402	0.3339	0.3794	0.9034
FL2	0.4237	0.2605	0.8222	0.4288	0.3298	0.7627
FL3	0.6975	0.4289	1.1565	0.6032	0.6298	1.2872
FL4 load	0.3719	0.2287	0.5885	0.3070	0.1632	0.2597
FL4 mov	0.1703	0.1047	0.2465	0.1286	0.0798	0.1556
TE1	0.5162	0.3009	1.3586	0.6084	0.4876	0.7923
WL1	0.9003	0.5421	1.2773	0.6286	0.2999	0.6953
WL2	0.4987	0.3003	0.7809	0.3843	0.2410	0.4296

Table 8. Risks assessment for the disc level L4/L5 at different (Swedish) exposure conditions after 45 years of exposure (between 20 and 65 years of age), 240 days per year, 4 hours per day. The forces were calculated by the model ‘Forwarder’. R – Risk factor FIOSH-approach, S_{ed} – daily compression dose according to FIOSH approach; bmi1 – body mass index ≤ 2.61224 [g/cm^2], bmi2 - body mass index > 2.61224 [g/cm^2], p50, – the 50th percentile of body mass; A(8) – daily exposure value in ms^{-2} r.m.s. according to the Directive 2002/44/EC, F ISO – factor calculated according to ISO 2631-5.

Type of machine	Working task, input accelerations	R p50 bmi1	S_{ed} (P50 bmi1)	R (p50 bmi2)	S_{ed} (p50 bmi2)	A (8) [ms^{-2}]	F ISO
Forwarder 2	Loading	1.3833	0.8395	1.4679	0.8615	0.2920	0.3925
Forwarder 2	Transport no Cargo	1.3606	0.8257	1.5407	0.9042	1.0654	1.0785
Forwarder 2	Transport with Cargo	1.1592	0.7035	1.2316	0.7228	0.6092	0.5487
Forwarder 2	Unloading	0.2373	0.1440	0.2501	0.1468	0.1585	0.2745
Forwarder 3	Loading	0.7763	0.4711	0.8488	0.4981	0.1928	0.4420
Forwarder 3	Transport no Cargo	0.8149	0.4946	0.9262	0.5435	0.9040	1.0372
Forwarder 3	Transport with Cargo	0.8602	0.5221	0.9377	0.5503	0.6029	0.6459
Forwarder 3	Unloading	0.1140	0.0692	0.1294	0.0759	0.1703	0.3650

Table 9. Risks assessment for the disc level L4/L5 at different (Italian) exposure conditions after 45 years of exposure (between 20 and 65 years of age), 240 days per year, 4 hours per day. R – Risk factor FIOSH-approach; bmi1 – body mass index ≤ 2.61224 [g/cm^2], bmi2 - body mass index > 2.61224 [g/cm^2], p05, p50, p95 – the 5th, 50th, 95th percentile of body mass; A(8) – daily exposure value in ms^{-2} r.m.s. according to the Directive 2002/44/EC, F ISO – factor calculated according to ISO 2631-5.

Model/ posture	Type of machine	File of input accelerations	Working task	Company, location	R p05 bmi1	R p50 bmi1	R p50 bmi2	R p95 bmi2	A (8) [ms^{-2}]	F ISO
Group 1	Forklift 1	p_1.asc	Transportation of stone blocks in the port area	Carrara port, Carrara	0.42	0.46	0.51	0.64	0.38	0.90
	Forklift 2	pts_02.asc	Transportation steel blocks	Trieste Port	0.42	0.55	0.624	0.82	0.33	0.76
	Forklift 3	via_l05	Marble slides loading – transportation	Marble Laboratory Bacci Pietrasanta LU	0.70	0.72	0.89	1.16	0.63	1.29
	Forklift 4	pml_03_load	Paper boxes loading	Paper mills, Cartiera Kappa Ania Paper – Ponte all'Ania (LU)	0.37	0.43	0.50	0.595	0.16	0.26

Model/ posture	Type of machine	File of input accelerations	Working task	Company, location	R p05 bmi1	R p50 bmi1	R p50 bmi2	R p95 bmi2	A (8) [ms^{-2}]	F ISO
	Forklift 4	pml_03_mov	Paper boxes transportation	Paper mills, Cartiera Kappa Ania Paper – Ponte all'Ania (LU)	0.17	0.18	0.21	0.25	0.08	0.16
Group 2	Wheel loader 1	c_5.asc	Marble blocks moving	Marble quarrie "Coop cavatori di Gioia", Carrara	0.90	0.63	0.72	1.28	0.30	0.70
	Wheel loader 2	via_c01.asc	Excavation wastes transporta-tion (soil and stones): quarry roads	Marble quarrie "Piastriccioni" – Stazzema, LU	0.50	0.52	0.59	0.78	0.24	0.43
Group 3	Truck excavator	c_3.asc	Marble block excavation, marble bank dejection	Marble quarrie "Coop cavatori di Gioia", Carrara	0.52	0.60	0.78	1.36	0.49	0.79

Table 10. Risks assessment for the disc level L4/L5 at different (Italian) exposure conditions after 45 years of exposure (between 20 and 65 years of age), 240 days per year. The ultimate strength was reduced to cover 95 percent of the population. R – Risk factor FIOSH-approach; bmi1 – body mass index ≤ 2.61224 [g/cm^2], bmi2 - body mass index > 2.61224 [g/cm^2], p05, p50, p95 – the 5th, 50th, 95th percentile of body mass; A(8) – daily exposure value in ms^{-2} r.m.s. according to the Directive 2002/44/EC, F ISO – factor calculated according to ISO 2631-5.

Model/ posture	Type of machine	File of input accelerations	Working task	Company, location	R p05 bmi1	R p50 bmi1	R p50 bmi2	R p95 bmi2	A (8) [ms^{-2}]	F ISO
Group 1	Forklift 1	p_1.asc	Transportation of stone blocks in the port area	Carrara port, Carrara	1.22	1.49	1.90	3.71	0.38	0.90
	Forklift 2	pts_02.asc	Transportation steel blocks	Trieste Port	1.24	1.77	2.29	4.77	0.33	0.76
	Forklift 3	via_l05	Marble slides loading – transportation	Marble Laboratory Bacci Pietrasanta LU	2.04	2.32	3.31	6.70	0.63	1.29
	Forklift 4	pml_03_load	Paper boxes loading	Paper mills, Cartiera Kappa Ania Paper – Ponte all'Ania (LU)	1.09	1.40	1.84	3.41	0.16	0.26

Model/ posture	Type of machine	File of input accelerations	Working task	Company, location	R p05 bmi1	R p50 bmi1	R p50 bmi2	R p95 bmi2	A (8) [ms^{-2}]	F ISO
	Forklift 4	pml_03_mov	Paper boxes transportation	Paper mills, Cartiera Kappa Ania Paper – Ponte all'Ania (LU)	0.50	0.60	0.78	1.43	0.08	0.16
Group 2	Wheel loader 1	c_5.asc	Marble blocks moving	Marble quarrie "Coop cavatori di Gioia", Carrara	2.78	2.25	3.10	13.14	0.30	0.69
	Wheel loader 2	via_c01.asc	Excavation wastes transporta-tion (soil and stones): quarry roads	Marble quarrie "Piastriccioni" – Stazzema, LU	1.54	1.86	2.54	8.03	0.24	0.43
Group 3	Truck excavator	c_3.asc	Marble block excavation, marble bank dejection	Marble quarrie "Coop cavatori di Gioia", Carrara	1.76	2.55	4.87	82.04	0.49	0.79

Further comparisons are conceivable, e.g., in order to estimate the consequences of a variable endplate area and/or the risks predicted for other disc levels. A higher body mass caused predominantly higher risk estimates. Since a larger endplate area with increasing body length cannot be excluded, the assumption of the same area for the low BMI and 5th percentile of body mass may have caused an underestimation, and for the high BMI and 95th percentile of body mass an overestimation of the risk. Contradictory results were published with respect to the correlation between body height and disc or endplate area. Turk and Celan (2004) reported a positive correlation with the size of the disc area, Pöpplau (2006) could not detect any correlation with the size of the endplate area.

Figure 20 - Figure 22 illustrate the input accelerations at the buttocks and associated time series of spinal forces for some selected exposure conditions.

According to ISO 2631-1 (1997) the weighted rms values a_w were calculated in the three directions of the input accelerations measured at the seat surfaces, the accelerations in the horizontal directions with the weighting curve w_d and k=1.4, the accelerations in z-direction with the weighting curve w_k and k=1 (cf.

Table 11). Considering an assessment period of 8 hours, the energy-equivaluent value A(8) was determined for the direction with the highest vibration level (e.g., for 'F1 transport with cargo' – y-direction, for 'H2 transport B ' - y-direction, for 'FL3' (Forklift 3) – z-direction, for the 'TE1' (Truck excavator 1) – z-direction, and for 'WL2' (Wheel loader 2) – y-direction) assuming a daily exposure time of 4 hours for each condition. Based on the ISO 2631-1 (1997) a health risk is likely to occur for seven conditions with a_w-values exceeding the upper limit of the health guidance caution zone. According to the EC Directive 2002/44/EC (2002) the daily exposure limit value standardized to an eight-hour reference period equals 1.15 ms^{-2} rms. Of all exposure conditions tested, only the conditions in files 'F1transportNoCargo' and 'H5transport' exceed this limit value under the assumptions made. The input accelerations of the truck excavator and the wheel loader did not exceed the daily action value of 0.5 ms^{-2} rms. The risk assessments by the FIOSH-approach indicate a certain health risk for considerably more conditions. R-factors are slightly higher for the personal characteristic bmi2. The results of the D_k-values and factors R (ISO 2631-5) for all conditions under the same assumptions as described above are given in Table 12. According to ISO 2631-5 R < 0.8 indicates a low probability of health effect, R > 1.2 indicates a high probability.

Table 11. Characterisation of the input accelerations (in ms^{-2}) measured at the seat cushion and given as daily exposure A(8) (cf. DIRECTIVE 2002/44/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 June 2002) expressed as equivalent continuous acceleration over an eight-hour period, calculated as the highest (rms) value of awx, or awy, or awz; awx – w_d-weighted and multiplied by 1.4 acceleration in x-direction, awy - w_d-weighted and multiplied by 1.4 acceleration in y-direction, awz - w_k-weighted acceleration in z-direction (F – forwarder, H – harvester, FL – forklift, TE – truck excavator, WL – whell loader).

File name	A(8)	rms awx [ms^{-2}]	rms awy [ms^{-2}]	rms awz [ms^{-2}]
F1loading	0.2123	0.1857	0.3003	0.1801
F1transportNoCargo	1.3786	0.5622	1.9497	0.5100
F1transportWithCargo	1.0821	0.6428	1.5303	0.5234
F1unLoading	0.1414	0.1346	0.1999	0.1423
F2loading	0.2920	0.2460	0.4129	0.2070
F2transportNoCargo	1.0654	0.8137	1.5067	0.5454
F2transportWithCargo	0.6092	0.5935	0.8615	0.3233
F2unLoading	0.1585	0.1329	0.2241	0.1520
F3loading	0.1928	0.2060	0.2727	0.1267
F3transportNoCargo	0.9040	0.6141	1.2785	0.5614
F3transportWithCargo	0.6029	0.4369	0.8526	0.2741
F3unLoading	0.1703	0.1626	0.2409	0.1269
F4loading	0.2804	0.2430	0.3965	0.1998
F4transportNoCargo	0.9172	0.7563	1.2971	0.6316
F4transportWithCargo	0.7376	0.4395	1.0431	0.4191
F4unLoading	0.2112	0.1935	0.2987	0.1897
F5loading	0.1895	0.2680	0.2140	0.1321
F5unLoading	0.2329	0.3185	0.3293	0.1669
H1felling	0.2190	0.3097	0.2800	0.2277
H1transport	0.8477	0.7900	1.1988	0.5648
H2felling	0.2817	0.3638	0.3984	0.2514

File name	A(8)	rms awx [ms^{-2}]	rms awy [ms^{-2}]	rms awz [ms^{-2}]
H2transportA	0.6435	0.6605	0.9100	0.3698
H2transportB	0.6873	0.5685	0.9720	0.2592
H3felling	0.3715	0.3095	0.5254	0.1615
H3transport	0.6966	0.6033	0.9852	0.2759
H4felling	0.3179	0.3683	0.4496	0.2265
H5felling	0.3236	0.4577	0.3729	0.3287
H5transport	1.1570	0.8274	1.6363	0.8761
FL1	0.3794	0.2613	0.2831	0.5365
FL2	0.3298	0.3039	0.1960	0.4664
FL3	0.6298	0.6843	0.7782	0.8907
FL4 load	0.1632	0.1780	0.1462	0.2308
FL4 mov	0.0798	0.0740	0.0691	0.1128
TE1	0.4876	0.5913	0.6739	0.6896
WL1	0.2999	0.4241	0.3983	0.3395
WL2	0.2410	0.3257	0.3408	0.2718

Table 12. R-factors at different exposure conditions (File name) after 45 years of exposure (between 20 and 65 years of age), 240 days per year, 4 hours per day, and D_k-values according to ISO 2631-5 for the input accelerations measured at the seat cushion (F – forwarder, H – harvester, FL – forklift, TE – truck excavator, WL – wheel loader).

File name	R	D_{kx}	D_{ky}	D_{kz}
F1loading	0.4200	2.5164	5.5200	1.1955
F1transportNoCargo	1.8924	5.4208	18.3034	15.2377
F1transportWithCargo	1.6597	11.0347	15.5849	10.9311
F1unLoading	0.2587	2.2551	2.7167	1.1390
F2loading	0.3925	3.3322	4.5207	1.3330
F2transportNoCargo	1.0785	8.0522	11.1454	5.5771
F2transportWithCargo	0.5487	4.8286	6.2788	1.8278
F2unLoading	0.2745	1.8428	3.3129	0.9945
F3loading	0.4420	2.6275	3.6287	3.6287
F3transportNoCargo	1.0372	6.7199	12.1997	4.2225
F3transportWithCargo	0.6459	4.5349	7.5399	2.5283
F3unLoading	0.3650	2.5582	4.7435	0.9039
F4loading	0.4010	2.6506	4.8542	1.4580
F4transportNoCargo	0.9207	7.2543	9.5289	4.5677
F4transportWithCargo	0.8464	3.8362	9.6970	4.5008
F4unLoading	0.3543	2.7854	4.0495	1.3411
F5loading	0.2694	3.0097	2.5864	1.1418
F5unLoading	0.3950	3.3982	4.1622	1.7447
H1felling	0.3446	4.0242	3.1087	1.5962
H1transport	0.8653	7.1258	10.0378	2.9643

File name	R	D_{kx}	D_{ky}	D_{kz}
H2felling	0.5982	3.9989	6.9351	2.4876
H2transportA	0.6106	5.0423	6.4464	2.7815
H2transportB	0.6525	4.3199	8.2331	2.0029
H3felling	0.4756	3.9352	5.8794	1.2244
H3transport	0.5468	4.5760	6.4133	1.7629
H4felling	0.4101	3.5048	4.4371	1.6956
H5felling	0.4596	4.7120	4.4300	2.1252
H5transport	1.0648	5.7397	11.5836	5.9075
FL1	0.9034	4.1169	3.6920	12.0754
FL2	0.7627	3.8495	3.2018	9.9282
FL3	1.2872	8.7746	12.8624	7.5279
FL4 load	0.2597	2.6757	1.4149	2.3850
FL4 mov	0.1556	1.5045	0.9940	1.3159
TE1	0.7923	5.5145	8.3832	4.0707
WL1	0.6953	7.7801	3.7822	6.1049
WL2	0.4296	4.1903	3.5777	2.7036

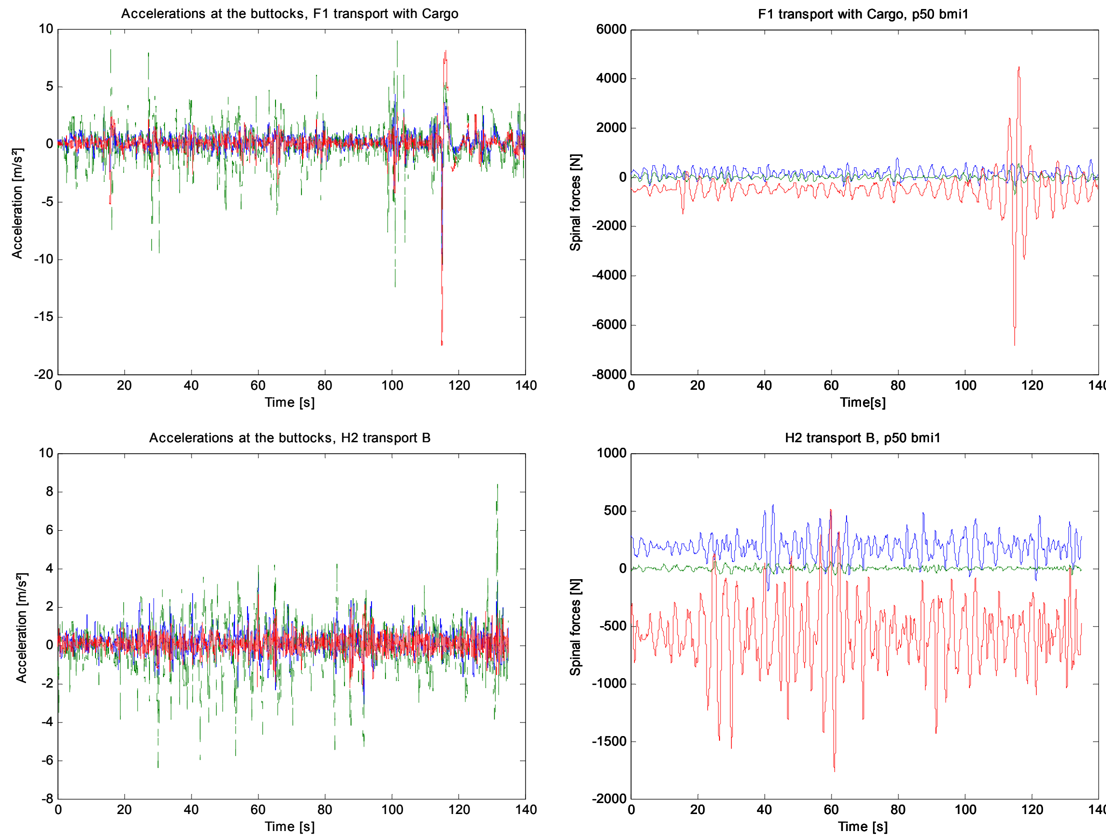


Figure 20. Input accelerations (left) and spinal forces (right, calculated for the 50th percentile and BMI1)) for the condition 'Forwarder 1 transport with Cargo' (top) and 'Harvester 5 transport B' (bottom) for a duration of 140 (blue- x-direction, green – y-direction, red – z-direction).

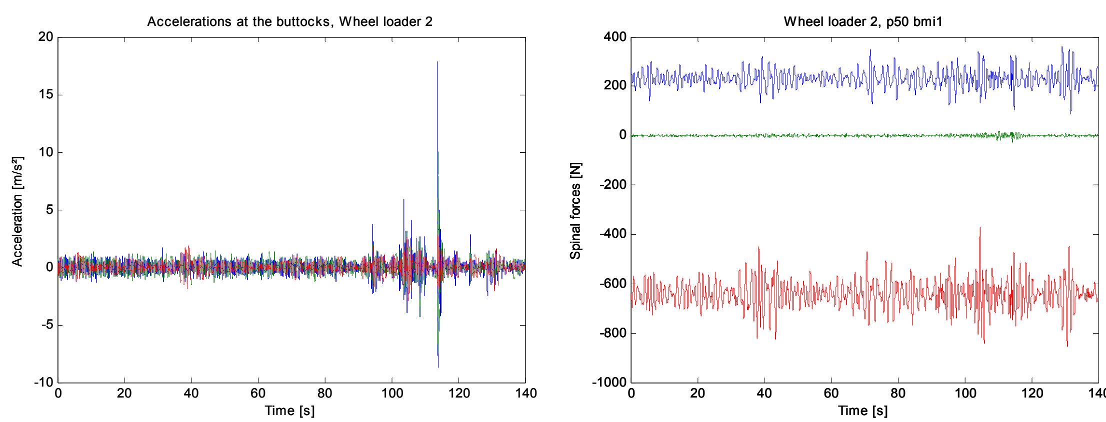


Figure 21. Input accelerations (left) and spinal forces (right, calculated for the 50th percentile and BMI1)) for the condition 'Wheel loader 2' for a duration of 140 (blue- x-direction, green – y-direction, red – z-direction).

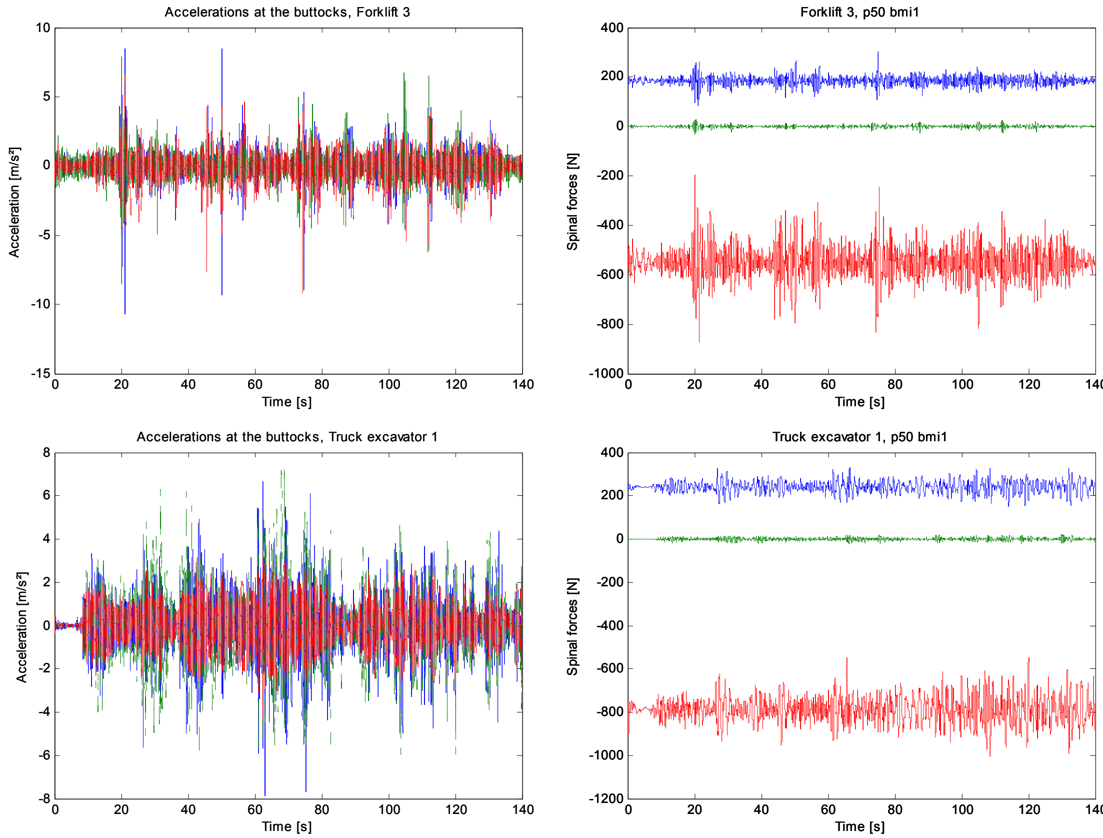


Figure 22. Input accelerations (left) and spinal forces (right, calculated for the 50th percentile and BMI1) for the condition 'Forklift 3' (top) and 'Truck excavator' (bottom) for a duration of 140 (blue- x-direction, green – y-direction, red – z-direction).

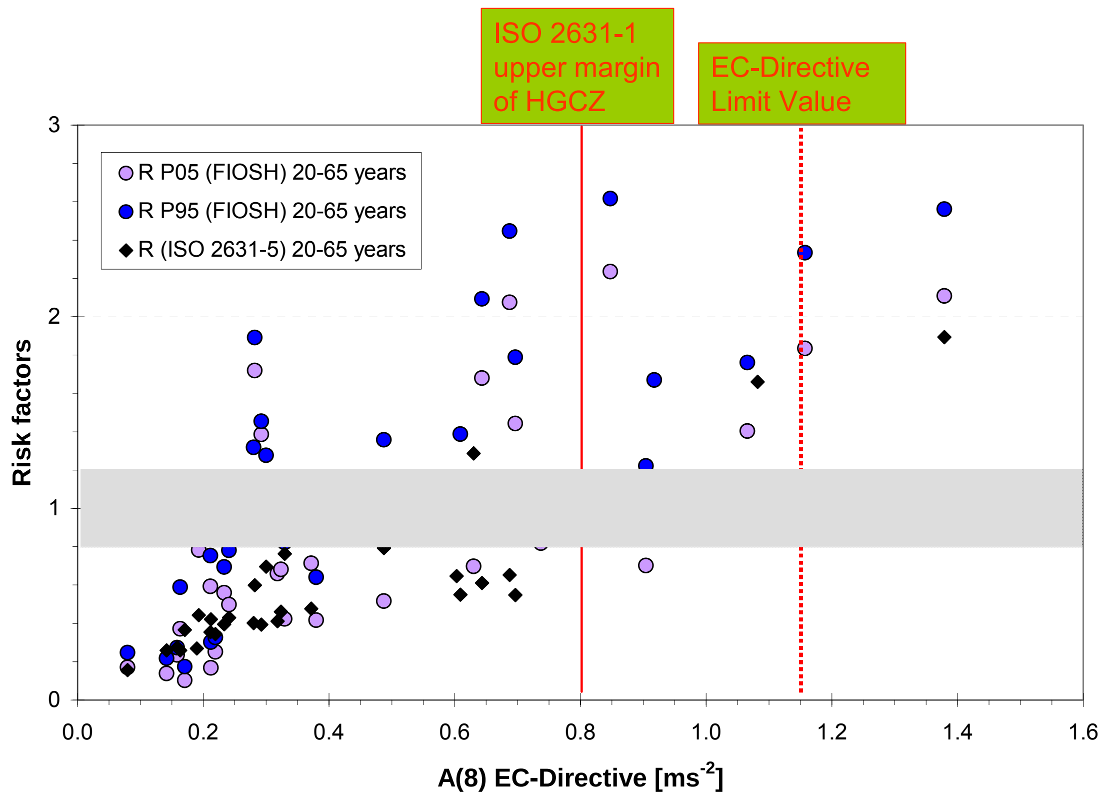


Figure 23 illustrates results of different methods of the risk assessment for the exposure conditions provided by partners. The A(8) values of the first 140 seconds of each exposure are given on the x-axis under the assumption of 4 hours daily exposure to these conditions. The red vertical lines stand for the upper margin of the health guidance caution zone (left continuous line) and the limit value of the EC-directive (right broken line). In order to compare the results of different methods, uniform assumptions were made for risk factors R according to the FIOSH-approach and factors R according to ISO 2631-5 (2004): a daily exposure of 4 hours, 240 days of exposure per year, long-term exposure from the age of 20 years to the age of 65 years. Black points stand for the R-values that were calculated according to ISO 2631-5. The grey area designates the potential risk area between the low and high probability of health effects according to ISO 2631-5. The latter assessment does not consider important factors that are taken into account with the risk assessments by the FIOSH-approach using the FE-model. These factors are: the posture of drivers, the anthropometric characteristics of drivers, the variable static load, the level of the lumbar spine, and the variability of the static strength in dependence on the share of the persons to be protected (either 50 or 95%). Another essential mistake was mentioned before – the summing up of doses of different compressive peaks with different locations on the time scale of components, instead of summing up these components in the time domain. Figure 24 illustrates the possible effects. The doses obtained from peaks of actually non-existing compressive components (green, blue, red curves) may underestimate (cf. peak of the black curve near the x-coordinate 190) or overestimate (cf. the peak of the red curve near the x-coordinate 150) the compression resulting from summing up the time series of these components (black curve) and the dose obtained from the peaks of this resulting compression. Due to the exponent 6, such error has serious consequences and can help to explain the significant discrepancies between the methods of risk assessment by the FIOSH-approach and ISO 2631-5 (2004), in addition to the reasons described in section 1.1.2.

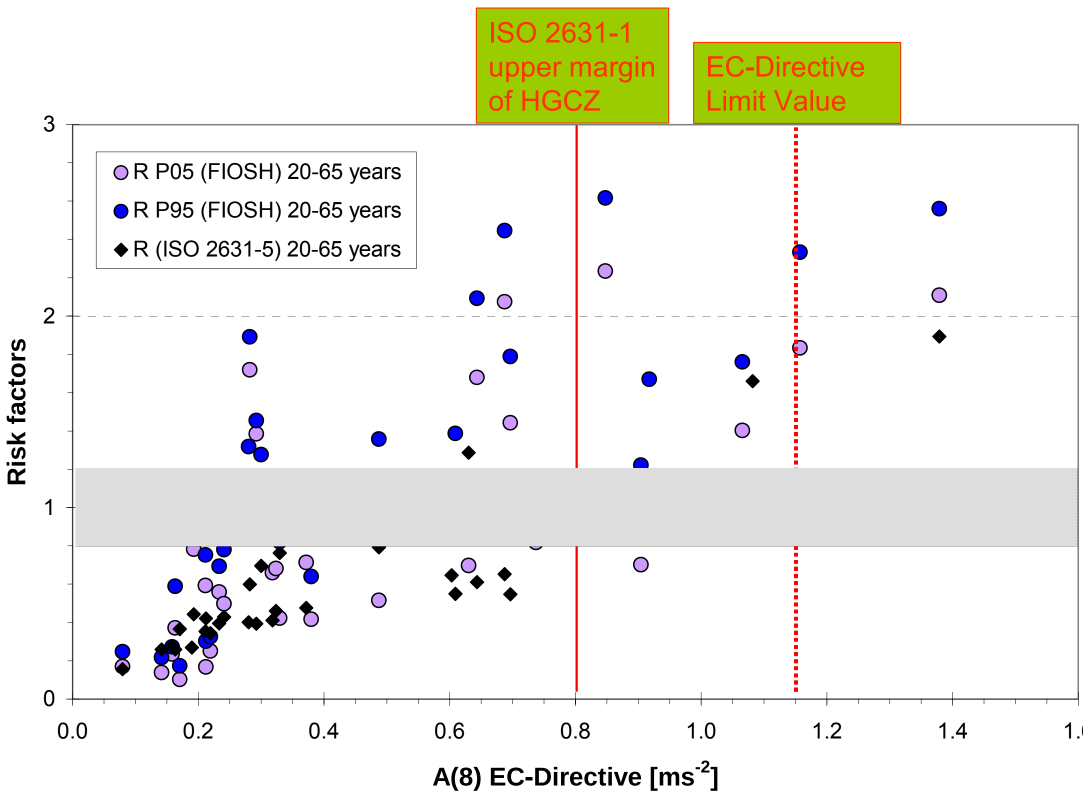


Figure 23. Comparison of risk assessments for exposure conditions listed in Table 3, R P05 and R P95 – risk factors described in Section 1.1, calculated for an ultimate strength of the 50th percentile and the lumbar level L4/L5, R – factor defined in ISO 2631-5 without specification of posture, anthropometric characteristics and disc level. P05 – body mass of the 5th percentile and BMI1, P95 – body mass of the 95 percentile and BMI2. HGCZ – health guidance caution zone.

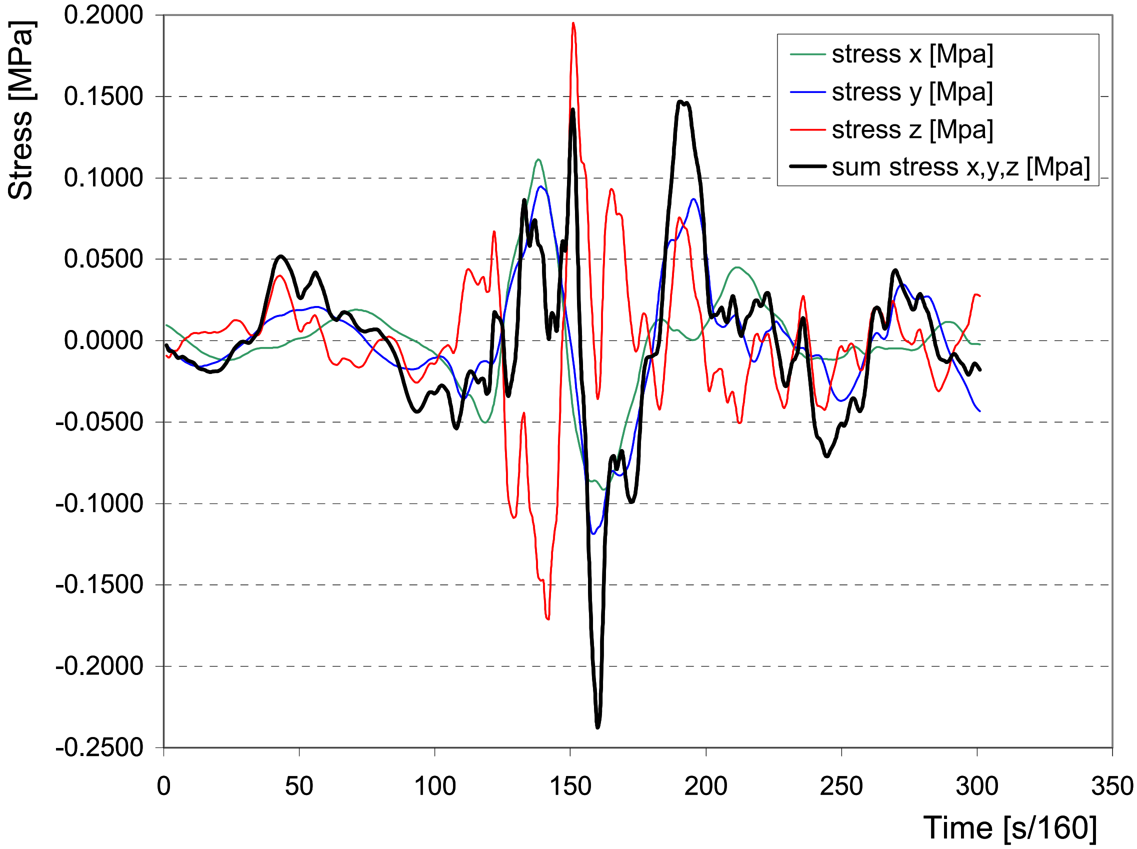


Figure 24. Small portion of predicted components of the compressive stress according to ISO 2631-5 (2004) due to spinal responses in x-, y-, and z-axis together with the sum of compressive stress. Exposure condition – WL1, 116.236 – 118.112 s from the beginning of the time series.

There are four exposure conditions (F2loading, F4loadin, F5unloading, H2felling) with risk factors (FIOSH-approach) above 1 for both percentiles, in spite of A(8)-values below the action value of the EC-directive (cf. Table 7 and Figure 23). Another three conditions (F5loading, TE1, WL1) caused R-factors above 1 only for the 95th percentile and BMI >2.61224, whereas the R-factors for the 5th percentile and BMI ≤ 2.61224 were smaller than 1. These results illustrate the significance to consider anthropometric characteristics. Figure 25 illustrates the apparent contradiction between a predicted high risk for the condition 'Forwader 2 loading', in spite of a much lower average acceleration and A(8) value than for the condition 'Forwarder 2, transport no cargo' (cf.

Table 11). The y-axis acceleration (green curves) is dominant in both cases. The former condition goes along with a smaller number, but higher amplitudes of peak-to-peak compressive forces for both classes of statures, the 5^{th} percentile with a BMI ≤ 2.61 g/cm^2 and the 95^{th} percentile with a BMI > 2.61 g/cm^2 (red curves in the upper half of Figure 25).

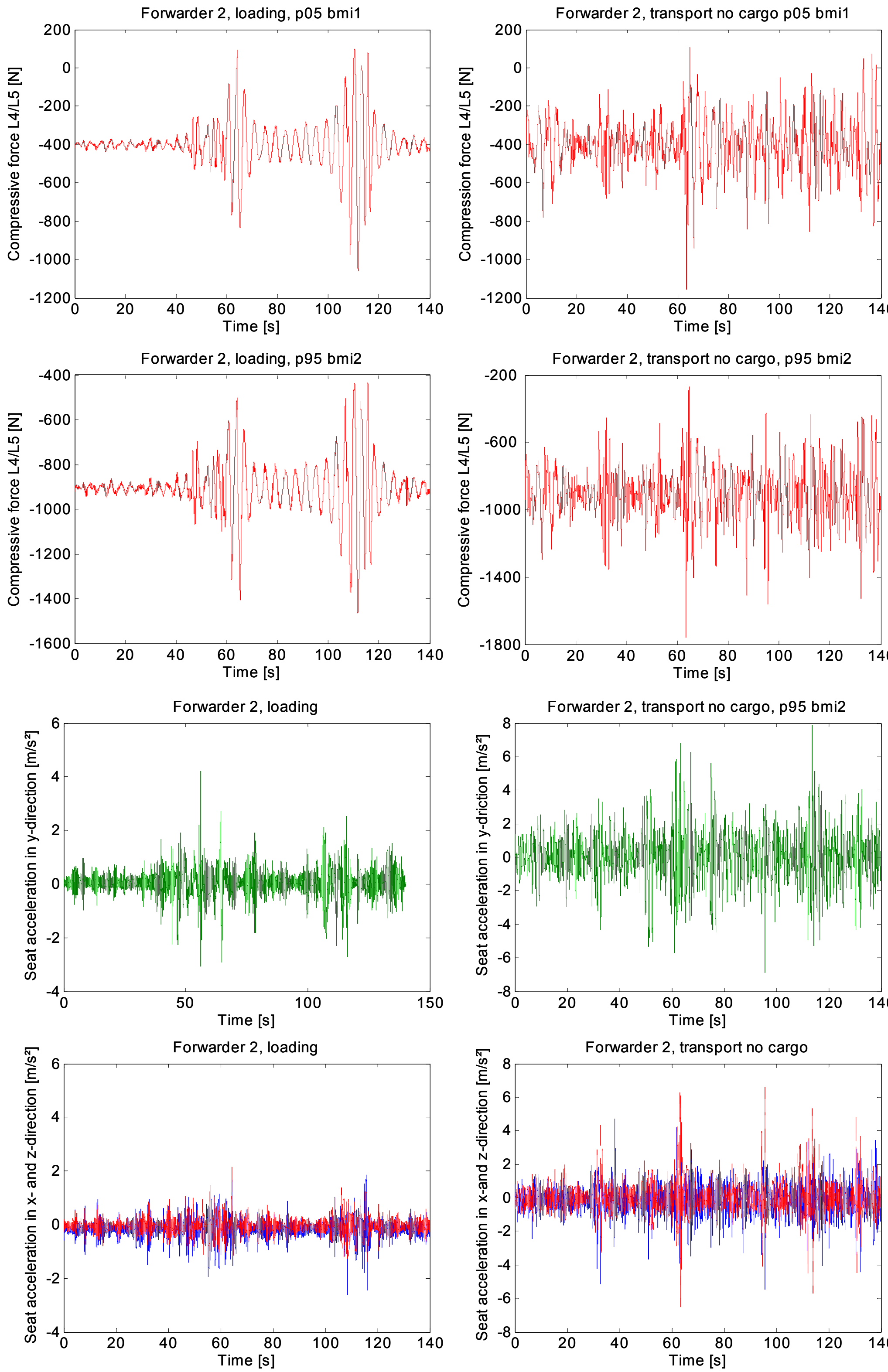


Figure 25. Predicted compressive forces acting on L4/L5 during seat accelerations in x-, y- and z-directions. p – percentile of body mass, bmi – body mass index. See text for details.

4 Discussion

The combination of predicting spinal stress with a risk assessment referring to fatigue failure can be used to judge the effects of the biological variability and/or posture. It offers the possibility to predict the health risk for different shares of the exposed population as a contribution to subsequent decisions on tolerated risks. Unlike ISO 2631-5 (2004), the FIOSH approach considers additionally significant variables like posture, body mass and body height, BMI, size of the disc area, disc level, and variable ultimate strength covering either 50 or 95% of the general population. The consideration of different significant variables enables a more sophisticated assessment to identify health risks arising from exposure conditions and/or personal characteristics. Both, the variable static compressive force resulting from posture and anthropometric characteristics, and the variable ultimate strength can cause large differences between assessments for the same exposure condition. The kind of dose calculation overcomes the limitations inherent in the current basic method of ISO 2631-1. Up to now, no comparable evaluation procedure is known.

Obviously, the risk assessment methods lead to different results which often contradict the assumptions underlying the EC-directive and international standards. The interpretation of Table 10 should consider that (i) these assessments are related to one lumbar level only and (ii) do not consider shear forces. So far, systematic calculations for other segments have not been performed. An important limitation of all assessment methods is the missing consideration of shear forces. The new procedures for an assessment of health risk do not intend to provide a quantitative risk assessment for internal stresses caused by shear forces, bending and torsion, because reliable strength data for such stresses, especially for dynamic repetitive loads are not available yet. One might consider peak-to-peak shear forces exceeding 30 percent of the provisionally estimated final strength limits (different sources reported 2700 N ± 400 N for shear, or a maximum of 1250 N shear for the disk alone, cf. Morrison et al. Part 5, p. 65 after Begemann et al 1994 2700 N ± 400 N for shear, Seidel et al. 1995 after Farfan (1979) maximum 1250 N shear for the disk alone) of such loads as potentially harmful. Recent data by Cripton et al. (1995) suggest an ultimate shear strength of lumbar functional spinal units between 1300 and 2900 N. Hence, the maximum sum of static and dynamic positive shear peak forces in x-direction predicted in this study could reach more than 50% of the ultimate shear strength. Therefore, the high repetitive fore-and-aft shear forces predicted for several exposure conditions should be considered in the future as an important possible damaging mechanism for the disc and the facet joints. The risk will be higher, if peak shear forces coincide with a compression reduced below the static compression value, thus reducing the stability of the lumbar spine.

The results disagree with the predictions of spinal stress according to ISO 2631-5. Several reasons can explain the differences. (1) The spinal stress predicted by FE-models was different from that predicted by the simplistic and fundamentally wrong method of ISO 2631-5. The effects of the latter are non-predictable, because they vary with the phase relations between the spinal responses in different directions calculated according to ISO 2631-5. (2) A variable static stress was predicted instead of the “constant c representing the static stress due to gravitational force” in ISO 2631-5, equation A.3. The general assumption of only 0.25 MPa as static stress that 'can be normally used for driving posture' would lead to a significant underestimation of health risk in many cases.

Results of recent in vitro experimental research not associated with VIBRISKS (Huber et al. 2005) may give a rough orientation concerning load-effect relationships. 30 lumbar specimen (age of male donors 33.3 +/-5.8 years) in five groups (D1 – D5) were loaded with five different combinations of compressive static loads and 100,000 cycles peak-to-peak dynamic compressive loads (5 Hz). The sizes of endplate areas were precisely determined from CT scans and used for the calculation of spinal stress. The bone mineral density was measured. The ultimate strength of functional spinal units could be predicted by the formula derived by Brinckmann et al. (1989). Calculations of risk factors were performed according to the FIOSH approach with different exponents. Table 13 summarises the results. The highest risk is predicted for group D4, independently of the exponent. The risk factors calculated with an exponent 6 seem to discriminate between risky and risk-free conditions by values above and below 1, thus supporting the use of this exponent.

Table 13. Stress, loading conditions, and risk factors R of in-vitro experiments with lumbar spinal units L4/L5, R = risk factor, e = exponent. Stress calculated for the cranial endplates of L5, ultimate strength determined by endplate area and bone mineral density according to Brinckmann et al. (1989). 100,000 load cycles, 5 Hz. Group D4 – 2 specimens out of 6 failed. p-t-p – peak-to-peak.

Group	Static stress/load [MPa]/[N]	Dynamic stress/load p-t-p [MPa]/[N]	R e = 4	R e = 6	R e = 8
D1	0.31/500	0.63/1000	1.24	0.48	0.30
D2	0.63/1000	0.63/1000	1.15	0.44	0.27
D3	0.63/1000	0.95/1500	2.13	0.81	0.50
D4	0.65/1000	1.30/2000	3.21	1.23	0.76
D5	0.90/1500	0.60/1000	1.21	0.46	0.29

There are further relevant factors that would increase the variability of health risk, but have not been examined with the assessments described in the results section. The size of the vertebral endplate was kept constant, although the normal variation was estimated near ± $2cm^2$. The postures reflected by the FE-models vary moderately and do not yet include exceptional conditions like a bent-forward posture.

The new risk assessments definitely contradict the limit value set by the Directive 2002/44/EC (2002). The high risk factors of several exposures with rms-values below the health guidance caution zone (ISO 2631-1) may help to explain results of epidemiological studies that described an increased health risk due to WBV-exposures with low magnitudes and could not verify a safe limit. The missing systematic consideration of anthropometric characteristics, posture and age during the exposure are further factors probably explaining the missing simple relationships between exposure and long-term effects in former epidemiological studies. A closer inspection of relationships between exposure data and predicted effects shows that often horizontal accelerations in the y-axis seem to be responsible for a tendency to underestimate the health risk by ISO 2631-1 (1997) as compared with model calculations. This is a surprising fact, because the multiplying factor k = 1.4 for this axis (ISO 2631-1, 1997) indicates already a stronger effect. Further research is urgently needed to clarify, how WBV in this axis should be weighted in order to reflect the health risk adequately.

The method presented in this paper might apparently be too complicated for general use, but the enormous progress of computing technology will alleviate this problem in the near future.

5 Conclusions

The combination of experimental laboratory research on human biodynamics, field research on anthropometry and posture of drivers and FE-modeling based on real anatomy proved to be a promising approach to elaborate the scientific base for an improved assessment of the health risk associated with occupational whole-body vibration.

The results indicate an underestimation of the health risk by the limit value set in the DIRECTIVE 2002/44/EC for many real exposure conditions. The reliable protection of workers' health suggests an urgent revision of this limit. Keeping to the action value does probably not exclude a potential health risk in all cases.

Future research is needed to

- examine the health risk arising from shear forces
- examine the health risk arising from torsion in combination with whole-body vibration
- develop further the FE-modelling, e.g., by a more sophisticated modeling of the soft

contact areas, consideration of non-linear biodynamics and active muscle responses

- study the kind and extent of backrest-contact under real conditions
- investigate the fatigue strength of spinal units in dependence on age
- explore the significance of simultaneous loading by decompression and shear.

The results suggest a fundamental revision of the international standard ISO 2631-5 (2004) with respect to the basically wrong approach of the presupposed association between a dose of spinal peak accelerations in three directions and health effects.

The results could be used for amendments to the international standard ISO 2631-1 (1997) with respect to (i) the applicability of the basic evaluation method, (ii) the use of evaluation methods for health, (iii) an extension of the guide to the effects of vibration on health concerning the significance of personal characteristics, posture, and alternative evaluation methods.

One question of the VIBRISKS-project was related to possible 'alternative weightings' in the analysis of machine vibration measures in WP5. As Seidel et al. demonstrated (2004), the use of the transfer functions derived from FE-model calculations includes frequency weightings that are specific for the respective model. The elaborated set of 50 FE-models means 900 specific frequency weightings (one for each input direction and disc level) from which frequency weightings for the exposure conditions might be derived (cf. Seidel et al., 2004, for the general procedure). A handling of such amount of new frequency weightings as in ISO 2631-1 (1997) does not seem to be practicable. At present one cannot decide, if an averaging of new frequency weightings without loss of significant information could be justified.

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7 Appendix A Figures

8 Appendix B Tables