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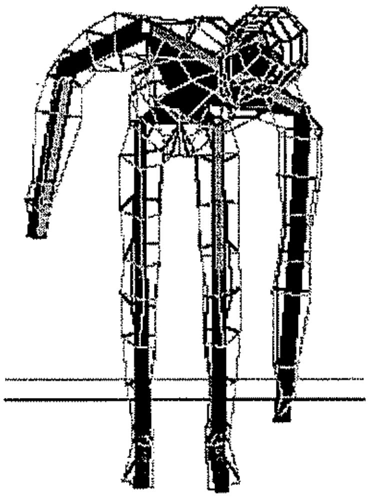
ANALYSIS OF BIOMECHANICAL LOAD WHEN WORKING WITH MANUALLY HANDLED SHAFT TOOLS



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ABSTRACT

This report describes a study of the biomechanical load when working with manually handled shaft tools. The tools studied are shovels, rakes and push hoes. The most comprehensive measurements study the effects of varying shovel design. Especially the load on the muscles in the back and the compression and shear forces directly on the spine are studied. The mounting angle and length of the shovel shaft are varied. The effects of using a tool with a higher and bent shaft are also studied, just as the effects of varying operator anthropometry. One conclusion of the results is that the spine forces can be decreased if an alternatively designed shovel is used. Another conclusion is that the anthropometry of the operator has major effects on the load levels.

The method used for the analysis of the biomechanical load uses optoelectronic measurement data of body positions as input to an computerized biomechanical analysis model. The external forces acting on each hand are simultaneously measured. The measurement procedure is standardized and the transfer of data from the optoelectronic measurements to the biomechanical model is computerized in order to increase the accuracy and also to enable analysis of measurement time series with reasonable time consumption.

1 INTRODUCTION

Also in modern agriculture and horticulture, work with manually handled shaft tools is a habitual occupation. Some of the frequently used tools require considerable muscle forces and stressful working postures. The biomechanical load on the person performing the work may often be high and may result, in the shorter perspective, in muscle fatigue and reduced capacity for work. In the longer perspective, the consequences may be cumulative and result in musculoskeletal trauma disorders and chronic muscle pain (Hansson et al., 1992).

Improvement of the design and handling of tools requires that the biomechanical load can be quantified and analysed. The postures of interest in this context are normally twisted and asymmetric and thus the analysis must be done in three dimensions.

Biomechanical studies must begin with a kinematic description of the subject's posture and movements. Instruments are now available with the capacity to record, with high accuracy and sampling frequency, the 3-dimensional coordinates of a large number of marker points placed on the subject's body. The positions of the marker points can then be used to estimate the positions of human link rotation centres and body segment centres of mass. Biomechanical models, describing the human body as a mechanical system of links connected by various types of joints, use the body posture data and information about external forces applied to calculate joint forces and moments.

This report describes a method useful for analysis of biomechanical load when working with manually handled shaft tools. Optoelectronic measurement data of body positions are used as input to an computerized biomechanical analysis model. The external forces acting on each hand are simultaneously measured. The measurement procedure is standardized and the transfer of data from the optoelectronic measurements to the biomechanical model is computerized in order to increase the accuracy and also to enable analysis of measurement time series with reasonable time consumption.

The analysis method is firstly used to study the biomechanical load when working with differently designed shovels. Especially the load on muscles in the back and the compression and shear forces directly on the spine are studied. The shaft's mounting angle and length are the variables studied. Also the load when working with a rake and with a push hoe is studied.

2 METHODOLOGY

An optoelectronic movement analysis system is used to measure the operator's body posture and the position of the tool. The external forces acting on each hand are simultaneously measured. A biomechanical model then calculates torques and forces at the most important human joints.

The biomechanical analysis is done with the 3DSSPP model developed at the University of Michigan (The Univ. of Michigan, 1993). This 3-D model uses values for a range of body segment angular positions to define body posture and calculates torques and forces on the most important joints such as the elbows, the shoulders, the hips, the knees and the lumbar region of the spine. Loads on the muscles working at the L4/L5 level in the torso are also calculated by a linear programming optimization algorithm. Most of the loads are also related to data on population strength capability. The input screen and the 7 output screens of the model are shown in the Appendix. The model is very well known, and a lot of work has been performed in order to verify the algorithms (for example Chaffin and Erig, 1991).

2.1 Measurement of body postures

The human segment angles are calculated by using the position coordinates from 17 semispherical reflective markers located at standardized positions on the subject's body (see Fig. 1). The positions are chosen in order to make them visible to two video cameras mounted in front of the subject at ± 30° from the sagittal plane.

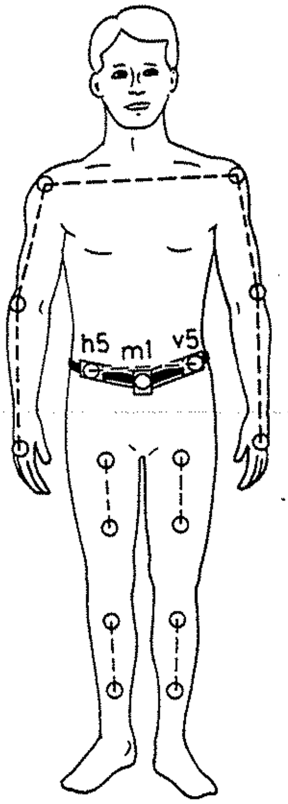

Fig. 1. The positions of the 17 reflective markers.

Two markers are placed at the front of both lower and upper legs in order to measure each segment's angle in relation to the horizontal plane. The positions for the markers on the skin surface in relation to the segment of the thigh are measured for each application. The position of the pelvis complex is decided by three markers (v5, m1 and h5 in Fig. 1) located on a small aluminium frame mounted on the subject to follow the pelvis's movements. The equation for the plane passing through these markers is (Spiegel, 1968):

$$\begin{vmatrix} y_{m1}-y_{v5} & z_{m1}-z_{v5} \\ y_{h5}-y_{v5} & z_{h5}-z_{v5} \end{vmatrix}(x-x_{v5})+\begin{vmatrix} z_{m1}-z_{v5} & x_{m1}-x_{v5} \\ z_{h5}-z_{v5} & x_{h5}-x_{v5} \end{vmatrix}(y-y_{v5})+\begin{vmatrix} x_{m1}-x_{v5} & y_{m1}-y_{v5} \\ x_{h5}-x_{v5} & y_{h5}-y_{v5} \end{vmatrix}(z-z_{v5})=0$$

where i_{v5}, i_{h5} and i_{m1} are the coordinates for the markers (i=x, y and z).

The centre between the hip joints and the L5-S1 joint are located on a plane which is perpendicular to the described plane and passes through the marker m1 and a point exactly in the middle of a line between markers v5 and h5. The relative positions of the centre of the hips and L5-S1 on this plane are measured manually for each mounting of the frame.

Markers are attached to the left and right shoulders, elbows and hands. A straight line between each pair of markers on each side of the body is approximately parallel to the lines between the rotation centres of the shoulder, the elbow and centre of the hand grip.

In order to keep the line between the elbow marker and the hand marker parallel to the forearm, the position of the marker on the hand must be chosen in relation to the lower arm's rotation and the hand's orientation for the special task performed in each study. For example, when the hand is in supined position, the marker must be placed on the hand's radial side, and when the hand is pronated, the marker must be placed on the ulnar side. If the wrist is deviated and the fist is clenched, the marker can normally be placed on one of the fingers, still keeping the line between the elbow and hand marker approximately parallel to the forearm.

The positions of the markers on the shoulders, together with calculated values describing the position of the pelvis, are used to estimate trunk flexion, lateral bending and axial rotation.

The positions of the reflective markers are measured with the 3-D position measurement system Mac-Reflex (Qualisys, 1993). This system is based on 2-7 infra-red cameras and measures the 3-D coordinates for up to 20 reflective markers with very high precision with a 50 Hz sampling frequency when using two cameras (100 Hz can be reached by using 4 cameras). The measurement system uses passive markers that reflect infra-red light projected from the cameras. The markers do not require any power input, and the subject is therefore not impeded by wires. The information from two or more cameras is used by a central processing unit to calculate the 3D coordinates. The measurement equipment is designed also to permit outdoor use with battery powering. The calibration of the system is a rather simple procedure using a calibration frame with 6 markers with known internal distances.

2.2 Measurement of hand force vectors

The amplitude and direction of the forces loading each hand have to be defined as input to the biomechanical model. The measurement of the force vector must be adapted to each type of studied tool. The measurement system is designed for synchronized measurements of marker positions and force transducer signals. It is also possible to record other signals synchronically, for example from EMG transducers. In this report, the measurement and calculation of the hand force vectors are described for each tool separately.

2.3 Data treatment

When measuring body postures using cameras and marker points there may be a problem of markers not beingrecorded by the system. One reason may be that two markers are very close to each other, and therefore are recorded as one. The usual reason for missed data is, however, that body segments are located so that a marker is hidden from at least one of the cameras, and the system is therefore unable to decide the marker's 3-D coordinates.

Since calculation of body posture angles is dependent on complete marker position information, a program was developed that is able to fill gaps in the data. The operator then studies the recorded coordinate time series, one marker and one direction at a time, and is asked to point out any time periods where he wants to complement the data. The data gaps in these periods are then filled using linear or, optionally, cubic regression. The operator also has the possibility to define new data points to be included in the regression, or to delete a defined time period from the analysis, if the uncertainty of the coordinate positions is too high.

A special program was developed in the Matlab software (The Mathworks Inc., 1993) to calculate the body segment angles from the 3-D marker position data. The first part of the algorithm transforms the recorded coordinates to a body-oriented coordinate system with origin at a point located at the middle of a line between the left and right hip joints. Formulas from 3-D solid geometry (Spiegel, 1968) are then used to calculate body posture angles and force vectors. The results are automatically written in files, one for each chosen sampling instance, with a format that simplifies the input to the biomechanical model.

The standardized marker positions result in the main part of the program being general for all measurements. Only the subroutine that deals with the force vectors must be adapted to each type of analysis. The open structure of Matlab is very valuable when adapting the data treatment to different types of input information. It also offers the possibility to program biomechanical models including more details than the 3DSSPP model, and to use the measured position data as input to these models.

3 BIOMECHANICAL LOAD WHEN SHOVELLING

These measurements are performed in order to analyse the load when working with different types of shovels. In the first part, a "normal" shovel is used in order to find critical working situations and load components. The following parts then study the effects when tools with alternative design are used.

The work was started with a survey of the shovels available on the Swedish market. Most of the available tools have a shaft mounting angle (see Fig. 2) around 35 degrees and a shaft length of approximately 1.00 m and these values were used for the tool defined as normal.

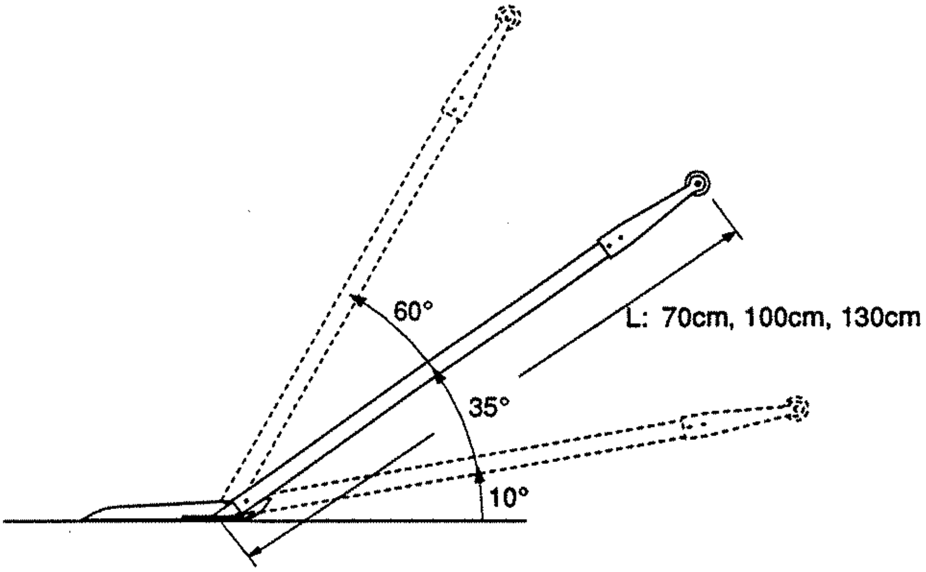

Fig. 2. Definition of the mounting angle and the length of the shaft of the shovel.

An experimental shovel was constructed so that the part connecting the shovel blade to the shaft was exchangeable and also with the shaft exchangeable. Thereby it became possible to vary the mounting angle of the shaft and the length of the shaft independently.

In most working situations the empty shovel is pushed into the material that is to be moved, for example gravel, and then lifted in order to place the material at a higher level and/or to move the material also in the horizontal plane. The heavy part of the job is, of course, when the blade is loaded and especially if the handled material is heavy. The studies performed are restricted to these situations.

Three reflective markers were used on the shovel. Two markers were used to identify the direction of the shaft. The positions of the grip centres of the hands were assumed to be those points on the shaft (the line between the two markers) that were closest to the markers on the left and right hand, respectively. The third marker on the tool was placed in order to indicate the position of the centre of gravity of the tool and the handled load. The position of this marker had to be decided for each individual tool design.

The horizontal force components necessary to move the loaded shovel in the horizontal plane are very small compared with the vertical components used to lift the shovel and were neglected in the analysis. Knowing the total weight and the centre of gravity of the loaded shovel and the positions of the hand grip centres, a simple balance equation was used to calculate the hand force vectors.

In order to limit the amount of varied variables, all studies except those in Ch. 3.5 were performed with the same male subject with height and weight close to the average (length 1.80 m and weight 75 kg). The load on the shovel was simulated with four weights of 1.00 kg each, mounted with a bolt to the shovel blade. The total mass of the loaded shovel was 6.5 kg with a shaft length of 1.00 m and the mass 6.2 and 6.8 kg for shaft lengths of 0.70 m and 1.30 m respectively.

3.1 Standard tool

The purpose of the first measurements was to study the biomechanical load in a typical working task using a normally shaped shovel.

The subject was instructed to lift the loaded shovel from the ground to a comfortable upright position and then turn the shovel to the left 45 degrees in the horizontal plane. Four working cycles were recorded in order to study the variations between repeated recordings of the same working task. Before the recordings were started, the subject was instructed to repeat the working task 10 times in order to find a comfortable working posture.

The data was recorded with 50 Hz and every third picture was used in the analysis. Fig. 3 shows one of the recorded postures. This posture is recorded in the beginning of the lifting phase.

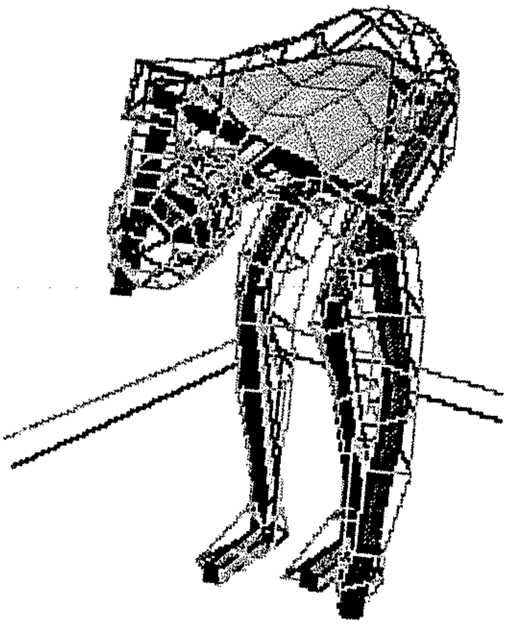

Fig. 3. A recorded posture.

The biomechanical model calculates loads on all the major human joints, but the variables related to the back and spine load have been studied most carefully, since this is the body region where the most severe problems are reported. All four measurements are analysed in the lifting phase, whereas, because of the low load levels, only one is analysed in the phase when the shovel is moved in the horizontal plane.

Figs. 4-8 show some of the results of the analysis. Figs. 4 and 5 show calculated compression and shear forces on the spine at the L5/S1 level when moving the shovel. The flexion moment at the torso is shown in Fig. 6. The calculated loads on the Right Erector Spinae and Right Latissimus Dorsi muscles are shown in Figs. 7 and 8.

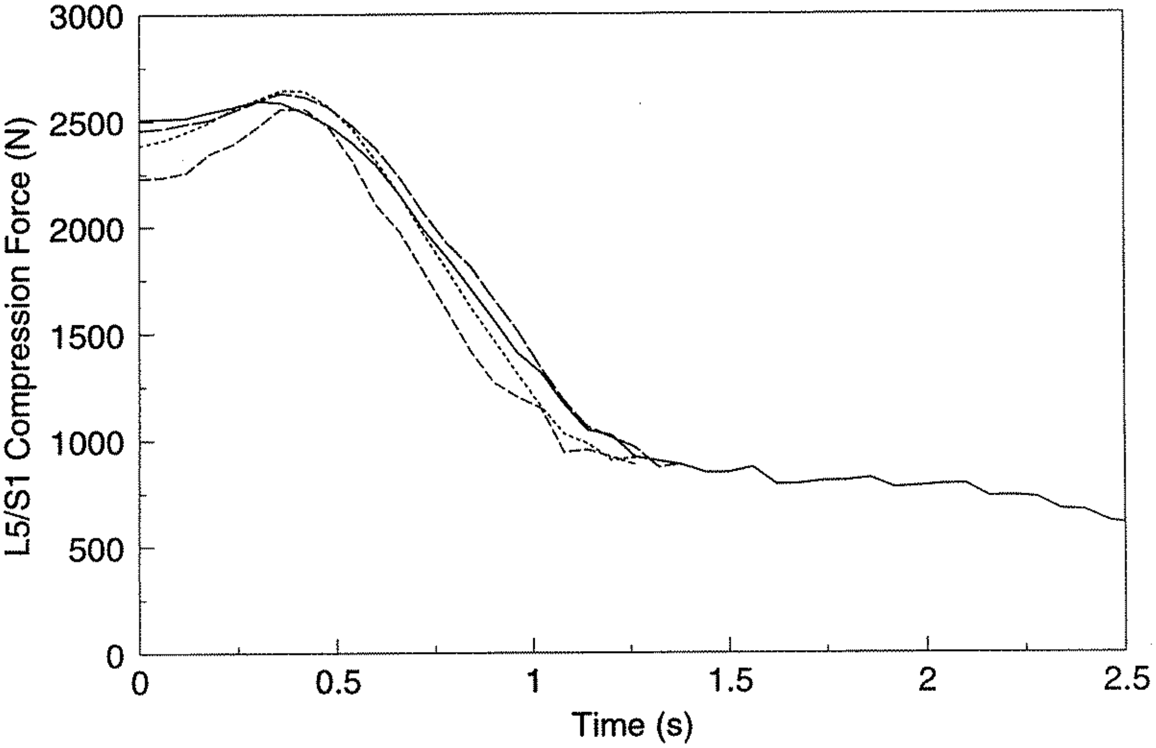

Fig. 4. L5/S1 Compression force.

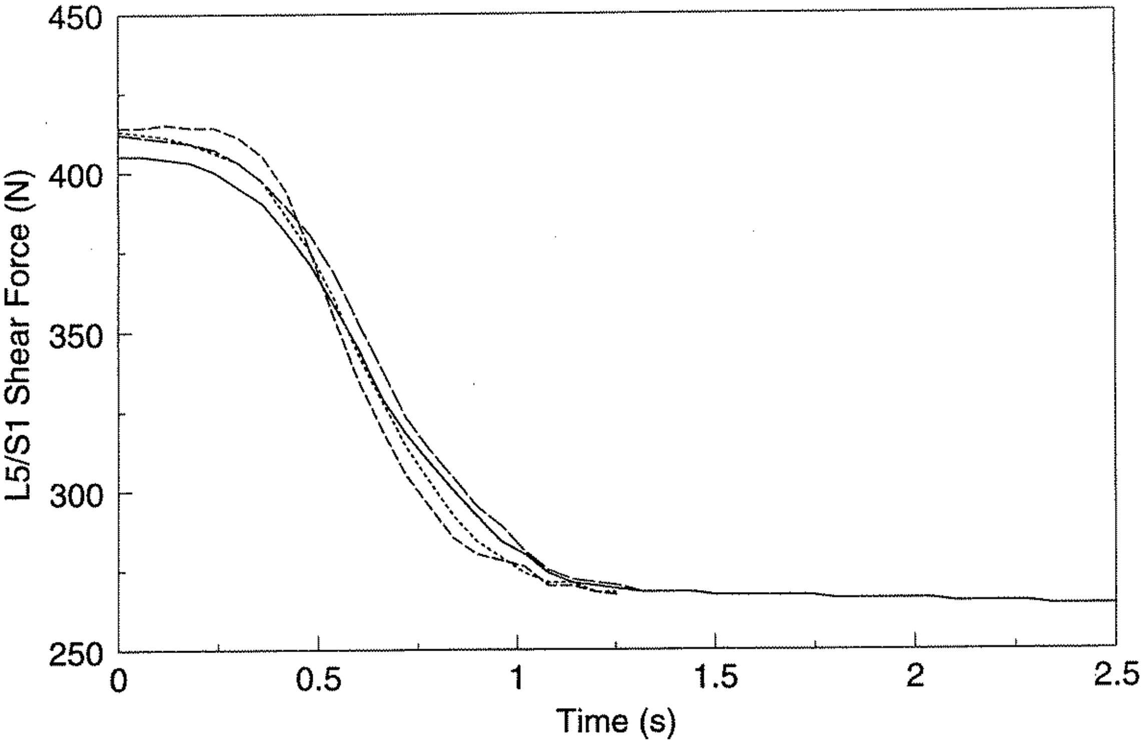

Fig. 5. L5/S1 Shear force.

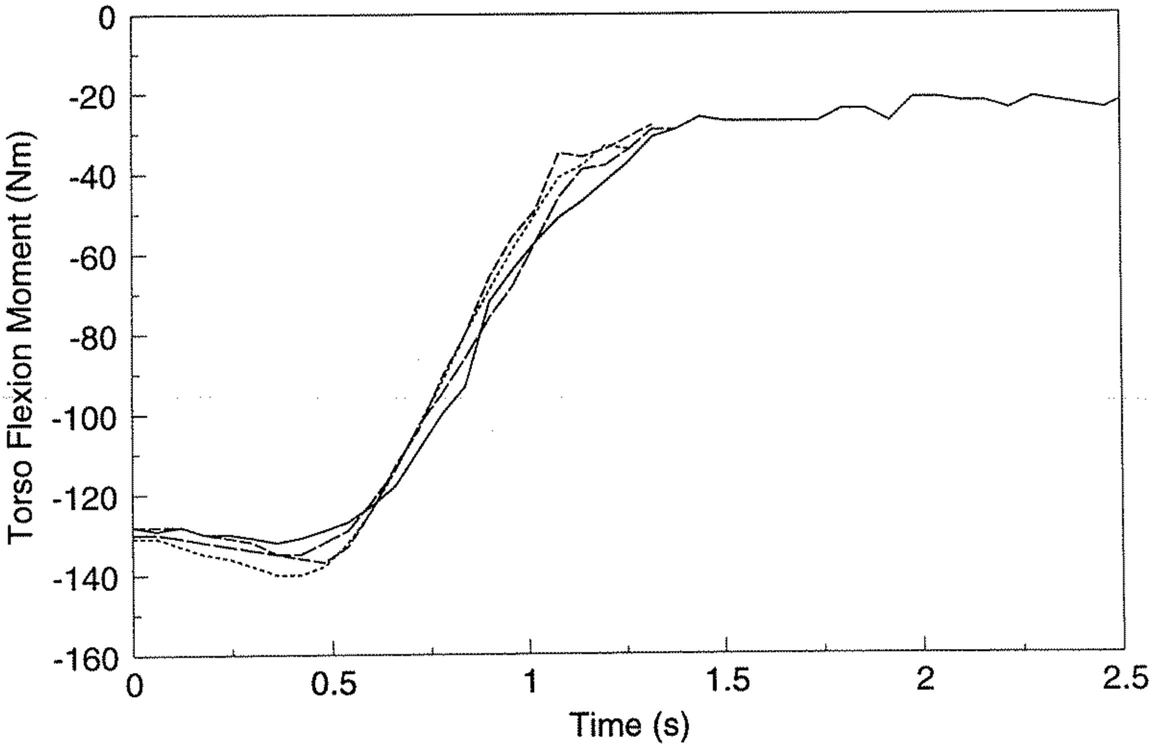

Fig. 6. Flexion moment on the torso.

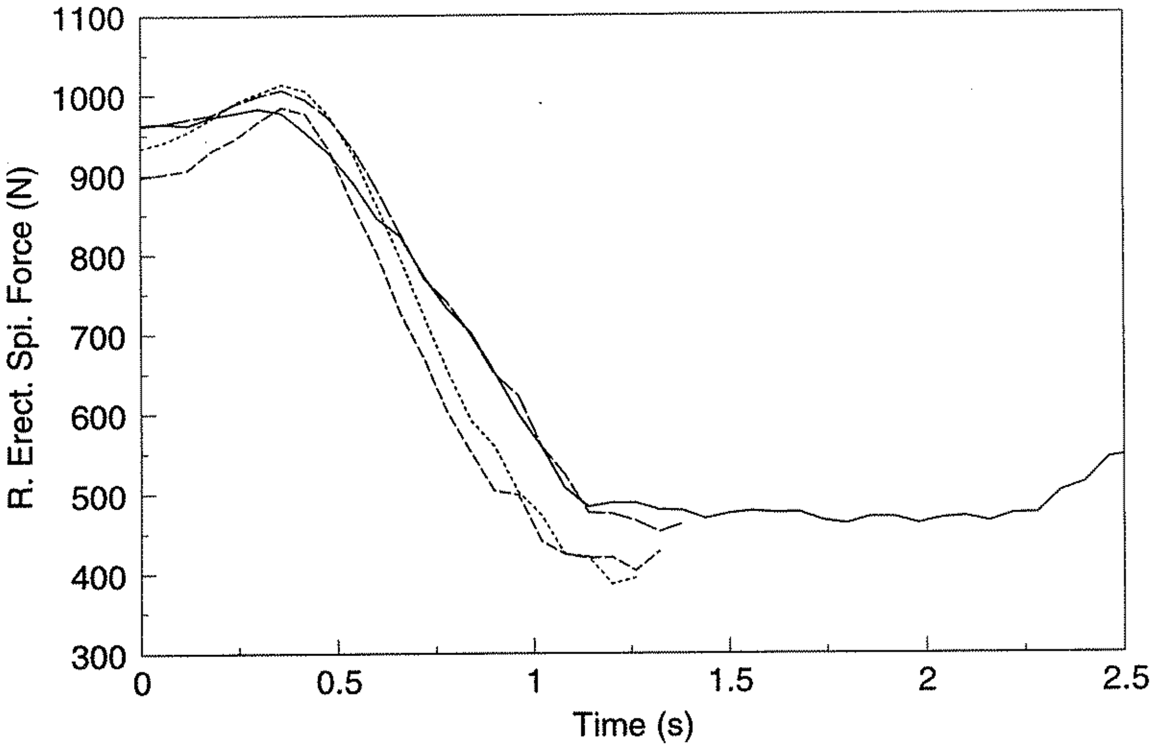

Fig. 7. Force on the Right Erector Spinae muscle at the L4/L5 level.

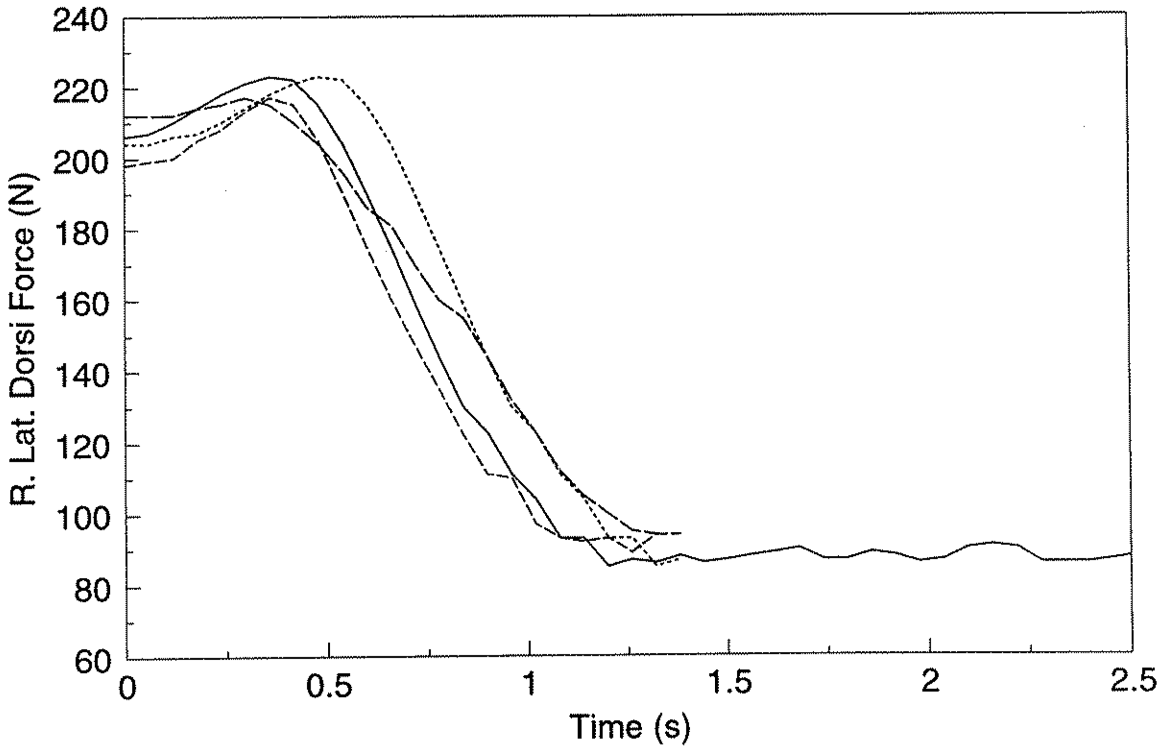

Fig. 8. Force on the Right Latissimus Dorsi muscle at the L4/L5 level.

The durability of the lifting phase in the recorded measurements is approximately 1.25 s. All variables analysed have their critical values in this phase and the loads when moving the shovel in the horizontal direction are much smaller.

The differences between the four analysed measurements are rather small. The main part of the disagreement between the curves can be explained by the subject not using exactly the same technique in all recorded working cycles. Since the subject was free to decide the speed of the lifting, and no normalisation of the time scaling has been done, some of the disagreement between the curves is explained by some of the lifts being made a little faster or slower than the others. An analysis of the recorded posture angle time series showed that in one of the lifts, the subject increased the axial rotation of the trunk in order to decrease the trunk flexion necessary for the left hand to be able to reach the lower part of the shovel. This working cycle is the one with the lowest values for spine shear forces and the highest values the spine compression forces in the beginning of the lifting phase.

There are no standardized limits for the allowed ranges for the analysed biomechanical load variables, except for the compression force at the spine. The American NIOSH action limit (NIOSH, 1981) for this variable is 770 lb. (ca 3425 N) and the maximum values when performing the analysed working task are uncomfortably close to this value. However, even without accepted limits for the load components, the well-known occurence of body injury, both in longer and shorter terms, implies that the loads are (too) high and all possibilities to decrease the loads have to be considered as positive.

3.2 Effects of shaft length

The purpose of these measurements was to investigate the influences of the length of the shovel's shaft on the biomechanical load when handling the tool.

The shaft length was varied between 0.70, 1.00 and 1.30 m while the shaft angle was kept at a constant 35 degrees. As the previous study showed that the highest load levels appeared in the lifting phase, only this part was now studied. The data were recorded with 50 Hz and analysed with 25 Hz. The same load variables as in the previous study were analysed and shown in Fig. 10-14.

Fig. 9 shows postures recorded in the beginning of the lifting phase with the short shaft to the left and the long shaft to the right.

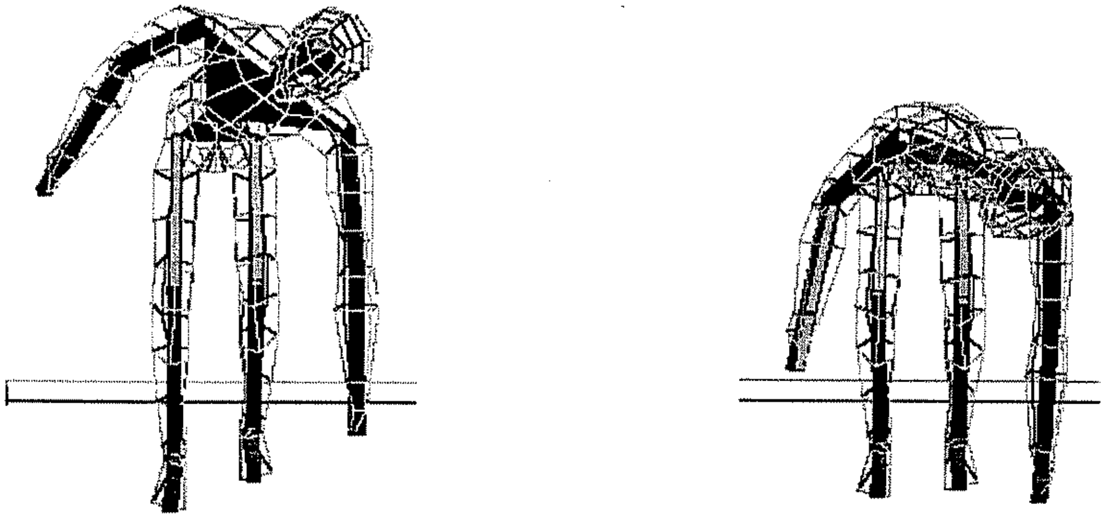

Fig. 9. Postures recorded when using the shovel with the short shaft (left) and the long shaft (right).

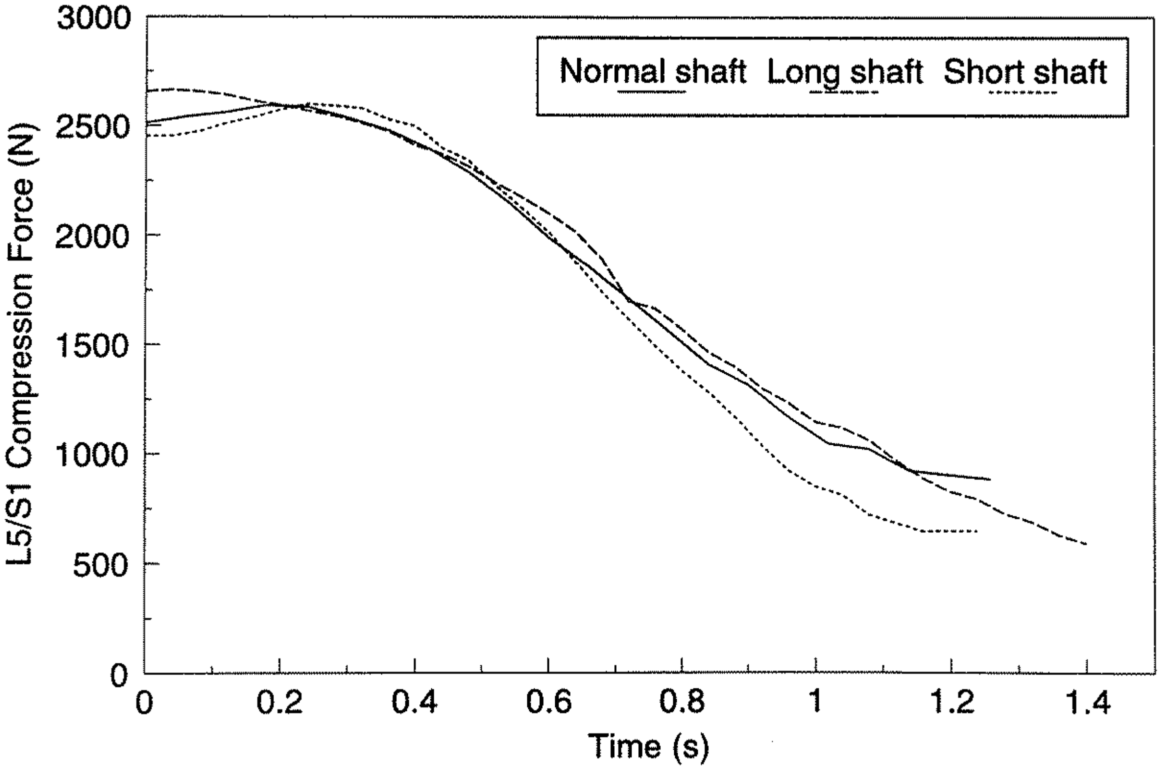

Fig. 10. L5/S1 Compression force.

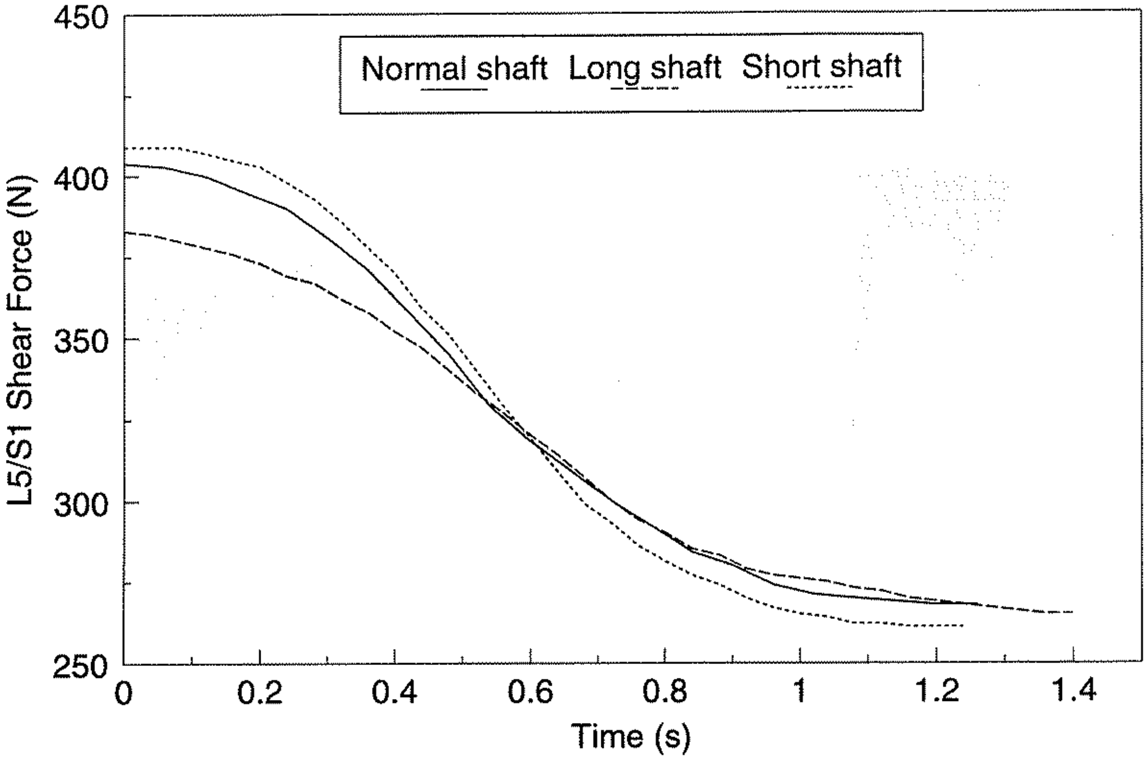

Fig. 11. L5/S1 Shear force.

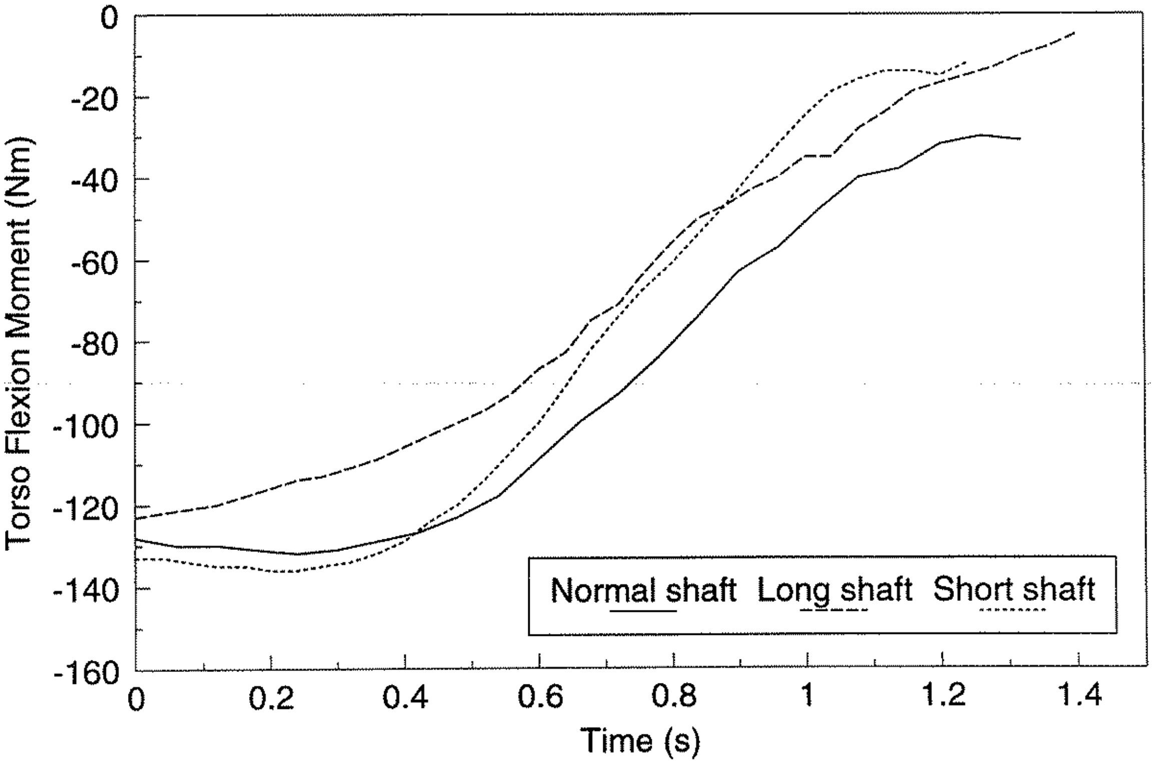

Fig. 12. Flexion moment on the torso.

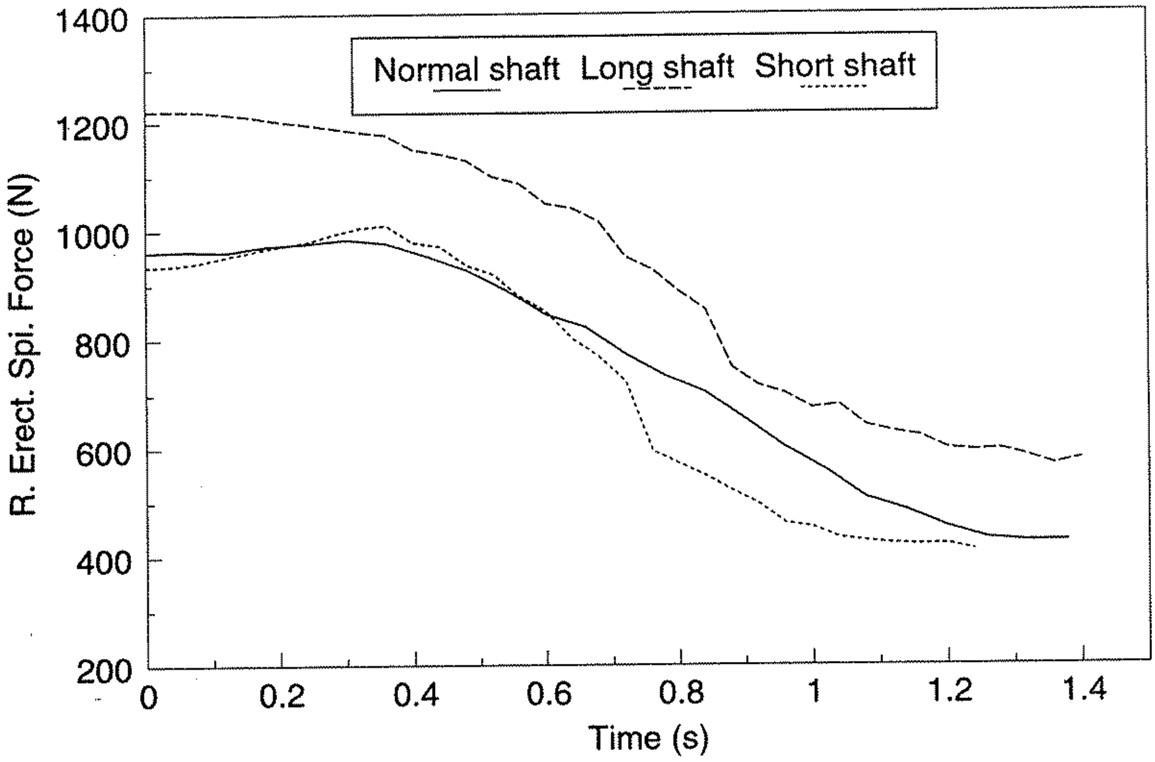

Fig. 13. Force on the Right Erector Spinae muscle at the L4/L5 level.

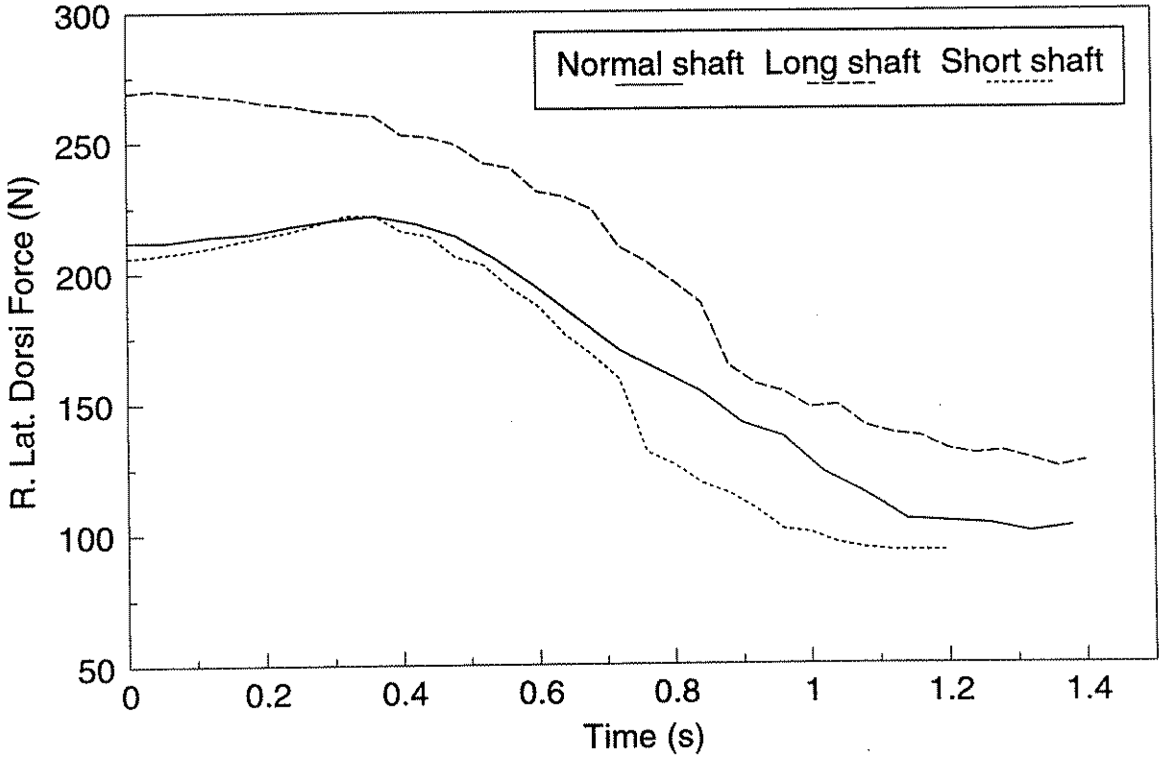

Fig. 14. Force on the Right Latissimus Dorsi muscle at the L4/L5 level.

A simplified relation between torso bending angles and spine load is that the maximum compression forces appear approximately when the torso is in the horizontal position but that the shear forces continue to increase when the trunk is flexed even below the horizontal plane. When working with the long shafted tool, the trunk is approximately in the horizontal position when starting the lift and maximum spine compression is reached directly. When using the shovel with the short shaft, the trunk is below the horizontal plane when starting the lift and maximum compression is not reached directly. Since the trunk never needs to be so flexed when using the long shafted tool, the maximum spine shear forces and torso flexion moments are reduced.

When the length of the shaft is increased, the hands have to be placed on the shaft at longer distances from the load on the blade, and the forces necessary to lift the shovel thereby increase. Since the force on the right hand is directed upwards and that on the left hand is directed downwards, the increase in the amplitudes of the forces results in an increase of the lateral moment loading the trunk. That moment is counteracted by the muscles in the trunk and the increased moment results in an increase of the forces on the Right Erector Spinae and Latissimus Dorsi muscles.

3.3 Effects of shaft mounting angle

The purpose of these measurements was to investigate the influences of the mounting angle of the shaft on the biomechanical load when handling the tool.

The angle was varied between 10, 35 and 60 degrees while shaft length was kept constant at 1.00 m. Only the lifting phase was studied. The data were recorded with 50 Hz and analysed with 25 Hz. The same load variables as in the previous studies were analysed.

Fig. 15 shows postures recorded in the beginning of the lifting phase using the tool with the small shaft angle to the left and the big angle to the right.

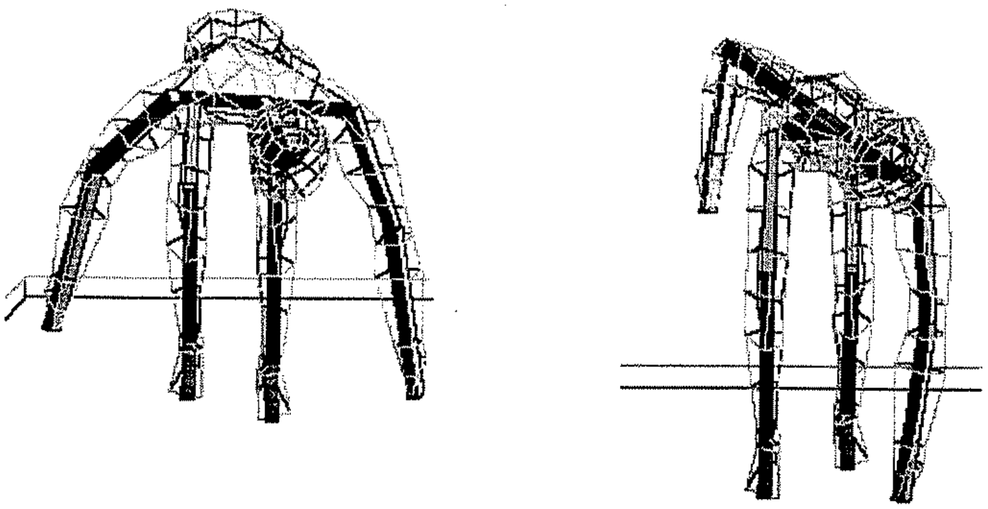

Fig. 15. Postures recorded when using the shovel with a small shaft mounting angle (left) and a large mounting angle (right).

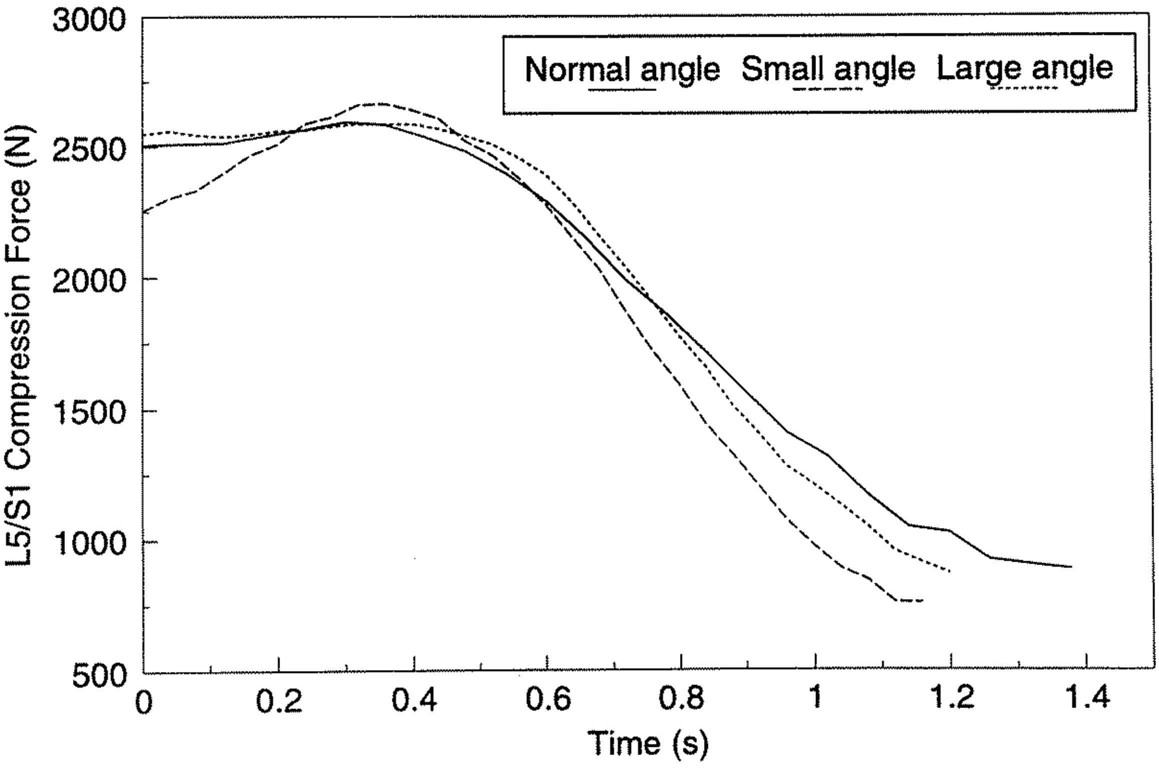

Fig. 16. L5/S1 Compression force.

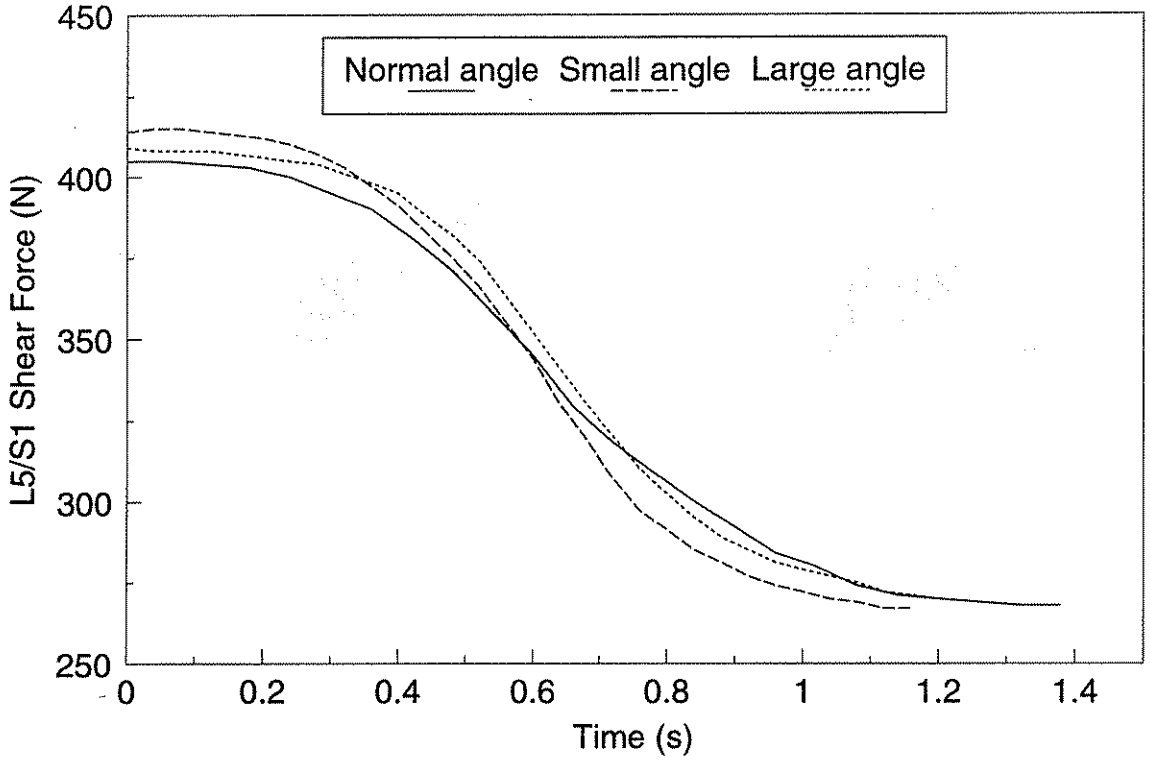

Fig. 17. L5/S1 Shear force.

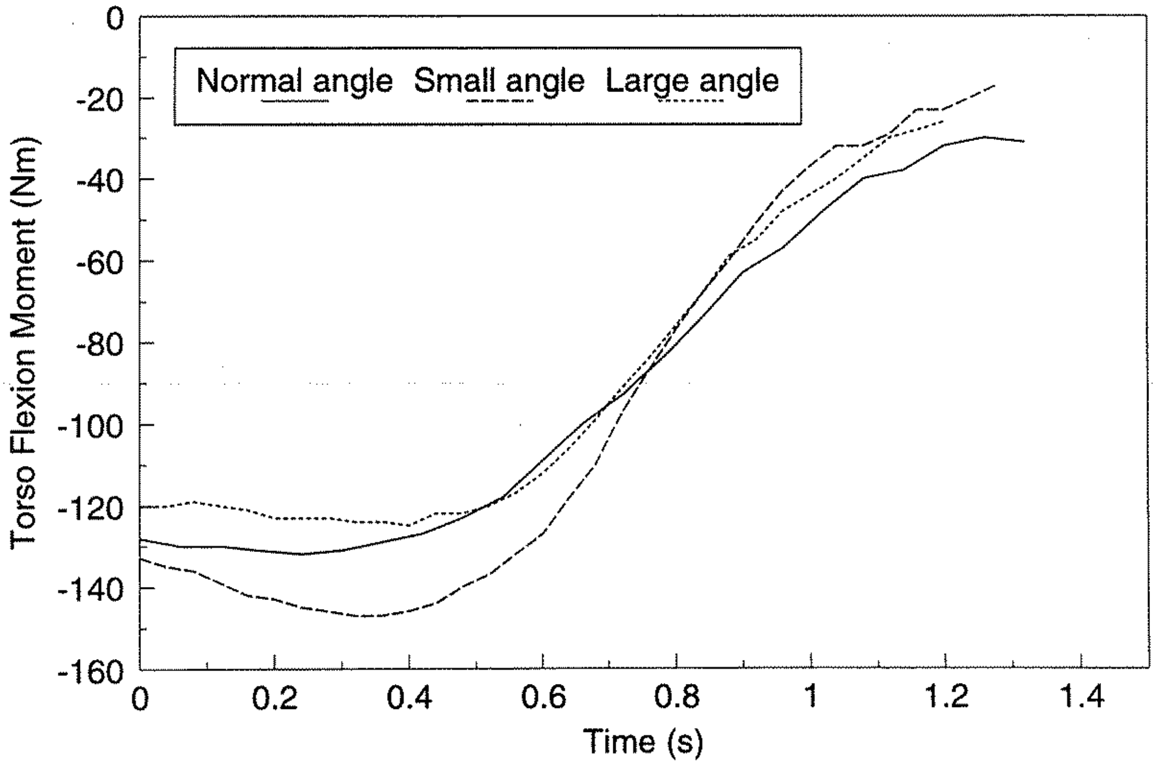

Fig. 18. Flexion moment at the torso.

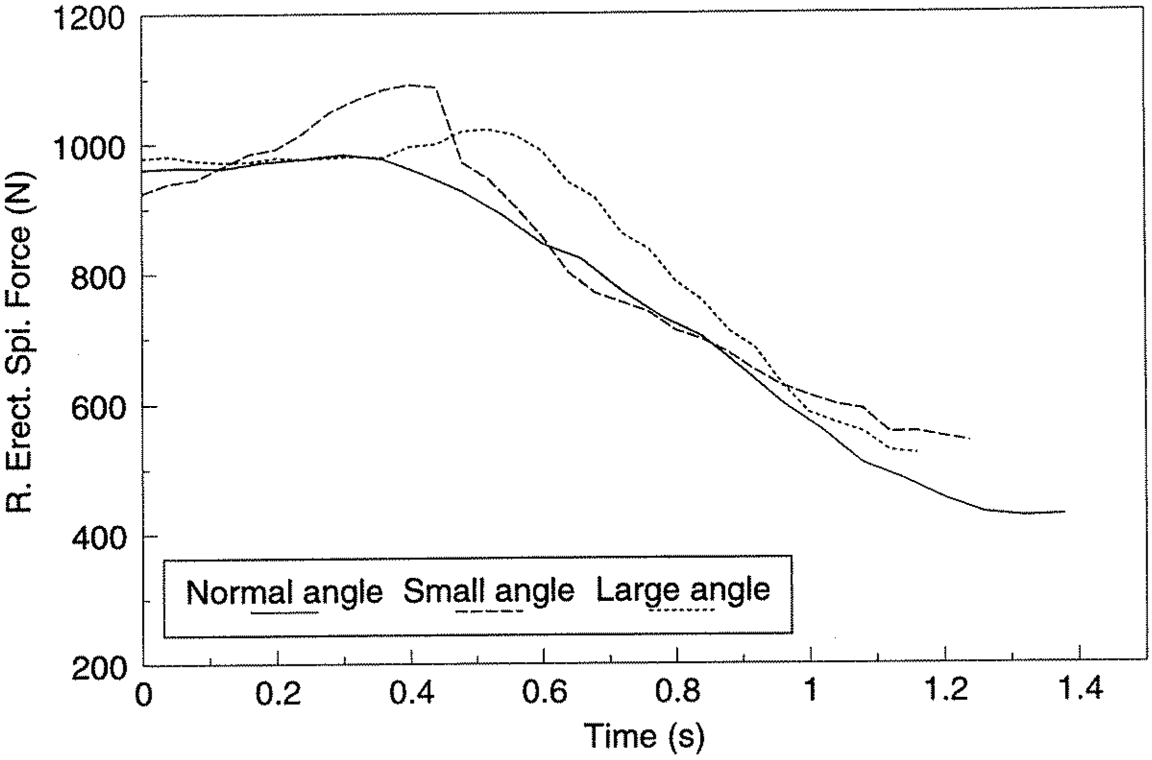

Fig. 19. Force on the Right Erector Spinae muscle at the L4/L5 level.

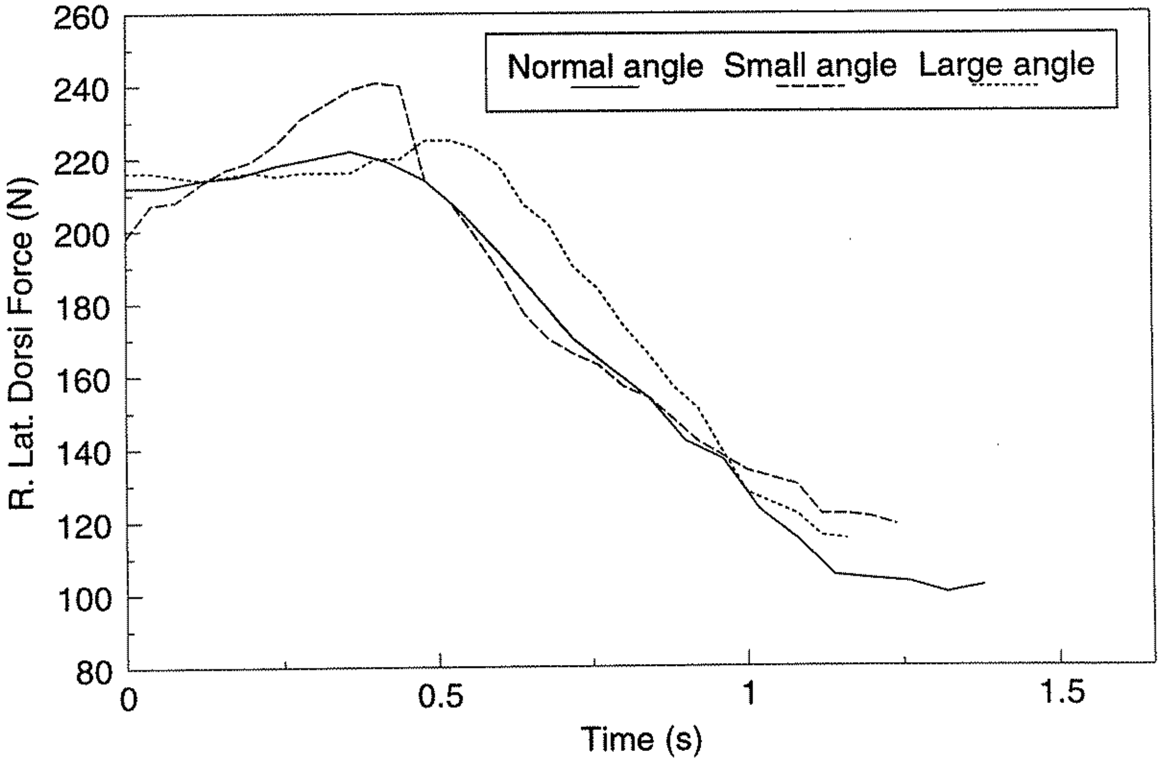

Fig. 20. Force on the Right Latissimus Dorsi muscle at the L4/L5 level.

When using a tool with a small shaft mounting angle, the subject has to increase the trunk flexion angle to reach the shaft. The trunk has to be flexed below the horizontal and the maximum compression force is not reached until approximately 0.4 s after the lift is started. With a large shaft mounting angle, the maximum flexion angle is decreased but the corresponding decrease in spine shear forces is smaller than expected. This may be explained by the effects of the decrease in trunk flexion being counteracted since the trunk is more bent in the lateral plane when the lifting of the shovel with large shaft angle is started.

Also the load on the muscles in the back was analysed. When using the tool with the large shaft mounting angle, the vertical distance between the two hand grip centres in the beginning of the lifting phase is increased and the axial rotation of the trunk thereby also increased. However, the effects of these variations in posture seem to have little effect on the analysed muscle loads.

3.4 Effects of shaft design

Shovels with the shaft bent in order to improve the working postures are available at the market. The purpose of these measurements was to study the effects on the biomechanical load using such a shovel. The design of the studied shovel is described in Fig. 21.

The data were recorded with 50 Hz and analysed with 25 Hz. Fig. 22 shows postures recorded in the beginning of the lifting phase using the shovel with the "normal" straight shaft to the left and the bent shaft to the right. Figs. 23 and 24 show the compression and shear forces on the spine when lifting the shovels.

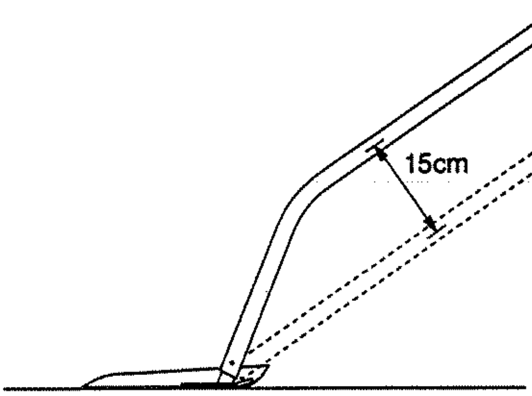

Fig. 21. Shovel with bent shaft used in the study.

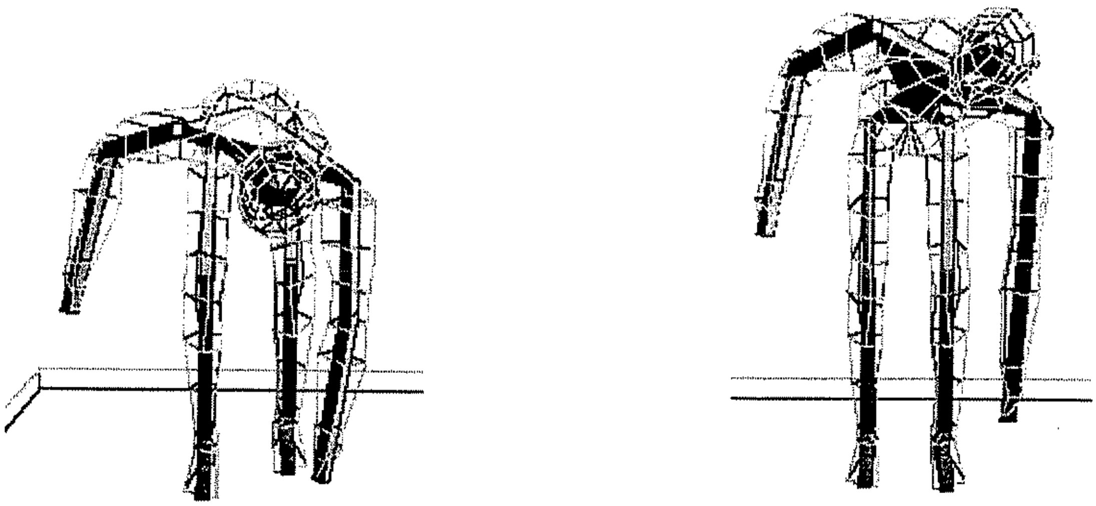

Fig. 22. Postures recorded when using the shovel with the normal straight shaft (left) and with the bent shaft (right).

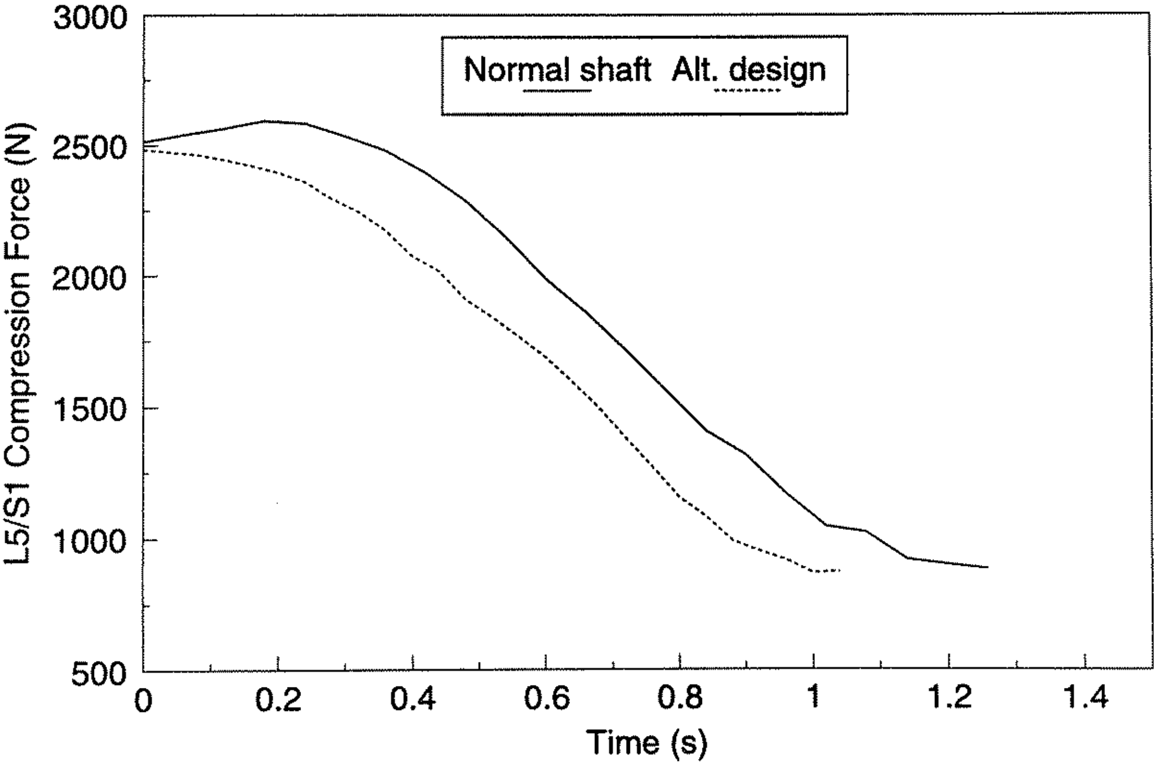

Fig. 23. L5/S1 Compression force.

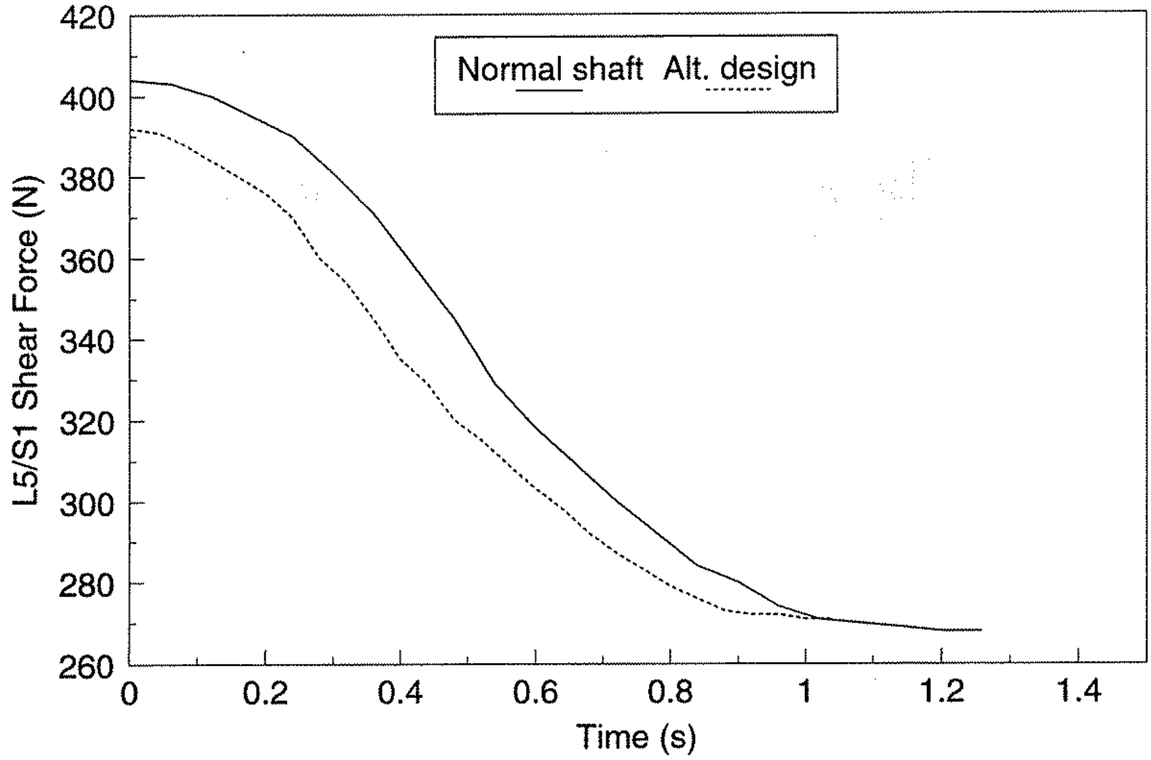

Fig. 24. L5/S1 Shear force.

Compared with the shovel defined as normal, the alternatively designed shaft decreases the trunk flexion in the beginning of the lifting phase. The maximum shear and compression forces are therefore decreased. Since the shovel is lifted a shorter vertical distance, the duration of the period with high load levels in the lifting phase is decreased.

3.5 Effects of operator anthropometry

The purpose of these measurements was to study the effects on the biomechanical load when subjects with varying anthropometry are handling the shovel. The loads on a "small" subject (length 1.69 m and weight 63 kg) and on a "large" subject (length 1.87 m and weight 92 kg) were therefore analysed and compared with the load on the "normal" subject studied in the previous measurements.

The data were recorded with 50 Hz and analysed with 25 Hz. Figs. 25 and 26 show the compression and shear forces on the spine when lifting the shovel.

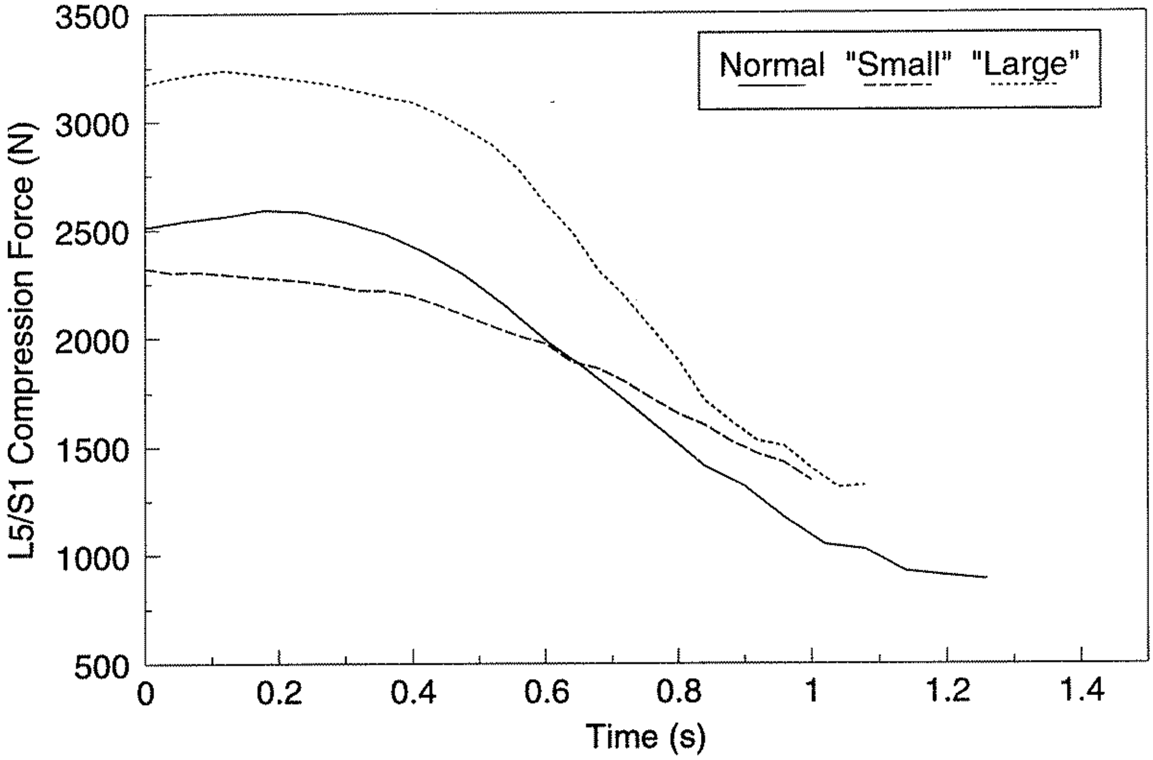

Fig. 25. L5/S1 Compression force.

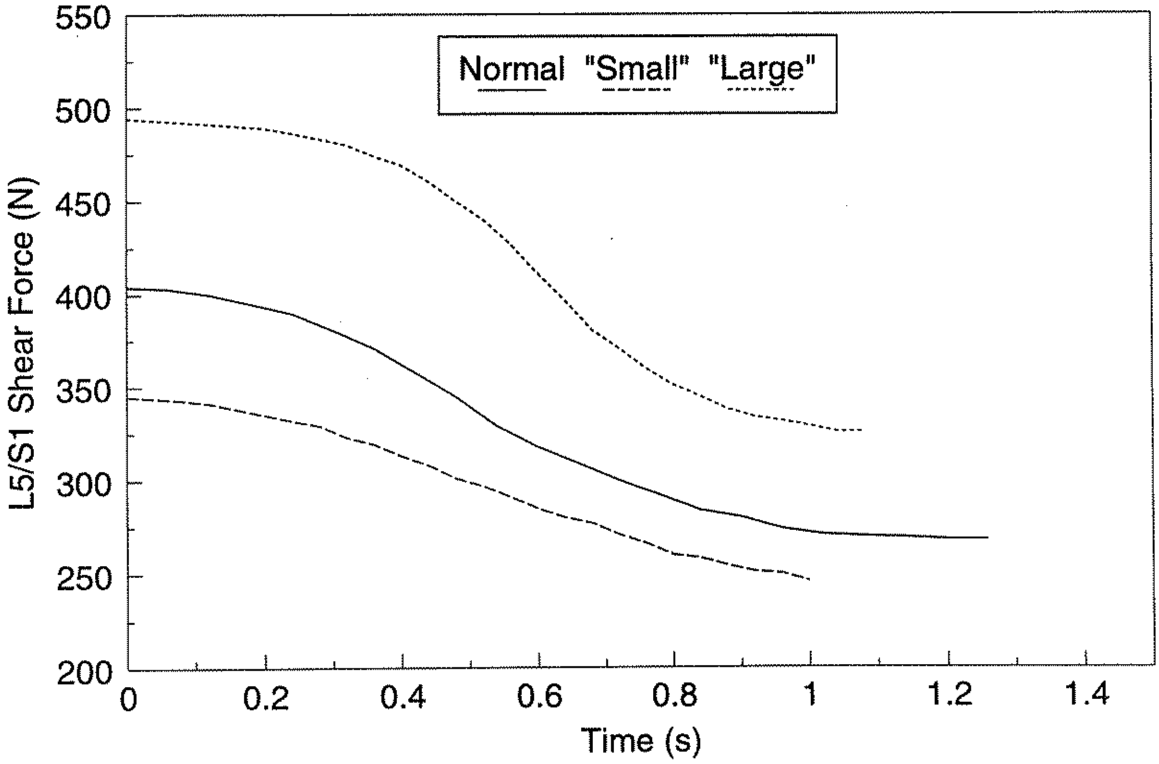

Fig. 26. L5/S1 Shear force.

The anthropometry of the subjects working with the shovel have great influence on the biomechanical load. The short subject does not have to flex the trunk so much to reach the lower part of the shovel and the spine forces are thereby decreased. The load components depending on the weight of the subject's own body are, of course, also smaller. The compression forces at the spine of the long and heavy person are very close to the NIOSH action limits.

4 BIOMECHANICAL LOAD WHEN WORKING WITH A RAKE AND A PUSH HOE

The analysis method developed was also used to study the biomechanical load when working with a rake and when working with a push hoe. The hand load vectors were calculated from data measured with strain gauge transducers on the shaft of the tool, and one purpose of these measurements was to find out if this technique was possible to use also in more comprehensive studies in the future.

When studying the load when working with a rake, two reflective markers were used to identify the direction of the tool, one on the upper part of the shaft and one on the lower part close to the rake. Strain gauge transducers were used to measure tension and bending moment at two places on the shaft; between the hand grips (G1 in Fig. 27) and between the lower hand grip and the rake (G2 in Fig. 27). It was assumed that no axial torque was applied to the shaft.

The measured axial tension forces at G1 and G2 were used together with the axial components of the weight of the tool and the shaft to calculate the hand force components in the axial direction. The positions of the grip centres of the hands were assumed to be the points on the shaft (the line between the two markers) that were closest to the markers on the left and right hand, respectively. The measured bending moment at G2 was used together with the radial components of the weight of the tool and the shaft to calculate the radial components of the hand force vectors.

The first experiment studied the loads when working with a rake to remove grass from a freshly-cut lawn. The body posture angles were measured using 17 reflective markers. The subject was the samw as before with a height of 1.80 m and a weight of 75 kg. The data were recorded at 50 Hz and analysed at 10 Hz. Fig. 28 shows the loading moment at the subject's right shoulder and Fig. 29 shows the moments at the lumbal spine (the L5-S1 level).

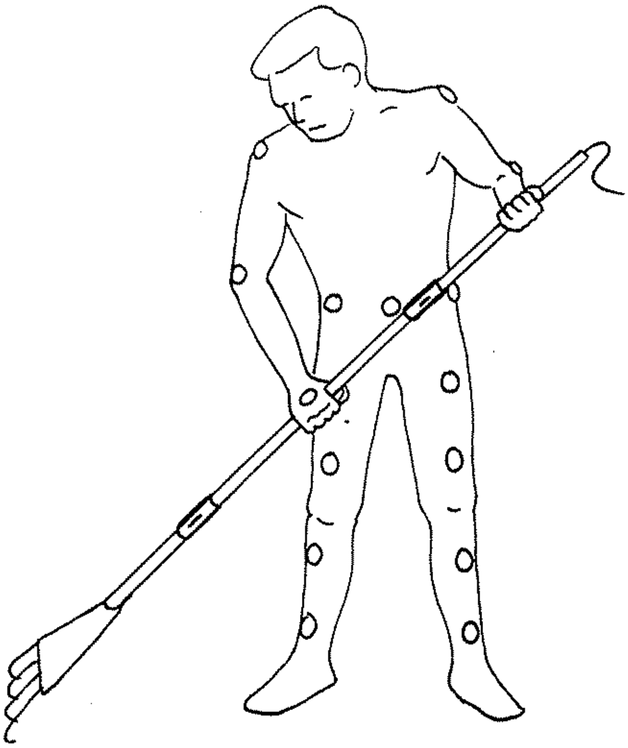

Fig. 27. The first experiment with a rake.

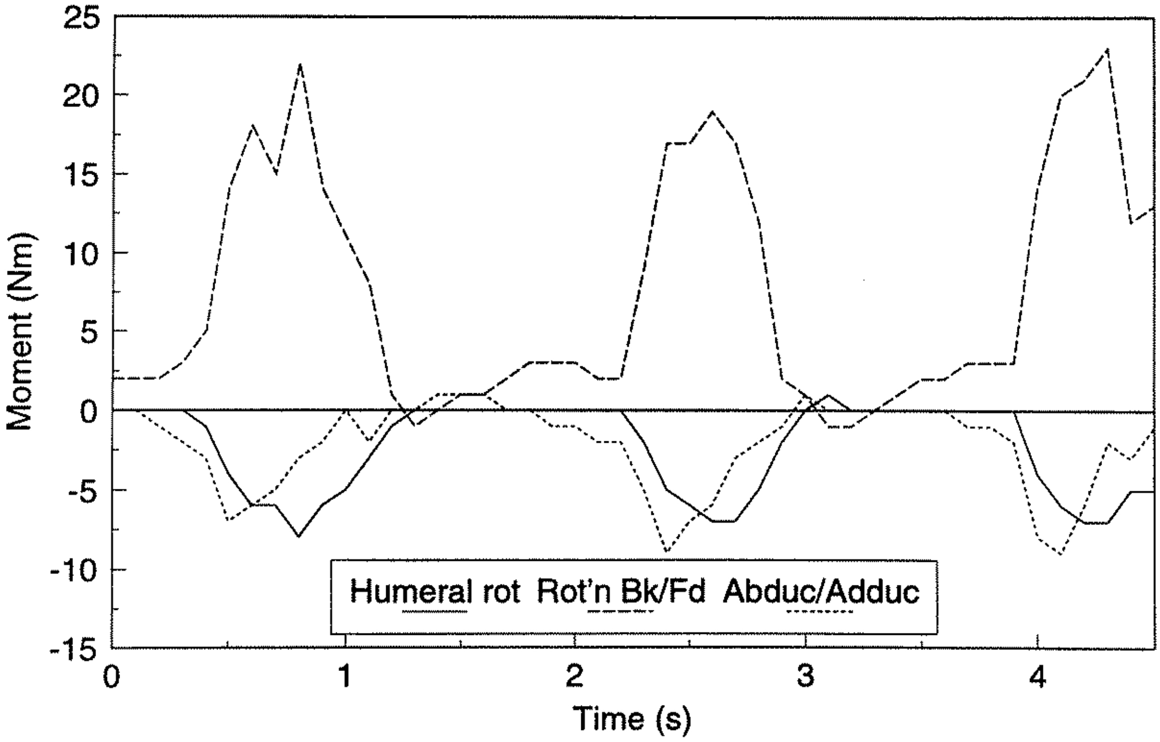

Fig. 28. Moments at the right shoulder joint.

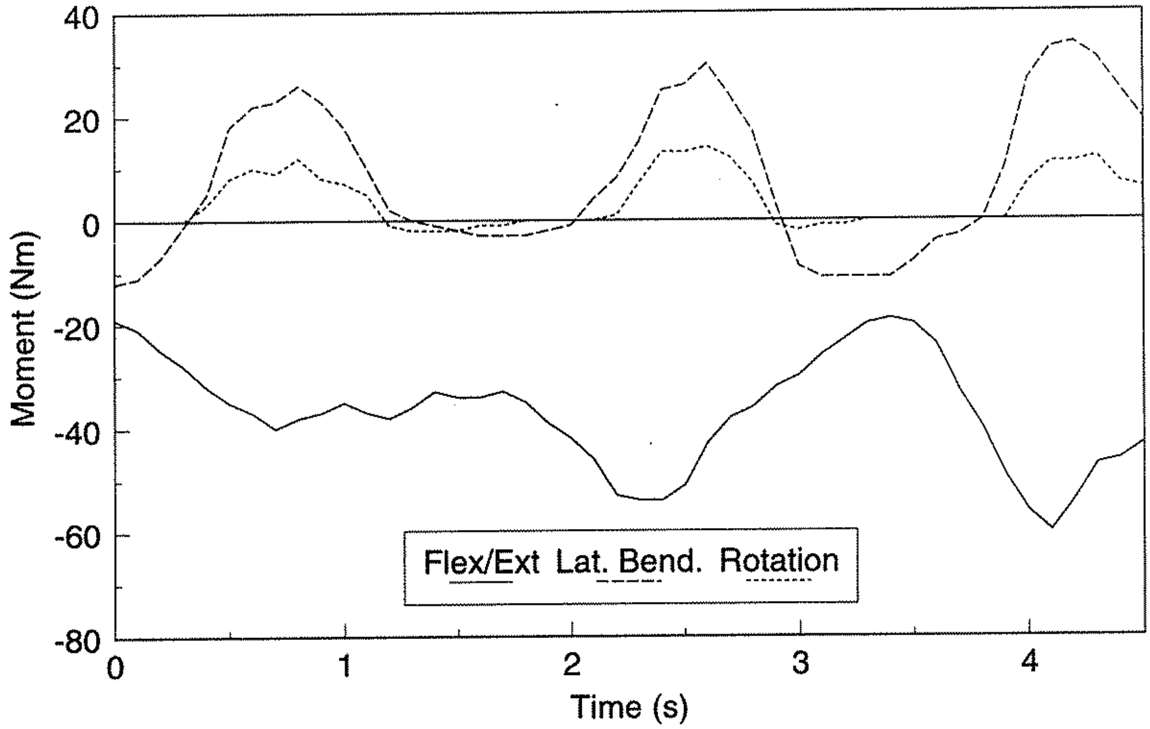

Fig. 29. Moments at the trunk (L5-S1).

The second experiment was performed to study the load when working with a hoe to remove weeds from a relatively compact soil. The subject was the same as in the prevoius experiment. The data was sampled at 50 Hz and analysed at 25 Hz.

Fig. 30 shows the loading moments in three dimensions at the right shoulder joint and at the right elbow.

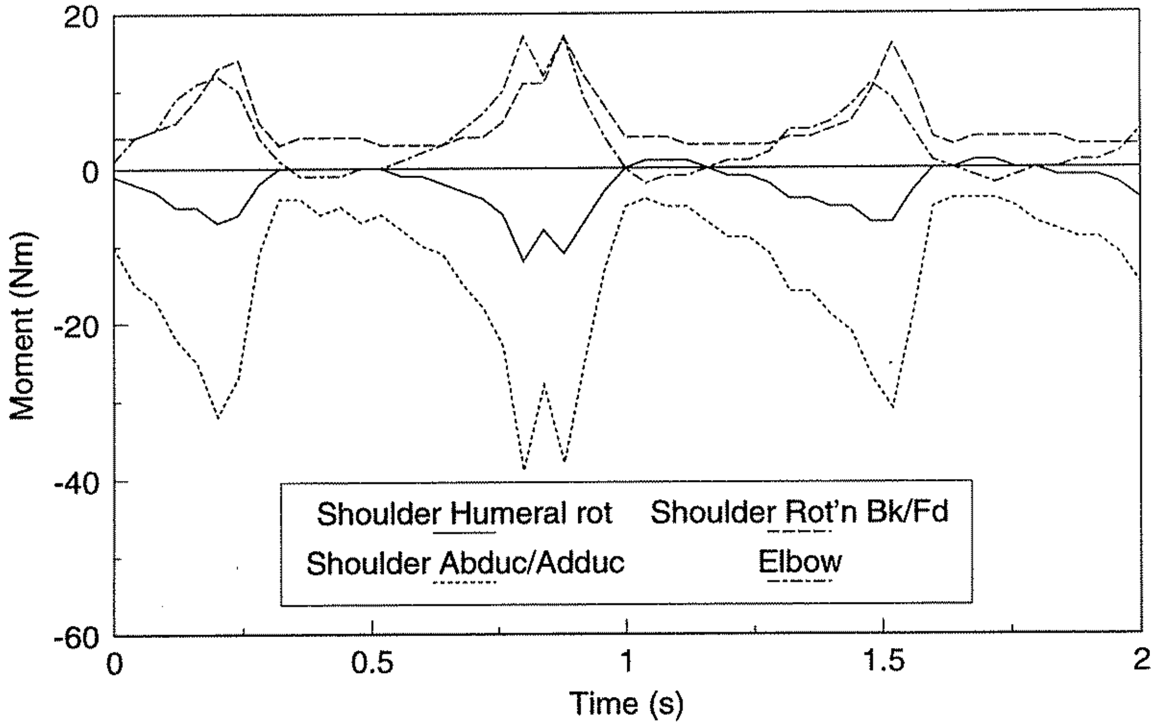

Fig. 30. Moments at the right shoulder joint and at the right elbow.

The analysis showed logical results and the measurement technique used seems to be very appropiate. However, especially the results of the hoe study were found to be very dependent on the type of soil and the technique applied when using the tool. To be able to identify representative amplitudes for the different curves, more studies must be performed.

5 DISCUSSION

5.1 The analysis method

The method showed good characteristics when performing the described studies and seems to be a very useful tool for studies of the biomechanical load when working with manually operated shaft tools. The possibility to compare the results with population strength capability data is very valuable for numerous applications even if not dealt with in this report. It must, however, be stated that the results from biomechanical models, static or dynamic, cannot be used as the only measurement of work load. Other criteria and professional judgements are also required to properly design safe and productive work places.

The method is based on calculation of static load and when a working task including dynamics is to be studied, the activity must be described as a sequence of static postures. This is a simplification and the validity of the results obtained when analysing working tasks including fast movements and/or dynamical load may be restricted.

The studies showed that it was impossible to avoid some markers being hidden by other body segments, and therefore not being recorded by the instruments. The program developed to fill in the gaps in the data was found to be very appropiate and with good function.

The position measurement system uses passive markers, not requiring any power input, and the subject is therefore not restricted in movement by any wires. However, it does carry the penalty of not being able to associate the bright projections on the recorded picture with the physical markers that created those projections. The identification of the markers and the assignment of the markers to the correct marker names are normally controlled by the MacReflex software. The operator only has to assist when markers reappear after a period of interruption or when the software by mistake confuses two markers. In some of the recorded postures, many markers were located in a small area in the camera pictures. The identification and sorting procedure when analysing some parts of these recordings were found to be rather time-consuming, mainly because of difficulties for the system to keep one marker tracked when another marker appears close to the first one.

The studies described were performed both in the lab and outdoors. The experiences from these studies showed that the use of battery power introduced no problems. However, the position measurement system seemed to be unsuitable for measurements in direct sunshine, when the recorded pictures were so bright that the video processors were unable to distinguish between reflections from the markers and the background.

The 3DSSPP biomechanical model was chosen as the base for the method since it is three-dimensional, well-known, validated against practical measurements, and presents a detailed output, which is especially useful when studying loads on the back and the upper parts of the body. One limitation for the 3DSSPP model is, however, that the subject's anthropometry is defined only by gender, height and weight, and no consideration is paid to individual variations.

Human joints are complex structures and it is very difficult to decide exactly the positions of the joint rotation centres. Factors complicating the task are pertubations of the marker positions depending on skin motion or muscle movements. If focusing on the position of the trunk, a reasonable maximal error for the estimation of the trunk flexion, rotation and lateral bend may be ±3 degrees, which corresponds to an error in marker position of approximately 3 cm if the length of the body segment is 0.50 m. A sensitivity analysis was performed in order to study the changes of the calculated forces at the spine, when the trunk posture angles were varied ±3 degrees one at a time. The calculated loads were relatively robust to these variations with a maximal deviation of 4 %.

The maximum noise when measuring the positions of the reflective markers is defined to be max 0.010 % of the field of view of the cameras (0.3 mm for f.o.w. = 3 m) (Qualisys, 1993). A study performed in order to study the characteristics of the optoelectronic system when used for acceleration measurements (Hansson and Öberg, 1994) also showed that the system is very accurate. The inaccuracies of the position measurement system can therefore probably be neglected when discussing the overall accuracy of the analysis method.

5.2 The results

There are no standardized limits for the allowed ranges of the analysed biomechanical load variables, except for the compression force on the spine. However, even without accepted limits for the load components, the well-known occurrence of body injury, both in longer and shorter terms, implies that the loads are (too) high and all possibilities to decrease the loads have to be considered as positive. This is especially important since most shovelling work is of repetitive nature, and the cumulative effects of a rather small improvement may be very marked in the longer term.

The highest spine compression load in the study is found when studying the "large" person in Chapter 3.5. However, it is reasonable to believe that a tall and well-built person also has a stronger spine capable of dealing with heavier loads without potential injury. The results also show that differences in biomechanical load between a "small" and a "large" operator is very high. The biomechanical model uses the same lever arms of the back muscles for both small and large subjects. It is likely that larger people also have somewhat longer muscle lever arms than smaller subjects. This factor may reduce the differences of the forces at the lumbar discs between the two types.

A lot of factors must be considered when designing a hand tool. Besides the ergonomics, is it, of course, very important that the tool is well suited for the working operation it is intended for. A more special design, as for example the shovel with a long shaft studied in Ch. 3.2, may have very good characteristics for a special type of working task, but may be of limited use for other working tasks. The shovel with the angled shaft studied in Ch. 3.4 is probably a better compromise between allround usability and biomechanical load reduction.

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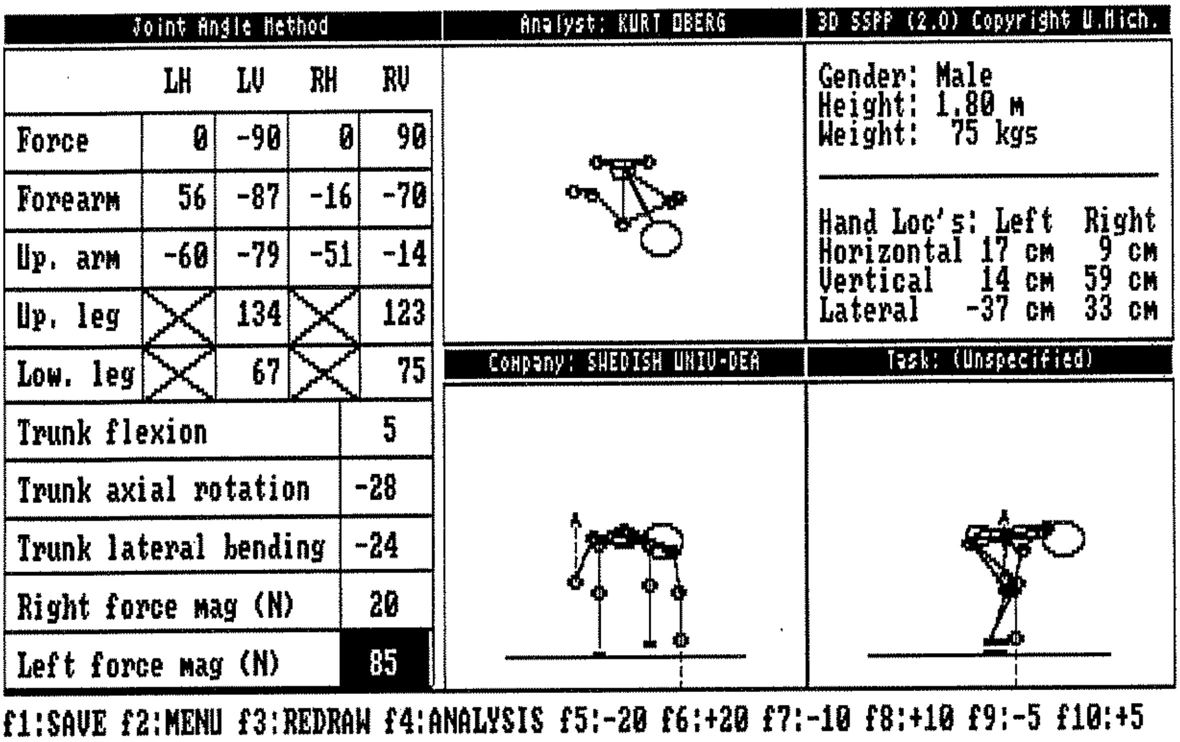
APPENDIX



Joint Angle Method | Analyst: KURT OBERG | 3D SSPP (2.0) Copyright U.Mich.

	LH	LV	RH	RV
Force	0	-90	0	90
Forearm	56	-87	-16	-70
Up. arm	-60	-79	-51	-14
Up. leg	☒	134	☒	123
Low. leg	☒	67	☒	75
Trunk flexion				5
Trunk axial rotation				-28
Trunk lateral bending				-24
Right force mag (N)				20
Left force mag (N)				85

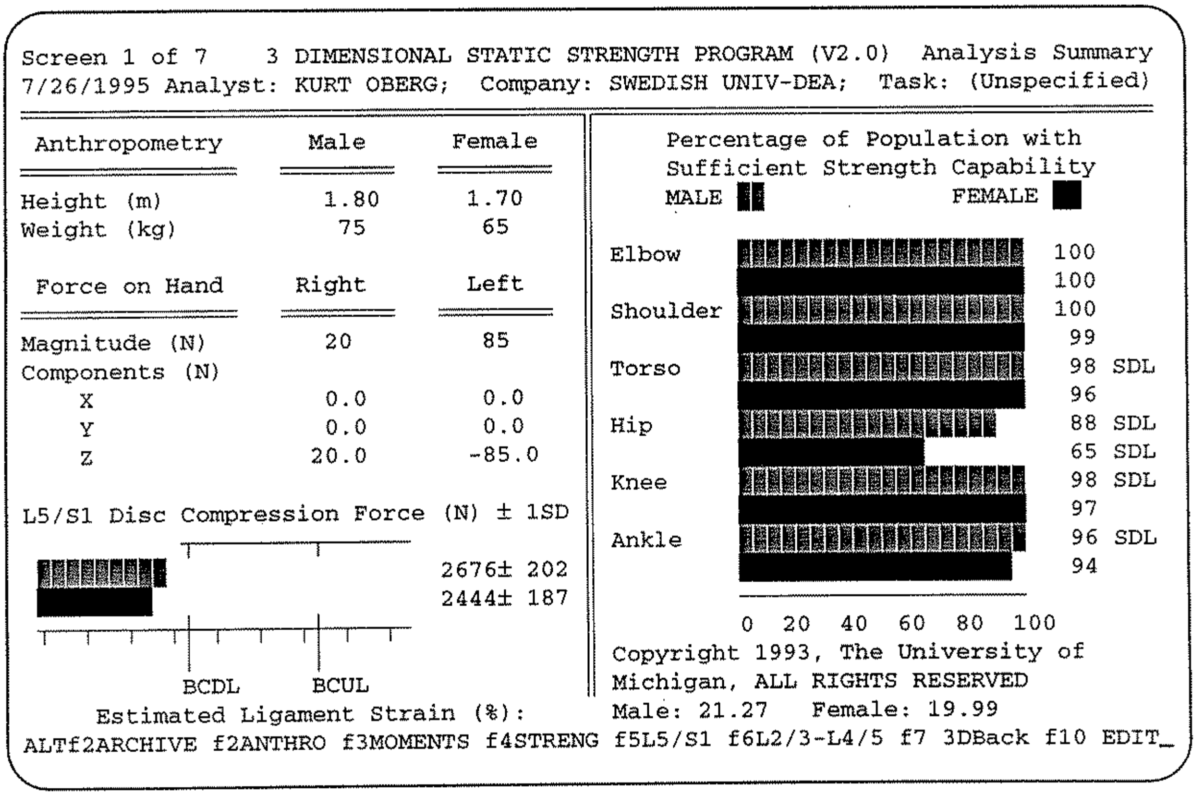
Gender: Male
Height: 1.80 m
Weight: 75 kgs

Hand Loc's:	Left	Right
Horizontal	17 cm	9 cm
Vertical	14 cm	59 cm
Lateral	-37 cm	33 cm

Company: SWEDISH UNIV-DEA

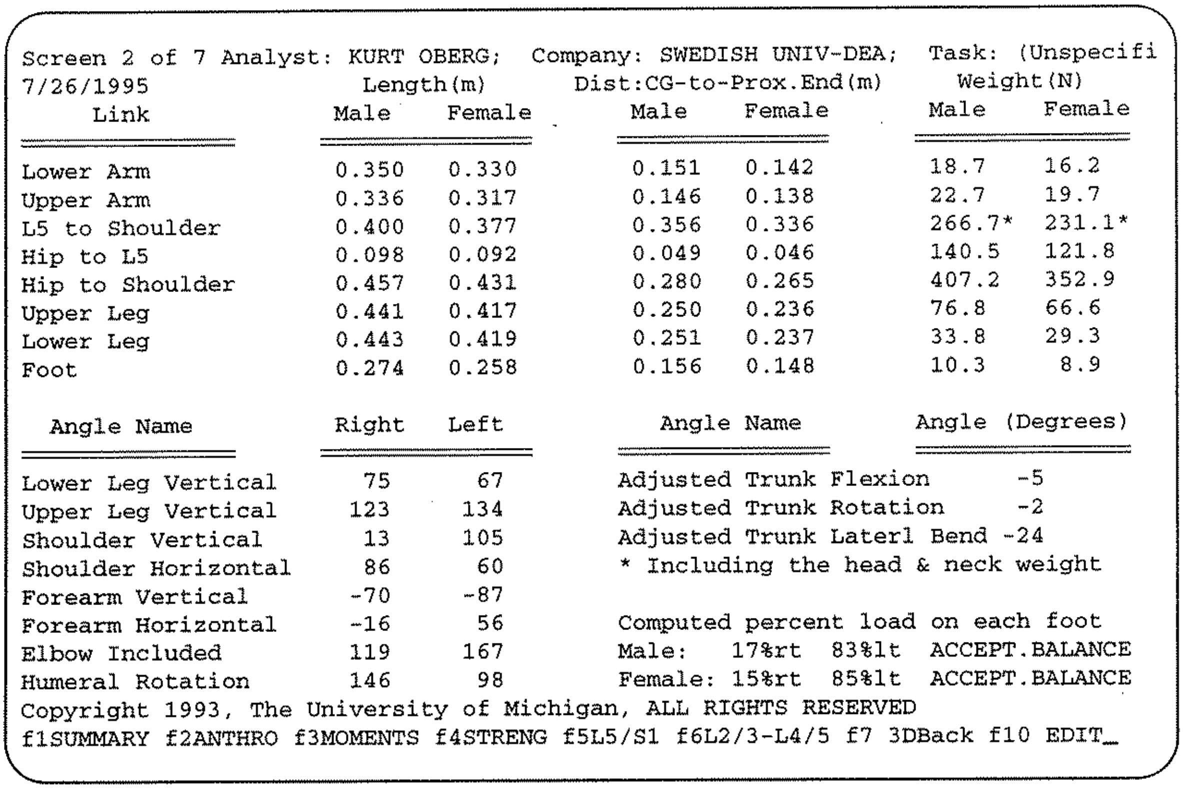
Task: (Unspecified)

f1:SAVE f2:MENU f3:REDRAW f4:ANALYSIS f5:-20 f6:+20 f7:-10 f8:+10 f9:-5 f10:+5



```
Screen 1 of 7     3 DIMENSIONAL STATIC STRENGTH PROGRAM (V2.0)  Analysis Summary
7/26/1995 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecified)

 Anthropometry        Male      Female     Percentage of Population with
                                           Sufficient Strength Capability
Height  (m)           1.80      1.70       MALE                 FEMALE
Weight  (kg)           75        65
                                         Elbow                        100
 Force on Hand       Right      Left                                  100
                                         Shoulder                     100
Magnitude (N)          20        85                                    99
Components (N)                           Torso                         98  SDL
    X                 0.0       0.0                                    96
    Y                 0.0       0.0      Hip                           88  SDL
    Z                20.0     -85.0                                    65  SDL
                                         Knee                          98  SDL
L5/S1 Disc Compression Force (N) ± 1SD                                 97
                                         Ankle                         96  SDL
                             2676± 202                                 94
                             2444± 187
                                              0  20  40  60  80  100
                                         Copyright 1993, The University of
         BCDL      BCUL                  Michigan, ALL RIGHTS RESERVED
    Estimated Ligament Strain (%):       Male: 21.27    Female: 19.99
ALTf2ARCHIVE f2ANTHRO f3MOMENTS f4STRENG f5L5/S1 f6L2/3-L4/5 f7 3DBack f10 EDIT_
```

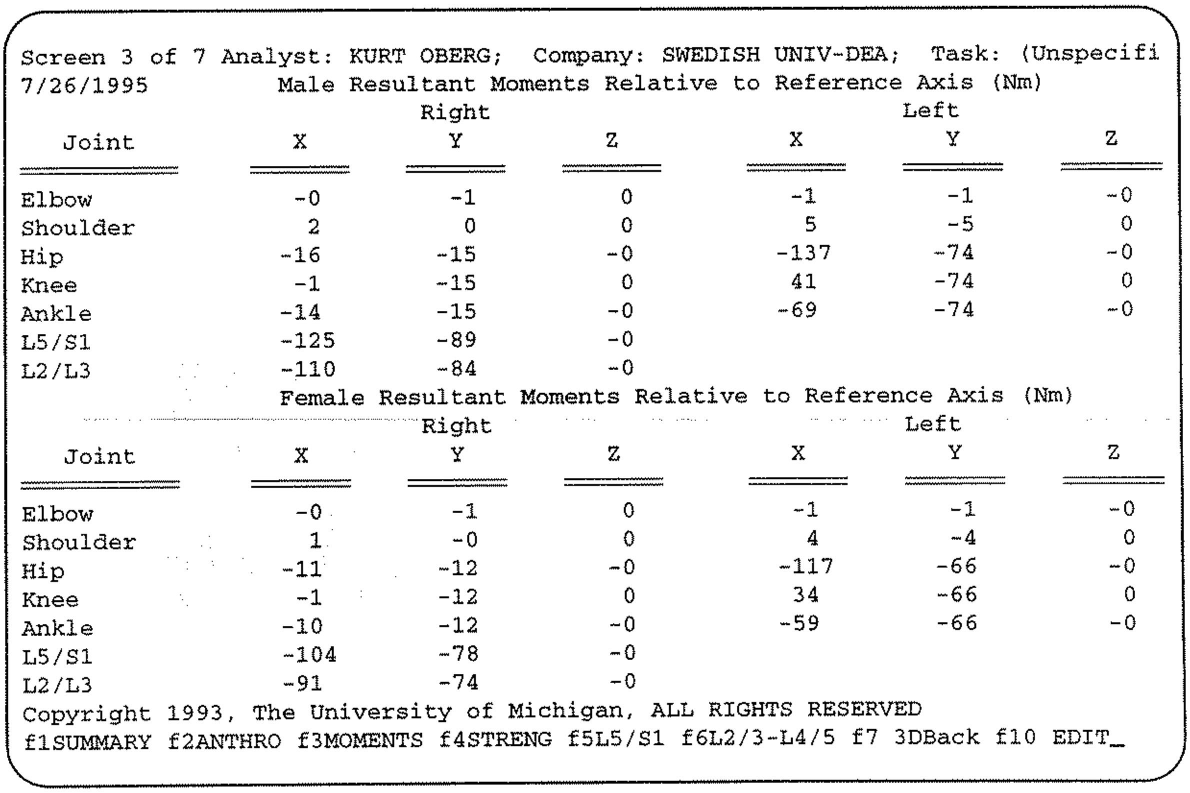


```
Screen 2 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
7/26/1995              Length(m)         Dist:CG-to-Prox.End(m)     Weight(N)
     Link            Male    Female        Male    Female        Male    Female
===============      ==============        ==============        ==============

Lower Arm            0.350   0.330         0.151   0.142         18.7     16.2
Upper Arm            0.336   0.317         0.146   0.138         22.7     19.7
L5 to Shoulder       0.400   0.377         0.356   0.336         266.7*   231.1*
Hip to L5            0.098   0.092         0.049   0.046         140.5    121.8
Hip to Shoulder      0.457   0.431         0.280   0.265         407.2    352.9
Upper Leg            0.441   0.417         0.250   0.236         76.8     66.6
Lower Leg            0.443   0.419         0.251   0.237         33.8     29.3
Foot                 0.274   0.258         0.156   0.148         10.3      8.9

  Angle Name         Right   Left            Angle Name         Angle (Degrees)
===============      ==============        ==============        ==============

Lower Leg Vertical     75     67         Adjusted Trunk Flexion        -5
Upper Leg Vertical    123    134         Adjusted Trunk Rotation       -2
Shoulder Vertical      13    105         Adjusted Trunk Laterl Bend -24
Shoulder Horizontal    86     60         * Including the head & neck weight
Forearm Vertical      -70    -87
Forearm Horizontal    -16     56         Computed percent load on each foot
Elbow Included        119    167         Male:    17%rt   83%lt  ACCEPT.BALANCE
Humeral Rotation      146     98         Female: 15%rt   85%lt  ACCEPT.BALANCE
Copyright 1993, The University of Michigan, ALL RIGHTS RESERVED
f1SUMMARY f2ANTHRO f3MOMENTS f4STRENG f5L5/S1 f6L2/3-L4/5 f7 3DBack f10 EDIT_
```



```
Screen 3 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
7/26/1995         Male Resultant Moments Relative to Reference Axis (Nm)
                             Right                             Left
   Joint           X           Y           Z            X           Y          Z
===========     =======     =======     =======      =======     =======    =======

Elbow             -0          -1           0           -1          -1         -0
Shoulder           2           0           0            5          -5          0
Hip              -16         -15          -0         -137         -74         -0
Knee              -1         -15           0           41         -74          0
Ankle            -14         -15          -0          -69         -74         -0
L5/S1           -125         -89          -0
L2/L3           -110         -84          -0
                  Female Resultant Moments Relative to Reference Axis (Nm)
                             Right                             Left
   Joint           X           Y           Z            X           Y          Z
===========     =======     =======     =======      =======     =======    =======

Elbow             -0          -1           0           -1          -1         -0
Shoulder           1          -0           0            4          -4          0
Hip              -11         -12          -0         -117         -66         -0
Knee              -1         -12           0           34         -66          0
Ankle            -10         -12          -0          -59         -66         -0
L5/S1           -104         -78          -0
L2/L3            -91         -74          -0
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f1SUMMARY f2ANTHRO f3MOMENTS f4STRENG f5L5/S1 f6L2/3-L4/5 f7 3DBack f10 EDIT_
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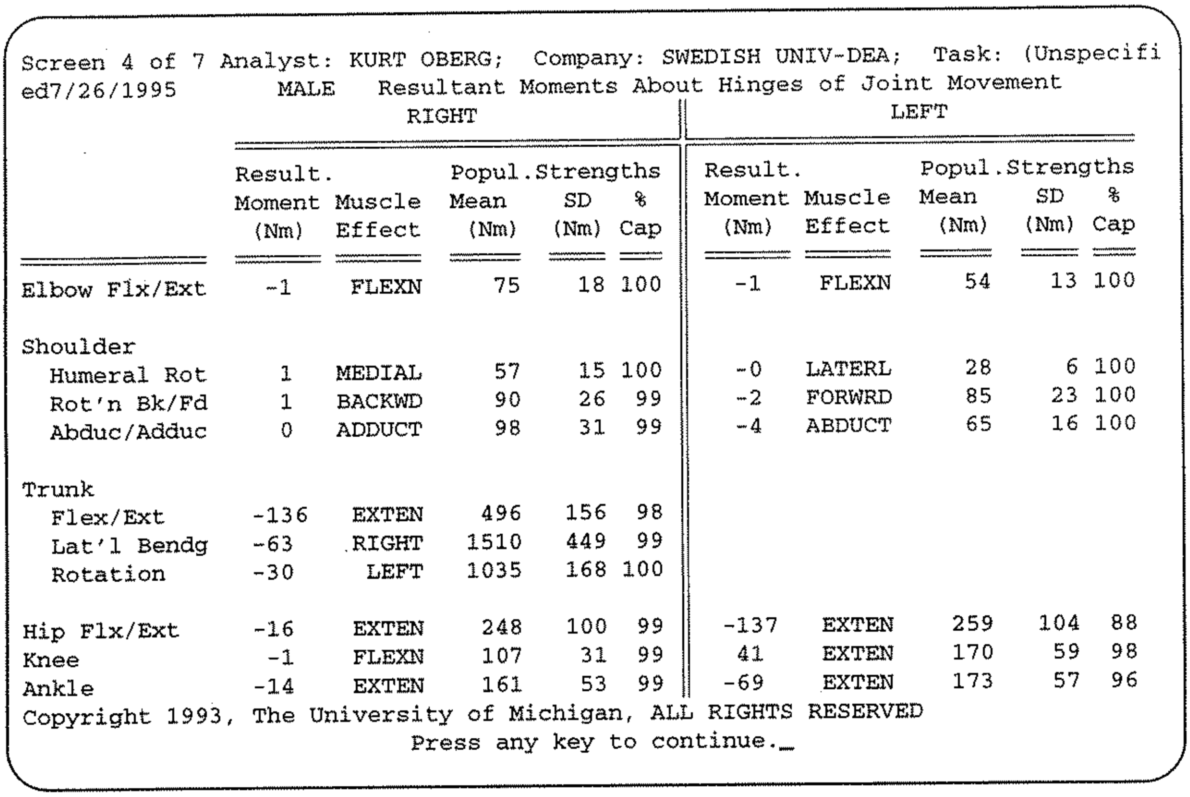

```
Screen 4 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
ed7/26/1995      MALE   Resultant Moments About Hinges of Joint Movement
                         RIGHT                  ||                 LEFT
                ==================================||===============================
                Result.           Popul.Strengths || Result.           Popul.Strengths
                Moment  Muscle    Mean    SD   %  || Moment  Muscle    Mean    SD   %
                 (Nm)   Effect    (Nm)   (Nm) Cap ||  (Nm)   Effect    (Nm)   (Nm) Cap
=======         ======  ======    ====   ==== === || ======  ======    ====   ==== ===
Elbow Flx/Ext     -1     FLEXN     75     18 100  ||   -1     FLEXN     54     13 100

Shoulder
  Humeral Rot      1    MEDIAL     57     15 100  ||   -0    LATERL     28      6 100
  Rot'n Bk/Fd      1    BACKWD     90     26  99  ||   -2    FORWRD     85     23 100
  Abduc/Adduc      0    ADDUCT     98     31  99  ||   -4    ABDUCT     65     16 100

Trunk
  Flex/Ext       -136    EXTEN    496    156  98  ||
  Lat'l Bendg     -63    RIGHT   1510    449  99  ||
  Rotation        -30     LEFT   1035    168 100  ||

Hip Flx/Ext       -16    EXTEN    248    100  99  || -137     EXTEN    259    104  88
Knee               -1    FLEXN    107     31  99  ||   41     EXTEN    170     59  98
Ankle             -14    EXTEN    161     53  99  ||  -69     EXTEN    173     57  96
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                      Press any key to continue._
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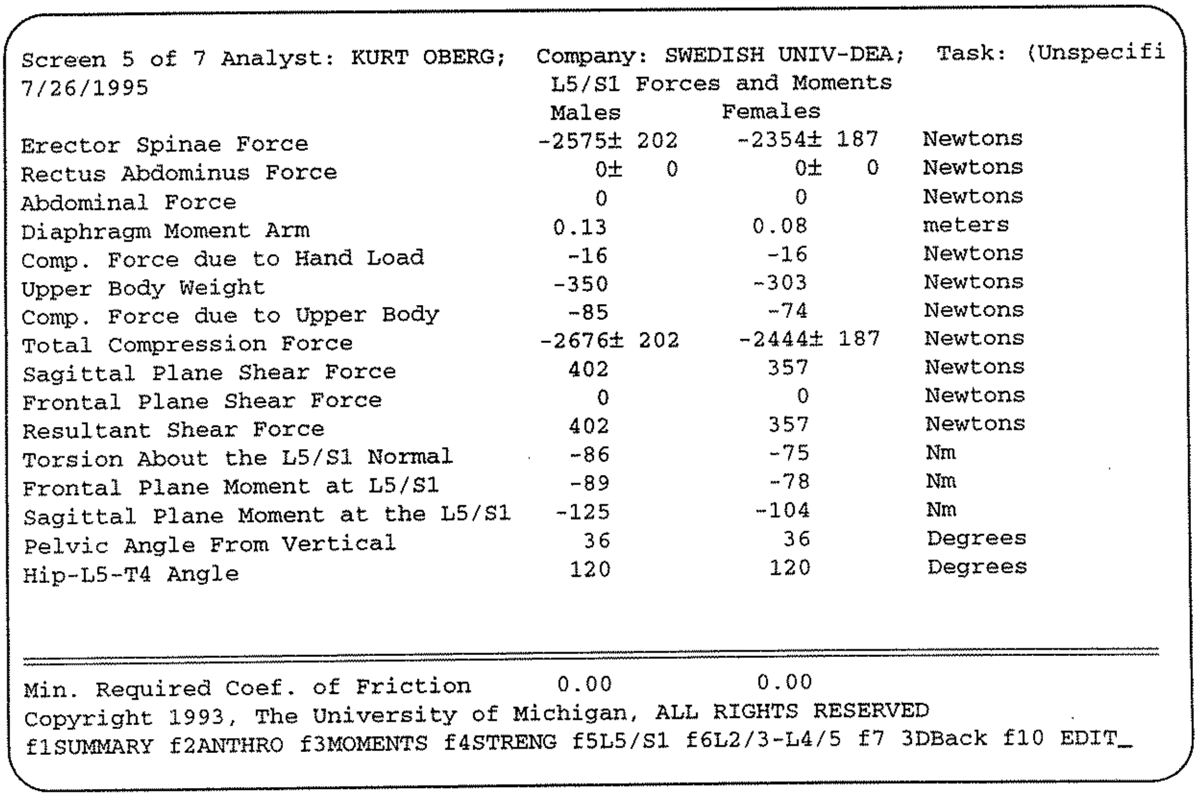

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Screen 5 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
7/26/1995                            L5/S1 Forces and Moments
                                      Males        Females
Erector Spinae Force                -2575± 202   -2354± 187   Newtons
Rectus Abdominus Force                  0±   0       0±   0   Newtons
Abdominal Force                         0            0        Newtons
Diaphragm Moment Arm                 0.13         0.08        meters
Comp. Force due to Hand Load          -16          -16        Newtons
Upper Body Weight                    -350         -303        Newtons
Comp. Force due to Upper Body         -85          -74        Newtons
Total Compression Force             -2676± 202   -2444± 187   Newtons
Sagittal Plane Shear Force            402          357        Newtons
Frontal Plane Shear Force               0            0        Newtons
Resultant Shear Force                 402          357        Newtons
Torsion About the L5/S1 Normal        -86          -75        Nm
Frontal Plane Moment at L5/S1         -89          -78        Nm
Sagittal Plane Moment at the L5/S1   -125         -104        Nm
Pelvic Angle From Vertical             36           36        Degrees
Hip-L5-T4 Angle                       120          120        Degrees


==============================================================================
Min. Required Coef. of Friction      0.00         0.00
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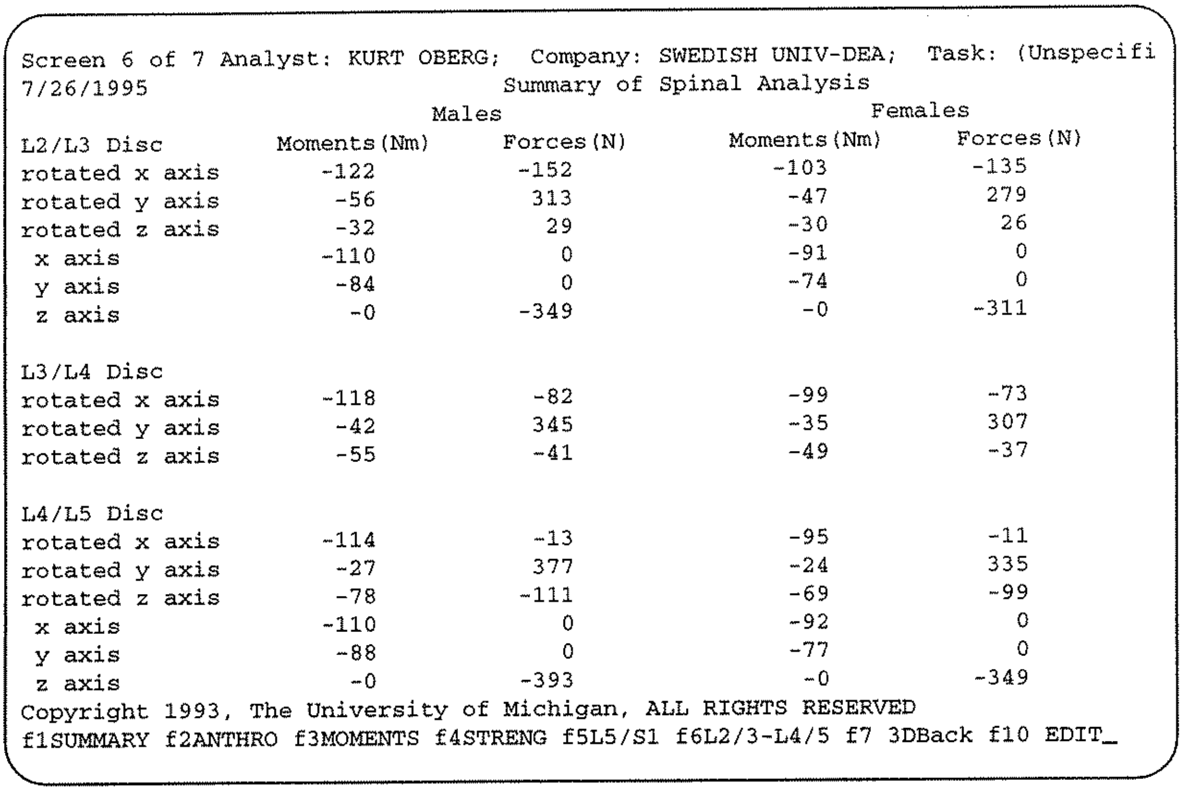
f1SUMMARY f2ANTHRO f3MOMENTS f4STRENG f5L5/S1 f6L2/3-L4/5 f7 3DBack f10 EDIT_
```



```
Screen 6 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
7/26/1995                          Summary of Spinal Analysis
                               Males                          Females
L2/L3 Disc          Moments(Nm)     Forces(N)       Moments(Nm)     Forces(N)
rotated x axis         -122           -152              -103           -135
rotated y axis          -56            313               -47            279
rotated z axis          -32             29               -30             26
 x axis                -110              0               -91              0
 y axis                 -84              0               -74              0
 z axis                  -0           -349                -0           -311

L3/L4 Disc
rotated x axis         -118            -82               -99            -73
rotated y axis          -42            345               -35            307
rotated z axis          -55            -41               -49            -37

L4/L5 Disc
rotated x axis         -114            -13               -95            -11
rotated y axis          -27            377               -24            335
rotated z axis          -78           -111               -69            -99
 x axis                -110              0               -92              0
 y axis                 -88              0               -77              0
 z axis                  -0           -393                -0           -349
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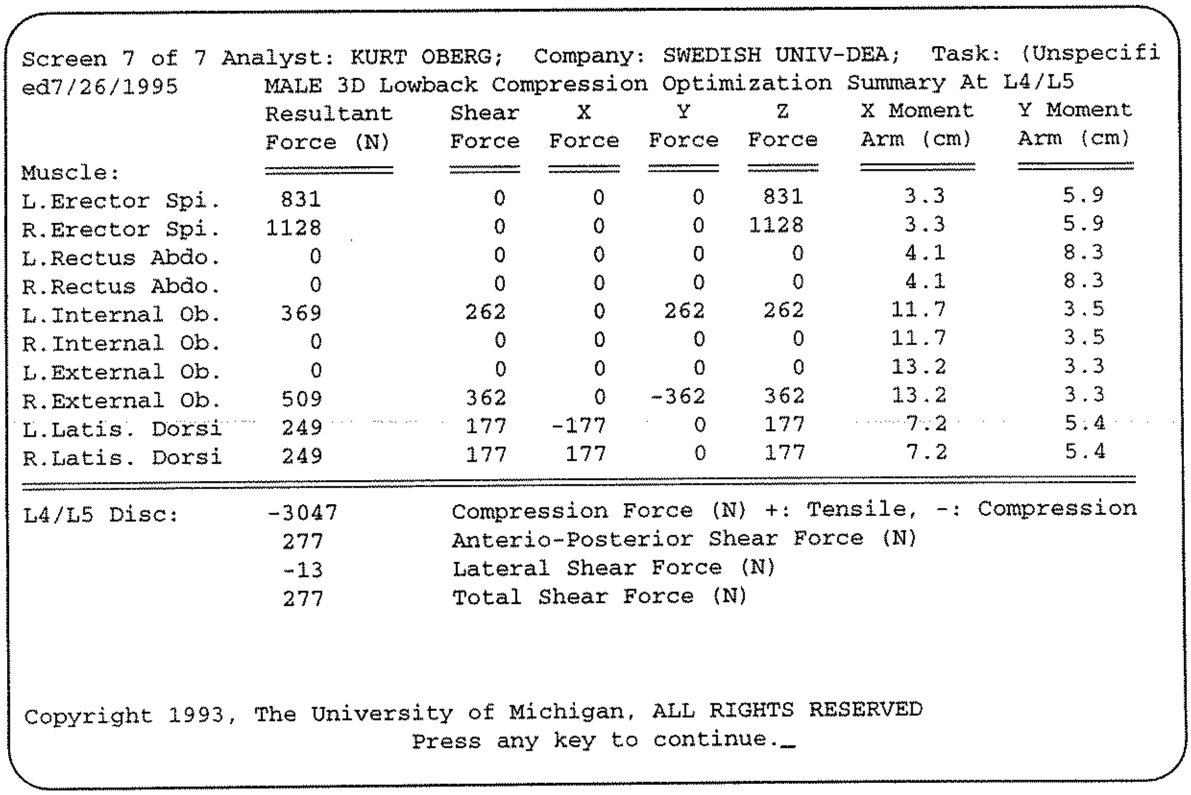
f1SUMMARY f2ANTHRO f3MOMENTS f4STRENG f5L5/S1 f6L2/3-L4/5 f7 3DBack f10 EDIT_
```



```
Screen 7 of 7 Analyst: KURT OBERG;  Company: SWEDISH UNIV-DEA;  Task: (Unspecifi
ed7/26/1995      MALE 3D Lowback Compression Optimization Summary At L4/L5
                 Resultant   Shear    X      Y      Z     X Moment   Y Moment
                 Force (N)   Force  Force  Force  Force   Arm (cm)   Arm (cm)
Muscle:          =========   =====  =====  =====  =====   ========   ========
L.Erector Spi.    831          0      0      0     831       3.3        5.9
R.Erector Spi.   1128          0      0      0    1128       3.3        5.9
L.Rectus Abdo.      0          0      0      0       0       4.1        8.3
R.Rectus Abdo.      0          0      0      0       0       4.1        8.3
L.Internal Ob.    369        262      0    262     262      11.7        3.5
R.Internal Ob.      0          0      0      0       0      11.7        3.5
L.External Ob.      0          0      0      0       0      13.2        3.3
R.External Ob.    509        362      0   -362     362      13.2        3.3
L.Latis. Dorsi    249        177   -177      0     177       7.2        5.4
R.Latis. Dorsi    249        177    177      0     177       7.2        5.4
=============================================================================
L4/L5 Disc:      -3047       Compression Force (N) +: Tensile, -: Compression
                   277       Anterio-Posterior Shear Force (N)
                   -13       Lateral Shear Force (N)
                   277       Total Shear Force (N)



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                              Press any key to continue._
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