On a 55/5 second minute of light assembly work by women: effects of work/recovery ratios on discomfort and loading on the low back

by

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ABSTRACT

On a 55/5 second minute of light assembly work by women: effects of work/recovery ratios on discomfort and loading on the low back

Competition in industry has resulted in a reduction in the workforce. To maintain production rate, tasks have been added to existing jobs resulting in longer work durations and shorter recovery pauses. Recovery pauses of 20-35 seconds in a work cycle of one minute in one large automobile industry are being reduced to five seconds so that individuals work 55 seconds per minute. The purpose of this thesis was to improve the understanding of the effects of a "55/5 second minute" of a simulated industrial "light" assembly task on the magnitude of risk factors which have been proven or proposed to be related to the reporting of low back pain. This thesis consists of four linked studies all addressing reductions in recovery time during a cyclic "light" assembly task.

In all four studies the same assembly task was performed which involved alternation between work with the trunk flexed forward 30° and recovery in upright standing within a one minute cycle. The task involved essentially zero external forces on the hands and in most plants would be considered to be a low loading job. Proven and proposed risk factors for low back pain reporting were measured; peak and cumulative spinal loading, perceived discomfort, muscular activation levels and local muscular fatigue. Trunk angle and lumbar spinal curvature were measured to evaluate alterations in work posture.

The first study was done to improve the understanding of an increase in work/recovery ratio of a "light" assembly task on the magnitude of risk factors. Nine female university students performed the assembly task with a fixed lordotic lumbar curvature at work/recovery ratios of 25/35, 40/20 and 55/5 seconds on three separate days, each for a duration of 25 minutes. An increase in work/recovery ratio was hypothesized to increase the magnitude of risk factors. Cumulative spinal loading, local muscular fatigue and ratings of perceived discomfort increased with increasingly more adverse work/recovery ratios.

Reduction of the magnitude of risk factors, by changing lumbar curvature from a fixed lordotic to a fixed flexed curvature, during a "55/5 second minute" of "light" assembly was addressed in the second study. Nine female university students performed the assembly task for 25 minutes in either a fixed lordotic or a fixed flexed lumbar curvature, which was hypothesized to reduce discomfort. Participants found both lumbar curvatures equally uncomfortable and painful.

The third study addressed the effects of a self-selected lumbar curvature on the magnitude of risk factors. Ten experienced assembly workers and five inexperienced participants performed the assembly task for one hour. On average, the self-selected curvature resulted in lower perceived discomfort, as was hypothesized, even after a full hour of task duration compared to 25 minutes of assembly in a fixed lordotic or fixed flexed curvature.

The responses during "light" assembly of individuals who had recently had low back pain compared to those who had not had low back pain were addressed in the forth study. Nine women who had recently had low back pain were recruited and it was hypothesized that they would alter trunk posture and lumbar curvature to alleviate discomfort and pain. After one hour of the assembly task, the individuals who had had low back pain did not alter trunk angle or lumbar curvature more than those who had not had low back pain. This might be explained by the similarity in discomfort ratings between the groups.

Whether ratings of perceived discomfort can replace instrumented measures of risk factors was addressed following the series of studies. Average ratings of perceived discomfort could replace instrumented measures when evaluating various situations of "light" assembly work that differed substantially in the magnitude of risk factors. However, perceived discomfort was not related to instrumented measures of risk factors when evaluating one and the same work situation. It is not clear on which risk factors individuals base their perceptions of discomfort. Therefore, when evaluating one work situation of "light" assembly, ratings of perceived discomfort can not replace instrumented measures of risk factors. They appear to be measuring different phenomena.

From this work it was concluded that the type of "light" assembly work done in this study during a "55/5 second minute" was not light in terms of cumulative spinal loading, local muscular fatigue and perceived discomfort. Use of the "55/5 second minute" during "light" assembly is not recommended and individuals should be encouraged to adopt a self-selected lumbar curvature. The introduction of changes in trunk posture, in flexion-extension, might induce postural relief.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Why was this research done?

Competition in industry has resulted in changes in the workplace. The number of workers has been reduced but production rates have remained constant or have increased. Working hours have been increased and tasks have been added to existing jobs which results in fewer and shorter pauses for recovery built into the work. Companies have reduced walking time, thinking time, waiting time and material handling time. In other words, jobs are loaded more tightly and as little time as possible is spent in operations other than fastening parts to the vehicle.

At the same time, however, some employers state that heavy work has been eliminated from jobs. This seems to mean that they have eliminated or reduced high peak forces. However, reduction of peak forces is not the only issue that has to be addressed. Cumulative loading is also present. It appears that the adverse effects of cumulative loading have not been fully recognized. Work that does not involve high peak loading, but does involve cumulative loading, is often wrongfully interpreted as light. An increased number of workers, often women, perform jobs that involve cumulative forces.

Targets for the tightening of work have been reported for three large automobile companies. Recovery pauses of 20-35 seconds in a work cycle of one minute are being reduced to five seconds so that individuals work 55 seconds per minute. In these companies this has been called a "55/5 second minute". The "55/5 second minute" consists of 55 seconds of work of which 75-95% is value-added work (41-52 seconds out of 1 minute, depending on the company) and not more than five seconds of recovery within a one minute cycle. By value-added work is meant the work that contributes directly to the product. In a car assembly plant, value-added work consists of fastening parts to the vehicle, whereas non-value-added work might include walking to get a part or tool. Thus, possibly biologically beneficial movements and built-in recovery pauses in the work cycle are being reduced to increase productivity. In at least one assembly operation, observation of the line shows no obvious recovery pauses between cars. The effects of the changes in the nature of work on the magnitude of risk factors, some of which have been epidemiologically proven and others that have been proposed to be related to low back pain reporting, must be more fully evaluated.

Statement of Purpose

The purpose of this work was to improve the understanding of the effects of a "55/5 second minute" of a simulated industrial "light" assembly task on the magnitude of risk factors which have been proven or proposed to be related to the reporting of low back pain.

The specific objectives of this work were:

1) to improve the understanding of the effects of an increase in work/recovery ratio in a "light" assembly task, on the magnitude of risk factors related to the reporting of low back pain.
2) to assess the effects of a work posture with a lordotic (hollow) and flexed (rounded) lumbar curvature during a "light" assembly task, on the magnitude of risk factors related to the reporting of low back pain.
3) to assess the effects of a self-selected lumbar curvature during a "light" assembly task, performed by experienced workers, on the magnitude of risk factors related to the

reporting of low back pain.

4) to determine whether ratings of perceived discomfort can replace instrumented measures of risk factors related to the reporting of low back pain.

5) to determine whether individuals who had recently had low back pain responded differently to the same "light" assembly task compared to those who had not had low back pain.

How is this thesis structured?

This thesis consists of a synthesizing overview of four linked studies which all address reductions in recovery time during cyclic "light" assembly in industry. The overview is followed by four manuscripts: the manuscripts have been submitted for publication. The first study was done to determine the effects on the magnitude of risk factors for low back pain reporting of increasing work/recovery ratios up to 55/5 seconds as is being done in some industries. This study showed that moving to a "55/5 second minute" increased the magnitude of risk factors. A change in lumbar curvature from a fixed lordosis to a fixed flexed spine, a posture often adopted voluntarily, was evaluated in the second study. This change in lumbar curvature, from a fixed lordosis to fixed flexion, did not reduce the magnitude of risk factors. A third study was done to evaluate whether a lumbar curvature that participants selected themselves would reduce the magnitude of risk factors. In addition, the responses to the assembly task of a group of experienced assembly workers were compared to those of inexperienced participants. The final question, whether individuals who had recently had low back pain responded differently to the same "light" assembly task compared to those who had not had low back pain, was addressed in the fourth study.

It was hypothesized that:

1) an increase in work/recovery ratio will increase the magnitude of risk factors related to low back pain reporting.
2) a flexed lumbar curvature will result in less discomfort compared to a lordotic lumbar curvature, thereby lowering this risk factor for the reporting of low back pain.
3) ratings of perceived discomfort will be lower for a self-selected lumbar curvature compared to a fixed lordotic or fixed flexed lumbar curvature.
4) ratings of perceived discomfort can not replace instrumented measures of risk factors. They are not based on the same mechanisms underlying low back pain reporting.
5) individuals who had recently had low back pain will vary trunk angle and lumbar curvature during the task performance to reduce discomfort and pain.

What is the magnitude of the back pain problem?

A large percentage of the population, 80 to 85 per cent, suffers from disabling low back pain at some point in time in their life (Waddell, 1987; Nachemson, 1992). A total of 80 to 90 per cent of low back pain cases recover within 6 weeks, independent of the type of treatment (Waddell, 1987). Only a small percentage of the low back pain cases with disability exceeding a duration of 6 months accounts for the majority of the costs (Snook, 1988). Spitzer *et al.* (1987) found that 7.4% of the workers who were off work for more than 6 months accounted for 75.6% of the costs. For the province of Quebec the total compensation cost of low back pain claims was $150 million in 1981, which is 28.5% of the total compensation costs for claims from all injuries at the Quebec Workers Compensation Board (QWCB) in that year (Spitzer *et al.*, 1987). The benefits paid by the Workplace Safety and Insurance Board (WSIB) in 1998 within the province of Ontario was $2,262 million. The lost-time claims due to back injury was 29.8% in the same year; the cost of back injury is therefore estimated to be roughly $674 million (Annual Report of the WSIB, 1998). In 1989 the cost of low back pain cases handled by Liberty Mutual was $991 million US, which is almost $4 million per working day. It was estimated that the total workers' compensation costs for low back pain cases was $11.4 billion in the U.S. in 1989 (Webster and Snook, 1994).

What are the risk factors for low back pain reporting during "light" assembly?

Both epidemiologically proven risk factors and risk factors that have been proposed for the reporting of low back pain which are relevant during "light" assembly will be addressed. The scope of this thesis involves predominantly biomechanical risk factors.

High peak forces on the lumbar spine have long been known to be a risk factor for low back pain reporting as shown by epidemiological studies (Kelsey *et al.*, 1984; Marras *et al.*, 1993). As a result, high peak loading has been reduced or eliminated from the workplace and the nature of work has been altered to low peak loading tasks which are sustained or repeated over prolonged periods of time. For example, such tasks often require workers to support their upper body weight in mild forward flexed trunk postures. However, there is evidence for a causal relationship between postural stress and low back pain. Punnett *et al.* (1991) showed that postural stress such as mild trunk flexion (21° to 45°), severe trunk flexion (> 45°) and trunk twist or lateral bend (> 20°) were related to back disorders with odds ratios ranging from 4.9 to 5.9. When the duration of exposure in these non-neutral postures increases, the risk of back injury increases as was shown by an increase in the odds ratios.

Maintaining non-neutral postures involves cumulative loading which has been shown to be a risk factor for the reporting of low back pain in a large automobile company (Norman *et al.*, 1998; Kerr *et al.*, 2000). These authors found that cumulative compression, moment and shear were significantly higher in cases, defined as individuals who reported low back pain, compared to controls, people who did not report low back pain. Kumar (1990) reported that cumulative compression forces were higher in male and female nurses and that cumulative shear forces were higher in male nurses who reported back pain compared to nurses who did not report back pain. Why cumulative shear forces did not differ between women who reported back pain and those who did not report back pain is not clear.

A different, but strong, risk factor for the reporting of low back pain in industry is the perception that one's job is physically demanding on the body as measured by subjective ratings of perceived exertion (Kerr *et al.*, 2000). Perceived exertion has been defined as the act of detecting and interpreting sensations arising from the body during physical exercise (Noble and Robertson, 1996). Ratings of perceived exertion have been used for tasks that strain the cardiovascular and/or respiratory system (Borg, 1982) which is common in physical exercise but these systems may not be strained during most occupational tasks. The use of ratings of perceived discomfort, defined as a lack of ease, instead of exertion, might be more appropriate when evaluating a static or quasi-dynamic occupational task which involves local sensations but does not involve strain to the cardiovascular and/or respiratory system.

A previous history of low back pain has repeatedly been shown to be strongly associated with the recurrence of back pain (Frank *et al.*, 1996). It is not clear why individuals with a history of low back pain experience repeated back pain episodes.

Risk factors that have been proposed to be related to injury, but have not yet been proven to be true for low back pain reporting in epidemiological studies, are sustained low muscular activation (Westgaard, 1988; Veiersted *et al.*, 1990) and muscular fatigue (Sjogaard and Jensen, 1999).

How can a "light" assembly task result in injury?

For the purpose of this thesis, injury is defined as ranging from minor tissue irritation to major bone fracture. Two mechanisms of spinal tissue injury, following sub-maximal loading, have been proposed (McGill, 1997). Repetitive sub-maximal loading can result in fatigue failure such as micro-trauma to the end plate or intervertebral disc. Micro-trauma decreases the tissue tolerance limit and reduces the margin of safety to zero, resulting in injury. In prolonged sub-maximal loading, creep deformation can occur, thereby reducing the tissue tolerance followed by a reduction in the margin of safety and injury. It is acknowledged that measures of cumulative loading, a summation of any type of loading over time, can not distinguish between the injury mechanisms of repetitive and prolonged sub-maximal loading.

Some evidence for adverse effects on spinal structures following cumulative spinal loading has been shown in *in vitro* work. Repeated, sub-maximal loading of a motion segment in compression resulted in damage to the end plate which reduced the strength of the vertebrae (Hansson *et al.*, 1987). Furthermore, combined loading created damage to the intervertebral disc by initially disrupting the annulus, followed by annular separation and finally disc prolapse (Adams and Hutton, 1985; Gordon *et al.*, 1991). Callaghan (1999), using a porcine model, showed that cumulative compression force as low as 876N in combination with repeated flexion-extension motion (on average 75670 repetitions) resulted in intervertebral disc herniations. This shows that repeated loading over time reduced the tissue tolerance level dramatically. Prolonged, sub-maximal loading of a motion segment decreased the intervertebral disc height due to visco-elastic deformation of the annular fibres and by fluid flow from the disc (Broberg, 1993). Although this type of loading has not yet been shown to result in injury *in vitro*, the reduction in disc height affects the bending properties of the specimens causing an increase in flexion (Adams *et al.*, 1987). Furthermore, Gunning (1999) showed that prolonged loading not only resulted in a reduction in disc height, but also affected the failure tolerance and injury site. Failure tolerance of dehydrated discs (after prolonged loading in neutral position) was increased compared to discs that were not loaded for a prolonged period of time. Prolonged loading in a flexed position did not alter the failure tolerance. The injury when loading a motion segment with a dehydrated disc is delamination of annulus fibres and bony damage of the trabecular bone. In a hydrated disc (no loading history) the end plate is more likely to be injured.

Static loading of the musculature, even at low levels, has been related to muscular pain of the trapezius musculature (Westgaard, 1988; Veiersted *et al.*, 1990). Aaras (1994) found that a reduction of static trapezius muscular activation below 1-2 % of maximum voluntary contraction (MVC) was associated with a reduced incidence of musculoskeletal illness. A possible pathway for musculoskeletal illness is the reduction in muscle oxygenation which occurs at activity levels as low as 2 % of MVC of the back extensor musculature (McGill *et al.*, 2000). Continuous activation of low threshold, "Cinderella" fibers (Hagg, 1991) has been shown to result in pathologic changes in these fibers (Larsson *et al.*, 1988). Furthermore, muscular fatigue develops at activation levels as low as 5% of MVC (Sjogaard, 1986). Bigland-Ritchie and Woods (1984) defined neuromuscular fatigue as "any reduction in the force-generating capacity of the total neuromuscular system regardless of the force required in any given situation". For purposes of this thesis, this definition will be used. Prolonged muscular fatigue without sufficient recovery can lead to the development of musculoskeletal disorders (Sjogaard and Jensen, 1999) and muscular fatigue has been proposed to predispose the spine to injury due to shifting of loading to more injury-susceptible tissues (McGill, 1997; Cholewicki and McGill, 1996).

Although ratings of perceived discomfort do not affect tissue injury, they are important in back pain reporting. Such perceptions possibly reflect the worker's capability relative to the job demands. Reduced capability might result from de-conditioning following a previous injury and current irritability of inflamed tissues, for example. Performance of a demanding task is likely to result in an increase in discomfort over time. Individuals who perceive high discomfort and pain are more likely to report low back pain possibly followed by time off work and expensive long term disability.

What are the effects of work/recovery ratio on the magnitude of risk factors for low back pain reporting?

Work/recovery models have been developed to guide selection of the duration and frequency of recovery periods during work, with the intent to increase productivity and reduce risk of injury. Various techniques to determine work/recovery ratios have been used. The psychophysical approach is based on the participants feelings of exertion or fatigue. Participants perform a task in which all except one variable, such as the weight of lift, is controlled. The instructions given to the participants were to alter, for example, the weight of lift to a level at which they perceived to work as hard as they could without straining themselves, or without becoming unusually tired, weakened, overheated, or out of breath. This approach has been used to evaluate tasks involving lifting, lowering, pushing, pulling and carrying (Snook and Ciriello, 1991). The drawback of this approach is that it is based on the participants feelings of exertion or fatigue and its relation to musculoskeletal disorders is not clear.

The muscular endurance approach uses maximum holding times to determine work/recovery ratios. Initially it was proposed that the maximum holding time at and below 15% of the maximum voluntary contraction was indefinite. This was based on the believe that muscular fatigue did not occur below 15% of maximum (Rohmert, 1960). It is now known that muscular fatigue does occur at activation levels below 15% of maximum and maximum holding times below 15% have been evaluated (Sjogaard, 1986; Manenica, 1986; Rose, 1992). The maximum holding times reported by Sjogaard (1986) were used in combination with a recovery model developed by Milner (1985) to determine work/recovery ratios (Dul *et al.*, 1991). The use of the maximum holding time to develop work/recovery schedules has been questioned. Maximum holding time has been shown to be highly variable, especially at activation levels below 15% of maximum due to participant motivation (Sjogaard, 1986). Furthermore, the relation between endurance time and musculoskeletal disorders is unclear (Mathiassen and Winkel, 1992).

The physiological approach is based on measures of, for example, blood flow and blood chemistry (Bystrom and Kilbom, 1990). The advantage of this approach is that it is one step closer to some of the possible injury processes compared to the other two approaches. However, the physiological approach is very specific to the body area of interest in contrast to the psychophysical approach in which the participants feelings of exertion or fatigue can arise from the entire body.

To the knowledge of this writer, work/recovery ratios during work that involves mild trunk flexion have not been evaluated using risk factors that have been shown to be related to low back pain reporting. This area requires further research.

What are the effects of lumbar curvature on the magnitude of risk factors for low back pain reporting?

From observation in the workplace, a flexed lumbar curvature, and not a lordotic curvature, is commonly and voluntarily adopted by individuals. This might suggest that individuals perceive a flexed curvature to be more comfortable and that this curvature induces less pain which is beneficial regarding low back pain reporting. However, a fully flexed lumbar curvature can result in anterior joint shear forces which are higher than those in a lordotic curvature due to changes in the interaction between muscle and ligament (McGill and Norman, 1986). High shear forces have been shown to occur during heavy lifting tasks (McGill and Norman, 1986, 1987; Potvin *et al.*, 1991) which presents a higher risk of injury. Whether shear forces are of concern during light assembly is not known.

On which variables do individuals base their perceptions of exertion?

Borg (1982) showed that ratings of perceived exertion during physical exercise such as cycling are linearly related to heart rate. Ratings of perceived exertion have been defined as "the act of detecting and interpreting sensations arising from the body during physical exercise" (Noble and Robertson, 1996). When handling weights that exceed the maximal acceptable weight of lift, heart rate contributed to perceptions of exertion. But when weights were below the acceptable weight of lift, heart rate did not play a role in perceived exertion (Jorgensen *et al.*, 1999; Davis *et al.*, 2000). Selection of acceptable loads for lifting has been found to be only marginally based on spinal loading variables such as shear force and the extensor moment (Jorgensen *et al.*, 1999). Thompson and Chaffin (1993) did not find a relationship between perceived exertion and risk factors for low back pain such as spinal loading. Recently, perceived exertion has been related to muscular force during handling of weights (Davis *et al.*, 2000). Furthermore, a moderate correlation of 0.41-0.50 between subjective ratings of fatigue, as measured by the Borg scale, and instrumented measures of muscular fatigue, using the mean power frequency, during a modified Sorensen's test, a fairly demanding task, was reported by Dedering *et al.* (1999). These findings suggest that perceptions of exertion are related to muscular force and muscular fatigue and whether this is true during light assembly is not known.

How are ratings of perceived discomfort and ratings of pain defined?

Ratings of perceived exertion were developed for tasks that strain the cardiovascular or respiratory system, which is common in physical exercise, but these systems may not be strained during occupational tasks. Discomfort, defined as being physically or mentally ill at ease, can be perceived without exertion. Therefore, ratings of perceived discomfort are thought to be more appropriate when evaluating occupational tasks that do not involve strain to cardiovascular and respiratory systems. Ratings of low back discomfort have been widely used to evaluate work conditions such as seated work (Van Dieen *et al.*, 1997), standing work (Hansen *et al.*, 1998; Van Dieen and Oude Vrielink, 1998) and lifting (Wang *et al.*, 1998).

Pain has been defined as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage or described in terms of such damage" (Merskey and Bogduk, 1994). The definitions of discomfort and pain include physical/sensory factors and mental/emotional factors, indicating that these terms are not very specific and span a broad range of perceptions.

Can a history of low back pain affect responses to "light" assembly?

A previous history of low back pain has repeatedly been shown to be strongly associated with the recurrence of back pain (Frank *et al.*, 1996). It is not clear why these individuals experience repeated back pain episodes. Possibilities that have been brought forward are an underlying personality trait or a reduced threshold for injury, pain or discomfort due to repeatedly injured tissues (Frank *et al.*, 1996). Differences in spectral measures of the lumbar extensor musculature between chronic low back pain patients and individuals who did not have a history of low back pain have been reported (Roy *et al.*, 1989; Biedermann *et al.*, 1991; Peach and McGill, 1998). For example, Roy *et al.* (1989) reported that the initial median frequency was significantly higher and that the slope of the median frequency was significantly steeper for the low back pain patients compared to the control subjects during back extensor contractions at 40% of MVC. The differences in spectral measures between low back pain patients and controls might be explained by differences in muscle fibre type area. Changes in spectral measures during fatigue have been shown to be related to the muscle fibre type area distribution (Mannion *et al.*, 1998). These authors showed that the % type I fibre area was correlated to the slope of the median frequency. The higher the % type I fibre area is the more fatigue resistant the musculature is.

Work that is predominantly static as occurs during some types of assembly will most likely result in discomfort and pain and static work will load the same tissues over the work duration. Variation in work postures has been proposed to reduce the demands on tissues (Sjogaard and Jensen, 1999) and possibly reduce discomfort and pain. Changes in posture are therefore thought to reduce perceived physical demands, especially in individuals who had had low back pain and might perceive more discomfort and fatigue.

What was the simulated industrial "light" assembly task?

The task consisted of assembly work in a 30° flexed trunk posture which was alternated with recovery in upright standing within a one minute cycle. Return to the 30° trunk flexion angle after recovery was obtained by performing the task on a height adjustable table. Therefore, the trunk angle, and not the hip or shoulder to table top distance, was controlled for each participant. Work involved assembly of small plastic building blocks which were located on a table in front of the participant (Figure 1). In the first two studies participants were tempted to lift the models that were built off the table. This strategy reduced the control of the trunk angle.

Therefore, in the 3rd and 4th study individuals were instructed to place building blocks on a base which had to be maintained on the table to reduce changes in trunk angle.

During recovery, the participants were allowed to move their torsos freely and shuffle their feet but they were not allowed to step away from the work station. Participants stood on a hard surface and no anti-fatigue mats were used. Furthermore, participants were instructed not to lean onto the table with their hands since this would help support their upper body weight and use of this strategy during the assembly duration was discouraged by the experimenter. The task involved essentially zero external forces on the hands and in most plants would be considered to be a low loading job since the trunk was at only a mild forward inclination angle.

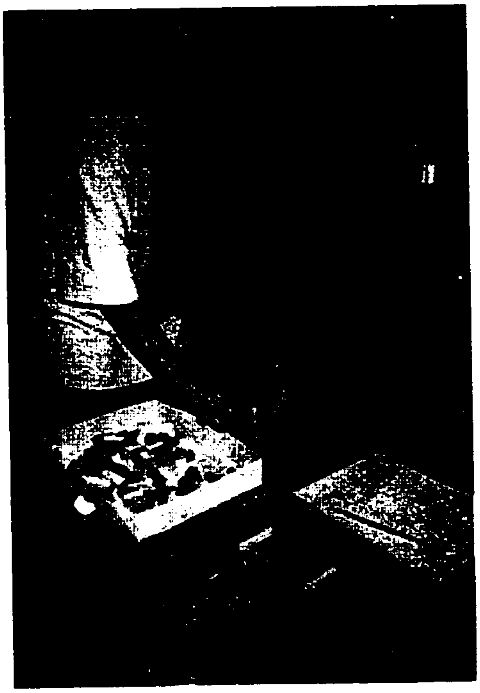


Figure 1. Assembly of small plastic building blocks onto a blue base, which was located on a table in front of the participant, is shown. Participants were instructed to place as many blocks onto the base as could be done comfortably during the allowed assembly time.

Work/recovery ratios of 25/35, 40/20 and 55/5 seconds were performed in the first study on three different days. In the following three studies, the 55/5 second work/recovery ratio was performed to further evaluate this condition. The task duration was 25 minutes in the first two studies whereas the duration was extended to one hour to better reflect a prolonged work duration in the last two studies.

A distinction between trunk angle and lumbar curvature should be made. In this research the trunk angle was set at 30° of flexion and the angle of lumbar curvature was varied. Participants were instructed to adopt one of three lumbar curvature conditions: a maximally lordotic (study 1; Figure 2, left side) or flexed (study 2; Figure 2, right side) curvature which had to be maintained over the work duration. These two curvatures can be seen as extremes at the end range of an envelope. A more realistic condition was selection of a preferred lumbar curvature by each individual (study 3 and 4; Figure 3); no instructions regarding lumbar curvature were given to these individuals and they were allowed to change their curvature during each work cycle and over the duration of the testing session.

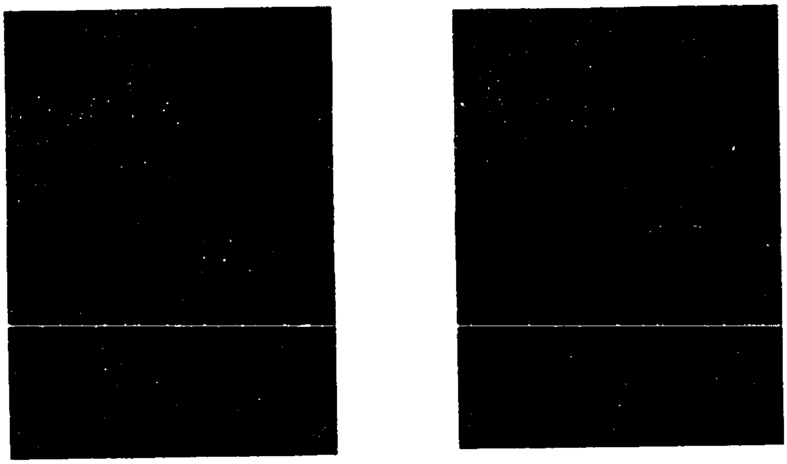


Figure 2. The posture during assembly with a maximally lordotic (hollow) lumbar curvature (left) and (b) a maximally flexed (rounded) lumbar curvature (right) is shown. Participants were instructed to return to the same maximally lordotic or flexed curvature at the beginning of each assembly period and to maintain that curvature during the assembly duration.

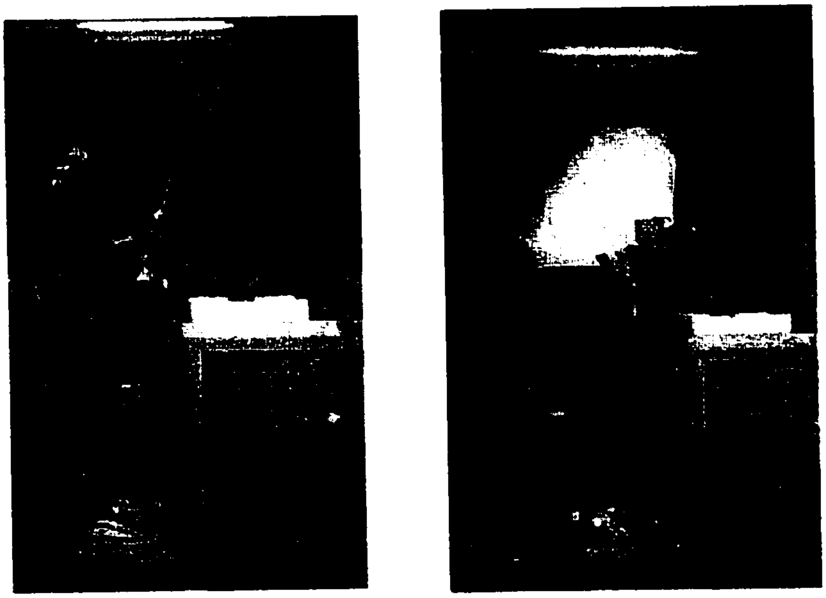


Figure 3. Two examples of participants with self-selected lumbar curvatures are shown. Participants were allowed to alter the curvature during each work cycle and during the full data collection session.

Which additional tests were performed?

EMG normalization test: Maximum Voluntary Contractions (MVC), to normalize the EMG signal, were performed at the beginning of data collection. The back extensor musculature was maximally activated by having participants lie on their stomach and lean over the edge of a bench with the legs restrained. In this position a maximum back extensor effort was performed against manual resistance. Each normalization test was repeated 3 times.

EMG fatigue test: EMG fatigue tests were performed in a standing position with the trunk flexed forward 30° from vertical. The low back was positioned in a lordosis (hollow back). A handle with a length adjustable chain was held in the hands and the end of the chain had to be kept just above the floor to allow for the 30° trunk angle thereby improving replication of this trunk angle. This static posture, involving sub-maximal loading, was maintained for 5 seconds at the beginning of testing and at set intervals during the task. At the end of the assembly task duration a maximum holding task was performed at the 30° trunk angle to determine maximum fatigue.

Spinal maximum range of motion test: Participants moved their torso through its maximum range of motion for spinal movement normalization purposes. The participants started in upright standing, slowly flexed forward as far as possible aiming to touch the floor and then returned to upright standing.

What was the protocol?

Participants were introduced to the lab environment and information regarding the testing session was given by the researcher. It was explained that an assembly task would be performed and that fatigue tests in mild trunk flexion, maximum voluntary contractions and maximum range of motion tasks would be done. Furthermore, the use of the required pieces of instrumentation (emg electrodes, 3SPACE Isotrak source and sensor, rating scales and questionnaires) were explained to them. An informed consent which was approved by the Office of Human Research at the University of Waterloo was given to the participants. This document outlined the experiment and individuals signed the consent form when they agreed to participate.

Participants were instrumented with emg electrodes and maximal voluntary contractions were performed. Then the 3SPACE Isotrak was placed around the torso. Individuals were asked to perform the assembly task briefly so that the table height could be adjusted to result in a trunk flexion angle of approximately 30° during assembly. Participants were instructed on how to complete the discomfort and pain scale. A fatigue test was done and subjective ratings were obtained right before the start of the assembly task. The assembly task was performed and data were collected (1 minute work cycles, fatigue tests and ratings scales) at set time intervals during the task duration and measures were taken at the end of the work duration. The assembly task performance was followed by a fatigue test which was maintained for as long as possible to determine maximum fatigue. After recovery from the fatigue test individuals performed maximum spinal range of motion tests. Participants were asked to sit down and to complete a questionnaire regarding their perceptions on how they performed the task. Instrumentation was removed and participants left the lab.

Who participated in this study?

All participants in this research were women. Participation of women in research experiments is important since women often perform light assembly work and research evaluating the female working population is sparse. Three different groups of individuals participated in the series of four experiments: university students, assembly workers and women who had recently had low back pain. The rationale for recruiting various populations was that university students were easily available for participation and they were recruited to evaluate differences between working conditions. Once the differences between the working conditions were established, one working condition was selected for further evaluation. Experienced assembly workers were recruited to perform this working condition to improve the applicability of the research findings to the workplace. In addition, several students were recruited to performed this working condition to be able to evaluate the effect of work experience on task performance. It is known that work experience can affect task performance and whether this is true during light assembly was questioned. Furthermore, women who had had low back pain were recruited to evaluate whether their task performance differed from those who had not had low back pain.

Nine healthy women from a university population were recruited for the first study and nine additional women were recruited for the second study. None of these women had experienced low back pain in the year preceding testing. In the third study, ten women with assembly experience, to reflect the working population, were recruited through an employment agency and five women, who did not have assembly experience, were recruited from a university population. The majority of these women did not have a history of low back pain. In the last study, nine women who had recently had low back pain, but were in no pain or only mild pain at the time of testing, were recruited. All participants read and signed an informed consent form approved by the Office of Human Research at the university.

Which methods were used to measure the magnitude of risk factors for low back pain reporting?

Various data collection techniques were used to obtain measures of spinal loading, ratings of perceived discomfort and pain, muscular activation, local muscular fatigue, spinal motion, self reported task performance and productivity. For more details on the methods, the reader is directed to the four manuscripts following this document.

Spinal loading: Peak and cumulative spinal loading were estimated using a biomechanical model (4DWATBAK, University of Waterloo). A detailed description of the two-dimensional version of this model can be found in work by Andrews *et al.* (1997) and Norman *et al.* (1998). Video was used to estimate the trunk flexion angle to guide the positioning of the model's moveable manikin to the body posture obtained during the task (Figure 4). The reliability of the replication of the peak trunk flexion angle from video by visual inspection has been shown to be good (intra-class correlation of 0.80; Neumann *et al.*, 1996). The manikin provided joint coordinate data which, in combination with gender, height and weight of the participants, were used to estimate peak spinal compression force, peak reaction shear force, peak joint shear force and peak extensor moment. Cumulative spinal loading was obtained by extrapolating single estimates taken at regular intervals during the task performance to a 7 ½ hour workday for literature comparison purposes.

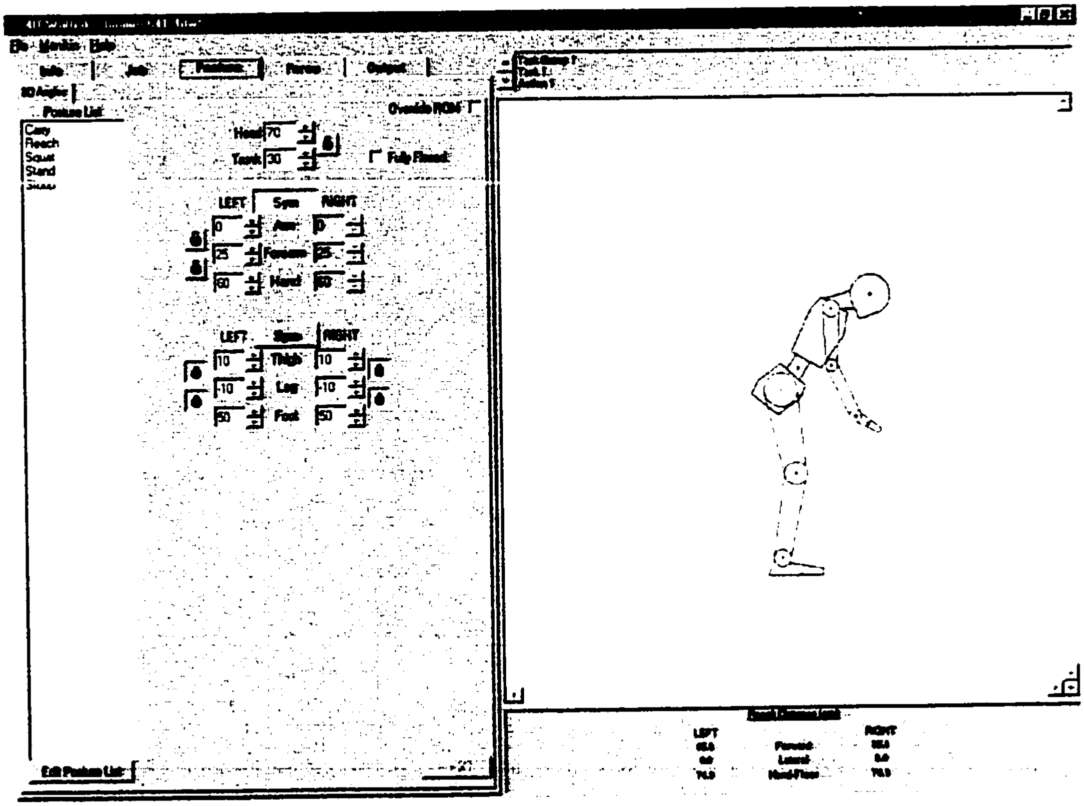


Figure 4. Joint angle data and the manikin in assembly posture are shown (4DWATBAK, University of Waterloo). The manikin can be positioned in the desired posture by entering joint angle data on the left panel or by clicking and dragging the manikin. The manikin provided joint coordinate data which, in combination with gender, body height and weight, were used to estimate peak and cumulative spinal loading.

Rating scales: Subjective measures were recorded using three 10 point rating scales: ratings of perceived discomfort, ratings of perceived risk of injury and ratings of pain. For the perceived discomfort scale, participants were told that the 0 point was defined as "no perceived discomfort" and 10 was defined as "extreme perceived discomfort". Furthermore, participants were told that by discomfort was meant a lack of ease which was physical in nature and not mental. Ratings of perceived discomfort were taken throughout the assembly task duration (Figure 5).

For the perceived risk of injury scale, participants were told that the 0 point was defined as "no perceived risk of injury" and 10 was defined as "extreme perceived risk of injury". No further instructions were given and it was evaluated whether the individuals perceived risk of injury was in agreement with other measures of risk of injury. As with ratings of perceived discomfort, ratings of perceived risk of injury were taken throughout the assembly task duration. It was found that the two ratings scales ran parallel, with perceived discomfort being rated higher than perceived risk of injury. Although ratings of perceived risk of injury increased with an increase in work/recovery ratio, as did other measures of risk of injury, ratings of perceived discomfort were more sensitive to changes in work/recovery ratios and its use above ratings of perceived risk of injury is recommended. Further discussion on this issue can be found in appendix A.

A pain diagram comprised of a front and back view of the entire body, was completed before and after the task performance; participants were asked to circle body areas in which pain was felt. Pain experienced in each body part was quantified using a 10 point scale with the 0 point defined as "no pain" and 10 was defined as "extreme pain" (Figure 6).

The meaning of the top end of the ratings scales is different for each individual and depends on past experiences. A continuous scale rather than a category scale was used because the other measures obtained in this research (estimates of spinal loading, muscular fatigue and muscular activation) are continuous.

Instructions:

Pick a number on the line from **no** to **extreme**perceived discomfort, reflecting your current perception of discomfort.

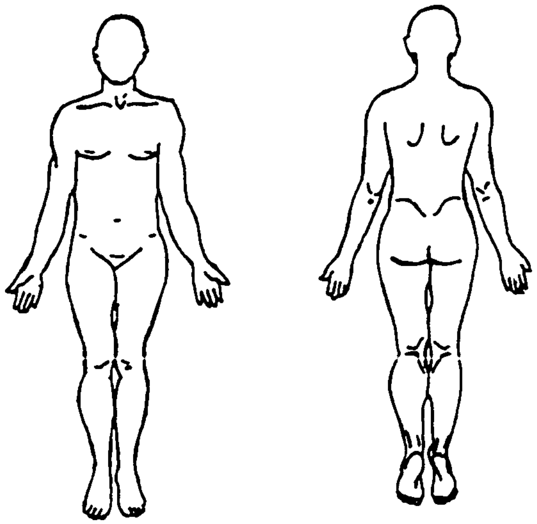
Ratings of Perceived Discomfort

0 1 2 3 4 5 6 7 8 9 10

No
perceived
discomfort

Extreme
perceived
discomfort

Figure 5. The 10 point rating scale which was used to record the participants' ratings of perceived discomfort is shown. The range of the scale, from no to extreme perceived discomfort was explained to the participants and they were allowed to rate any number reflecting their discomfort between 0 and 10.



Instructions:

Pick a number on the line from **no** to **extreme** pain, reflecting your current level of pain.

Pain Rating Scale

0 1 2 3 4 5 6 7 8 9 10

No pain

Extreme pain

Figure 6. The pain diagram with a pain rating scale was used to identify the location and pain magnitude experienced by the individuals. Participants were instructed to circle areas in which pain was felt and to write down the magnitude of pain, ranging from 0 to 10, next to the circled area(s).

Muscular activation and local muscular fatigue: Muscular activation was measured bilaterally, approximately 3 cm lateral to the 3rd lumbar vertebra representing the lumbar portion of the Iliocostalis Lumborum and approximately 1-2 cm lateral to the 5th lumbar vertebra representing the Multifidus. These muscles support moments about L4/L5. A time history of a 1 minute work cycle is shown in Figure 7. Estimates of low level muscular activity, average activity and peak activity were obtained from the 5th, 50th and 90th percentile of the Amplitude Probability Distribution Function (APDF; Jonsson 1978), respectively. The 5th percentile of the APDF, instead of the often selected 10th percentile, was used because the 55/5 second work/recovery ratio converts to 8.3 percent of the time that is assigned to recovery. The 10th percentile of the APDF would therefore have included part of the assembly work and could not possibly have reflected muscular activity levels during recovery only. The 5th percentile, instead of 8.3 percent, was used because there is a delay between the termination of assembly and the beginning of recovery due to the transition from mild trunk flexion to upright standing. The 5th percentile of the APDF therefore more closely reflects recovery in upright standing. Estimates were obtained during one minute cycle times, collected at regular time intervals during the task.

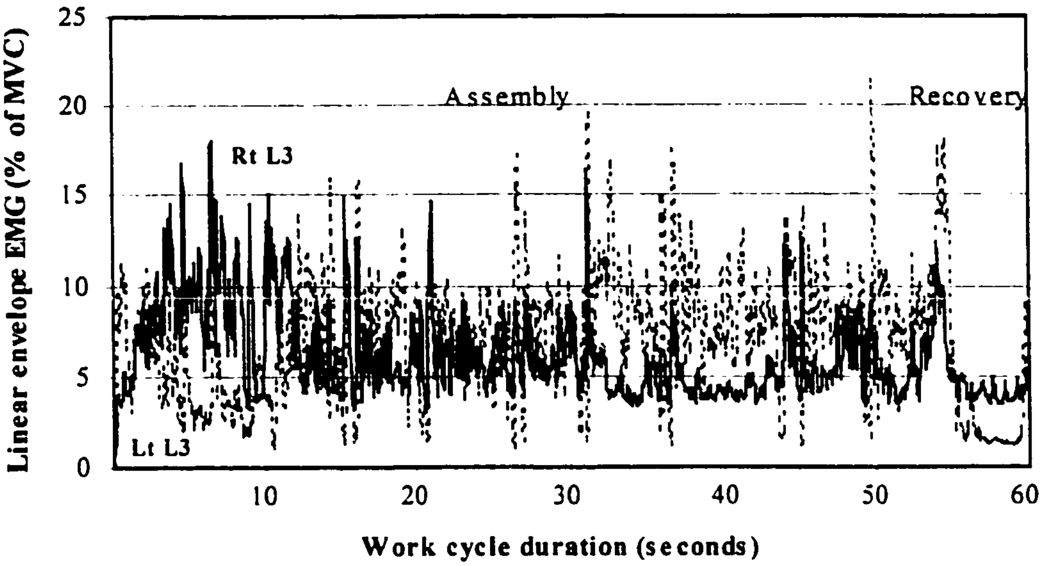


Figure 7. A time history of linear envelope emg expressed as a percentage of MVC is shown for right and left L3 during 55 seconds of assembly and 5 seconds of recovery at the end. This is data from one participant.

Local muscular fatigue was assessed using mean power frequencies (MPF). Participants obtained a 30° flexed trunk posture for 5 seconds while holding onto a handle bar with a length-adjustable chain. The length of the chain was adjusted for each participant and this was done to improve replication of the 30° flexed trunk posture (Figure 8). A fast fourier transform with a rectangular window was used to calculate MPFs at regular intervals during the task. At the end of the testing session participants maintained the flexed trunk posture for as long as they could (maximum holding trial). The change in MPF over the task duration was used to quantify the amount of local muscular fatigue that developed. The change in MPF over the task duration was expressed either as a percentage of the maximal change in MPF obtained during the maximal holding task or as an absolute change in frequency (Hz).

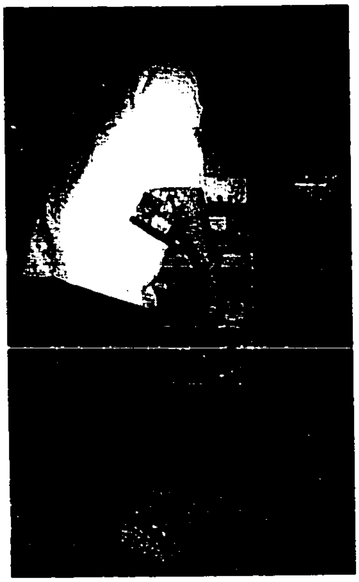


Figure 8. The assembly task was briefly interrupted to obtain fatigue measures (MPF). Participants stepped to the side of the work station and maintained a 30° flexed trunk posture for 5 seconds while holding onto a length-adjustable chain which was used to improve replication of this flexed trunk posture. After the 5 second hold. participants returned to the work station and continued the assembly task.

Spinal motion: Lumbar spinal kinematics in three dimensions were measured using 3SPACE Isotrak (Polhemus Inc.). This is an electromagnetic device that consists of a source which was placed over the sacrum and a sensor which was placed over the spinous process of the 12th thoracic vertebra (Figure 9). The accuracy and viability of the 3SPACE Isotrak has been evaluated by McGill *et al.* (1997). The angle of spinal curvature in flexion during assembly work was recorded at set time intervals over the test duration. A time history of the angle of the lumbar curvature over a one minute work cycle is shown (Figure 10). Changes in lumbar curvature were determined two different ways. 1) The angle was expressed as a percentage of the maximal range of motion in flexion as was determined during maximal range of motion tests. The change in lumbar curvature in flexion between work cycles that were recorded at set time intervals over the test duration was determined. 2) The variation in lumbar curvature in flexion, lateral bend and twisting, within the middle 45 seconds of an assembly work cycle for each recording at the set time intervals was quantified using the standard deviation. This measure reflects the amount of spinal movement around the average angle of lumbar curvature during assembly work (within 1 cycle).

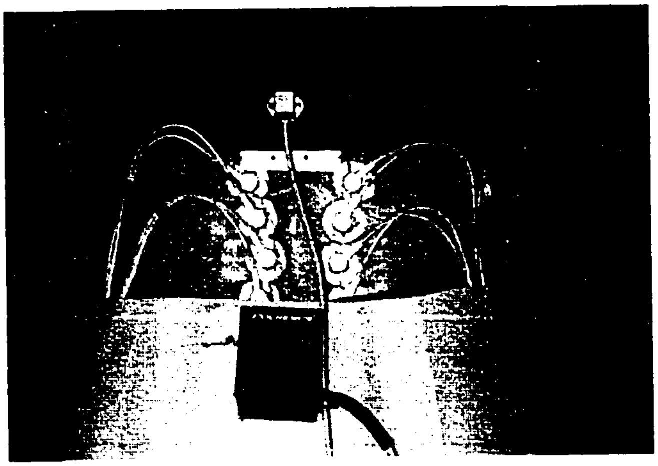


Figure 9. Instrumentation used to measure EMG of 4 muscle sites and lumbar spinal motion (3SPACE Isotrak. Polhemus Inc.) is shown.

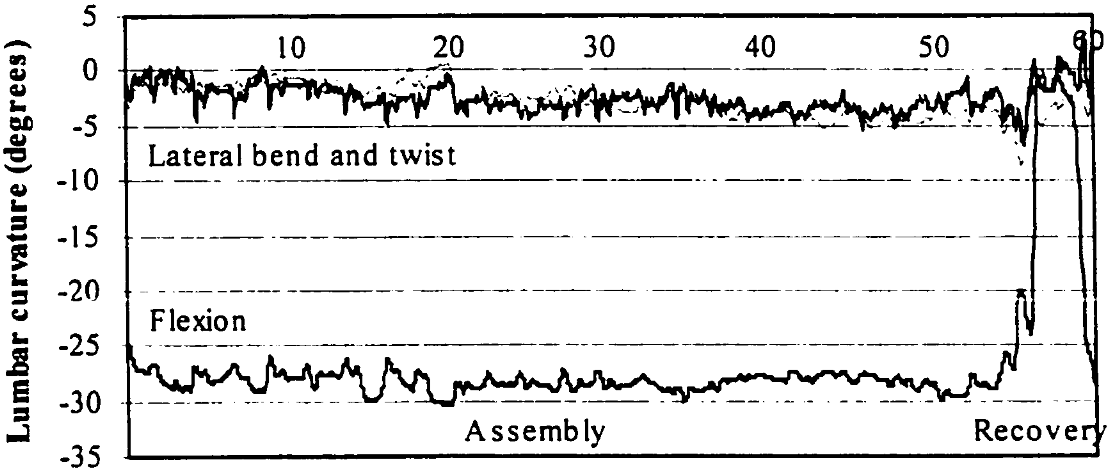


Figure 10. A time history of the angle of lumbar curvature, in flexion, lateral bend and twist, during 55 seconds of assembly and 5 seconds of recovery is shown. This is an example of one participant.

Self-reported task performance: The individual's perception of their work posture, in terms of whether they altered their work posture over time and why, was recorded at the end of the work duration. This questionnaire provided additional information about strategies adopted by the individuals to perform the assembly task.

Production rate: Production rate was measured by the number of assembly blocks put onto a base within the assembly duration. Participants were instructed to place as many assembly blocks onto a base as they could do comfortably and they were told to maintain this assembly pace over the task duration. The usefulness of measuring the production rate in this research was noted after collection of the first 2 studies was completed and data collection on production rate was done in the 3rd and 4th study.

Statistical analysis:

Repeated measures ANOVAs were used to determine whether the magnitudes of risk factors for low back pain reporting differed between work/recovery ratios and between lumbar curvatures. Repeated measures on the same participants were done to reduce the variability between participants and to improve the probability of finding significant differences between conditions (work/recovery ratios and lumbar curvatures). Furthermore, repeated measures over time were done to determine whether the magnitudes of risk factors changed over the assembly work duration. Significance of repeated measures was determined using the Greenhouse-Geiser p-values and the degrees of freedom were adjusted using the Greenhouse-Geiser epsilon to account for non-random allocation violation (Winer, 1971). Paired comparisons were done using the protected least significant difference (protected LSD) (Choi, 1978). The strength of the relation between various measures was determined using Pearson Correlation Coefficients. A level of significance of 0.05 was chosen.

Did an increase in work/recovery ratio increase the magnitude of risk factors for low back pain reporting?

Yes, cumulative spinal loading, local muscular fatigue and ratings of perceived discomfort increased with an increasingly more adverse work/recovery ratio. Work/recovery ratios differed significantly ($p<0.0001$) with the highest work/recovery ratio resulting in the largest cumulative loading, as was expected (Figure 11). Cumulative spinal loading during the task was high and, in general, exceeded the demands on auto workers in assembly and assembly support jobs who had reported low back pain to nurses. Cumulative spinal loading has been shown to be an independent risk factor for low back pain (Norman *et al.*,1998; Kerr *et al.*, 2000) and the odds ratio for cumulative spinal compression, for example, was high, 2.0 (Kerr *et al.*, 2000). Furthermore, the probability of being classified as a case, using the data by Norman *et al.*, was high and ranged from 0.61 to 0.79 for various modes of cumulative spinal loading during the "55/5 second minute".

A large amount of local muscular fatigue, a 28.1 % change in MPF with respect to rest, was found during the 55/5 second work/recovery ratio whereas the 25/35 and 40/20 second work/recovery ratios showed similar magnitudes that were significantly lower ($p<0.0004$) with an average of a 8.3 and 9.9 % change in MPF (Figure 12). A methodological limitation is that the maximum holding tests might have been terminated prematurely because these tests are very dependent on subject motivation. Premature termination of the maximum holding tests would have resulted in a less than maximal change in MPF which was used to normalize the change in MPF during the task. The implications are that the development of local muscular fatigue might have been overestimated. However, even with this limitation, the data showed that local muscular fatigue developed during assembly work and that the 55/5 seconds work/recovery ratio involved more fatigue compared to the 25/35 and 40/20 second work/recovery ratios.

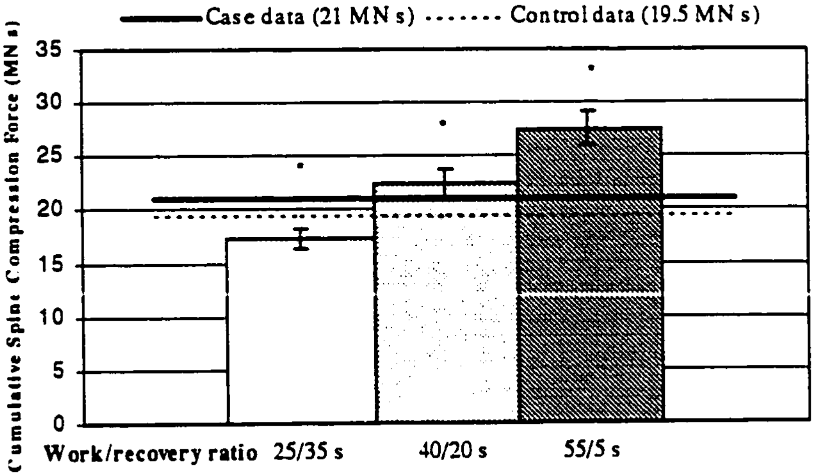


Figure 11. An increase in cumulative spinal compression force with an increase in work/recovery ratio is shown (significant differences are indicated by asterisks). Cumulative compression forces during the 40/20 and 55/5 second work/recovery ratio were high. Estimates exceeded that of controls, individuals who did not report low back pain to nurses, and cases, individuals who did report low back pain, in a large automobile industry (Norman *et al.*, 1998).

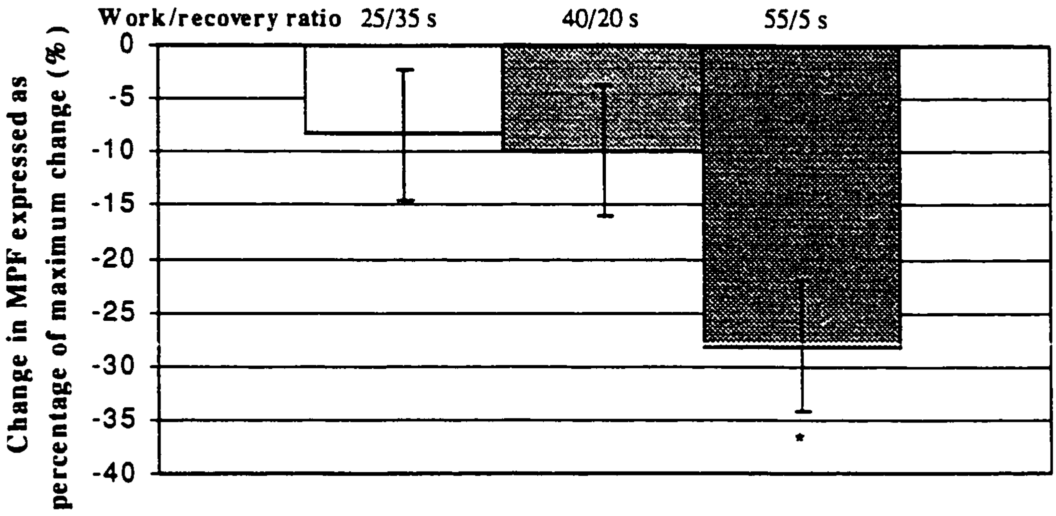


Figure 12. Local muscular fatigue was measured as a change in MPF and expressed as a percentage of maximal change obtained during the maximal holding trial. The 55/5 second work/recovery ratio resulted in a 28.1 % change in MPF which was significantly larger than the 8.3 and 9.9 % change in MPF during the other two work/recovery ratios ($p<0.0004$).

Perceived discomfort developed more rapidly in the 55/5 second work/recovery ratio compared to the other two work/recovery ratios (Figure 13). The average discomfort over time was higher during the 55/5 second work/recovery ratio compared to the two lower ratios in which the average ratings of discomfort were similar ($p<0.0001$).

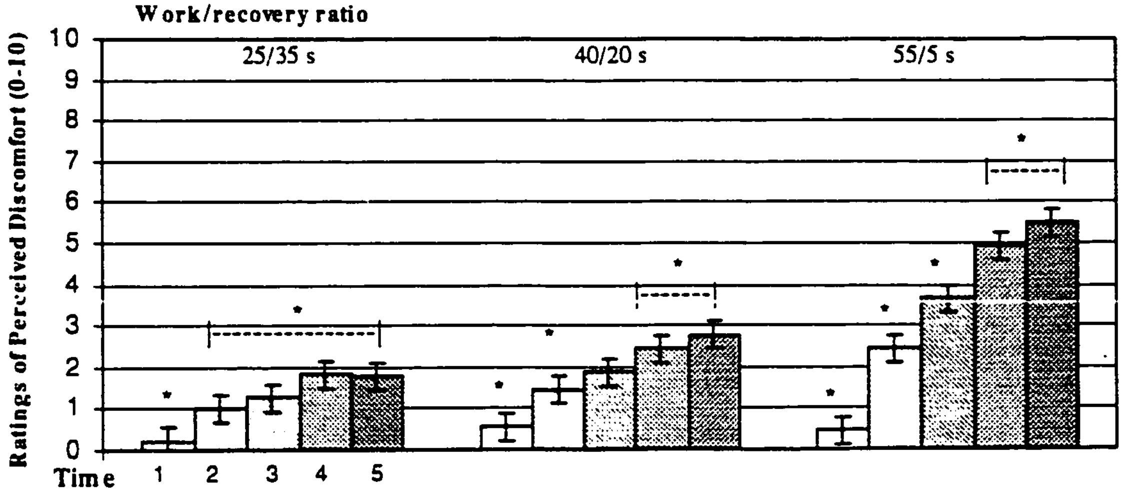


Figure 13. Ratings of perceived discomfort were measured at 5 minute intervals. Discomfort increased more rapidly over time during the 55/5 second work/recovery ratio compared to the other two work/recovery ratios.

These findings show that a "light" assembly task is not light during a "55/5 second minute" in terms of cumulative spinal loading, local muscular fatigue and perceived discomfort. This type of task is, however, often interpreted as being light by employers and industrial engineers since it does not involve high peak loading. For example, peak compression force is well below the NIOSH suggested action limit of 3433 N (Figure 14). It should be noted that although the magnitudes of risk factors for low back pain reporting during the 25/35 and 40/20 second work/recovery ratio were similar and lower than the 55/5 second work/recovery ratio, all three work/recovery ratios might be demanding when performed over a longer duration, such as a workday or workweek.

The results of this research were compared to those reported in the literature. The work load (magnitude of muscular activation) during the light assembly task performed in this study was in the magnitude of 15% of maximum. Maximal holding times that have been reported in the literature for a sustained static contraction at 15% of maximum are 17.4 minutes (Sjogaard, 1986), 15.7 minutes (Manenica, 1986) and 4.3 minutes (Rose, 1992). These maximal holding times are the worst case scenarios because no recovery periods were allowed. The reported maximal holding times are shorter than the light assembly work duration in this research (25 and 60 minutes) as was expected since the light assembly task allowed for 5, 20 or 35 second recovery periods during each one minute work cycle. Recovery is known to increase endurance.

Maximal possible work durations during tasks involving intermittent contractions, such as the assembly task in this research, were estimated using the work by Dul *et al.* (1991). At a muscular contraction level of 15% of maximum the model by Dul *et al.* (1991) estimated that a 25/35 second work/recovery ratio could be performed for 376 minutes, a 40/20 second work/recovery ratio could be performed for 92 minutes and a 55/5 second work/recovery ratio could be performed for 22 minutes. The Dul model underestimated the maximal work duration during the 55/5 second work/recovery ratio. Data from this research showed that participants were able to perform the 55/5 second work/recovery ratio, when using a self-selected posture, for up to 60 minutes. The duration of the assembly task in this research had been set to 60 minutes and this time limit does not reflect the maximum task duration. This is a less than maximal work duration. This research also showed that even though a 55/5 second minute of light assembly could be performed for 60 minutes, the magnitudes of some of the risk factors for low back pain reporting were high. Therefore, being able to perform a task from a endurance point of view does not necessarily mean that the magnitudes of risk factors are low. Various work/recovery models, including the Dul model, are based on maximal holding times. Aside from the questionable reliability of maximal holding times, they have not yet been proven to be related to the risk for low back pain reporting. The current research contributed to the evaluation of work/recovery ratios by directly measuring risk factors which have been proven or proposed to be related to the reporting of low back pain.

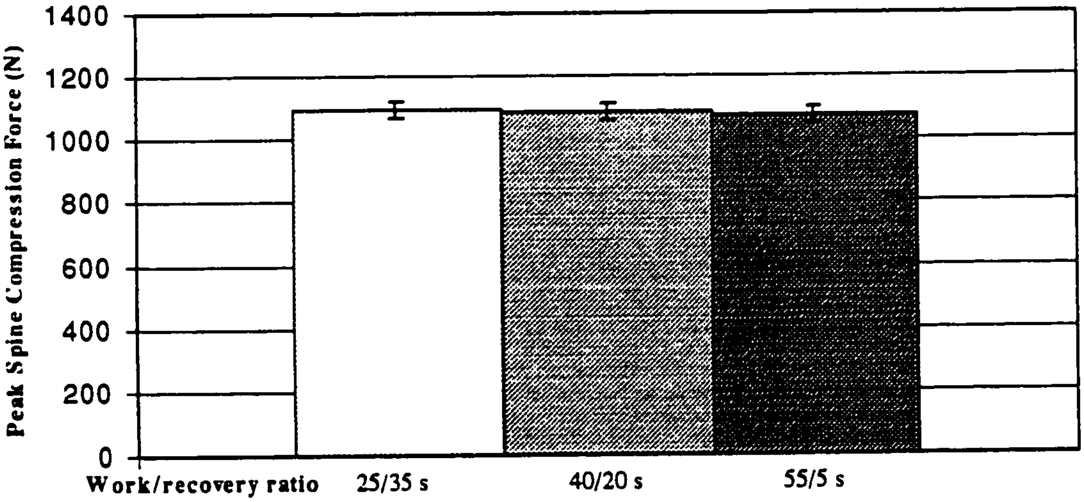


Figure 14. Peak spinal compression force was similar among the three work/recovery ratios as was expected since the same task was performed. The peak compression forces were low compared to the 1981 NIOSH suggested action limit of 3433 N, indicating that this risk factor for reporting of low back pain is not of major concern in this type of task.

An overview of the data, averaged over participants, is shown in table 1. This table can be used throughout this manuscript to compare among work/recovery ratios, lumbar curvature conditions and participant populations.

Table 1. An overview of the data, averaged over participants, for all four studies is shown. Fc = spinal compression force, Fsj = joint shear force, Fsr = reaction shear force, M = extensor moment, RPD = ratings of perceived discomfort, APDF = amplitude probability distribution function, MVC = maximal voluntary contraction, L3 = 3rd lumbar level, L5 = 5th lumbar level, MPF = mean power frequency.

Study	1	1	1	2	2	3	3	4
Work/recovery ratio (s)	25/35	40/20	55/5	55/5	55/5	55/5	55/5	55/5
Lumbar curvature	Lordosis	Lordosis	Lordosis	Flexed	Lordosis	Self-selected	Self-selected	Self-selected
Participant population	Students A	Students A	Students A	Students B	Students B	Students C	Workers	LBP / Students D
Number of participants	9	9	9	9	9	5	10	9
Peak Fc (N)	1096 (205)	1086 (188)	1074 (183)	1130 (176)	1057 (143)	1178 (158)	1111 (164)	1069 (219)
Peak Fsj (N)	78 (17)	76 (14)	75 (17)	85 (16)	75 (13)	165 (177)	163 (134)	120 (89)
Peak Fsr (N)	154 (34)	150 (29)	149 (30)	163 (36)	147 (22)	180 (36)	161 (24)	149 (29)
Peak M (N m)	49 (11)	49 (10)	48 (10)	52 (11)	47 (8)	56 (10)	51 (8)	49 (11)
Cum Fc (MN s)	17.4 (2.9)	22.5 (3.9)	27.5 (4.8)	28.6 (3.8)	27.1 (3.2)	29.9 (4.0)	28.2 (4.2)	27.1 (5.6)
Cum Fsr (MN s)	1.7 (0.4)	2.7 (0.5)	3.7 (0.8)	4.0 (0.7)	3.7 (0.5)	4.5 (0.9)	4.0 (0.6)	3.7 (0.8)
Cum M (MN m s)	0.6 (0.1)	0.9 (0.2)	1.2 (0.2)	1.3 (0.2)	1.2 (0.2)	1.4 (0.2)	1.3 (0.2)	1.2 (0.3)
RPD (0-10)	1.8 (1.9)	2.8 (1.4)	5.5 (2.5)	4.7 (2.3)	6.2 (2.7)	3.8 (2.6)	1.4 (1.5)	3.2 (2.8)
5th % APDF (%MVC); L3	1.0 (0.7)	2.4 (1.6)	5.8 (1.9)	2.8 (1.8)	3.2 (1.3)	5.3(1.9)	3.7 (2.0)	NA
5th % APDF (%MVC); L5	2.6 (1.4)	3.8 (2.5)	6.9 (3.1)	4.9 (2.0)	4.7 (2.5)	7.7 (1.3)	6.5 (1.6)	NA
50th % APDF (%MVC); L3	4.5 (1.7)	9.9 (2.3)	12.7 (2.5)	6.5 (2.6)	9.3 (2.1)	8.3 (3.1)	7.5 (3.9	NA
50th % APDF (%MVC); L5	6.6 (2.9)	14.1 (3.7)	13.4 (3.1)	10.5 (2.8)	15.4 (4.3)	10.9 (1.8)	11.6 (3.8)	NA
90th % APDF (%MVC); L3	10.3 (3.2)	12.9 (2.9)	15.4 (3.0)	8.9 (3.0)	11.6 (2.9)	10.8 (3.8)	10.6 (4.9)	NA
90th % APDF (%MVC); L5	16.9 (5.0)	17.4 (4.5)	18.1 (4.7)	13.6 (3.1)	18.4 (4.9)	13.3 (2.5)	15.1 (5.1)	NA
Change in MPF (Hz); L3	- 2.8 (5.0)	- 3.2 (3.6)	- 5.2 (4.5)	NA	NA	- 4.3 (5.0)	- 6.3 (4.2)	- 5.4 (4.9)
Change in MPF (Hz); L5	- 3.5 (7.1)	- 3.2 (4.8)	- 7.0 (5.2)	NA	NA	- 8.1 (8.6)	- 6.7 (4.9)	- 9.2 (8.3)

Is the magnitude of risk factors for low back pain reporting of a flexed lumbar curvature lower than that of a lordotic curvature?

No, both lumbar curvatures were statistically equally uncomfortable and painful after just 25 minutes of assembly time (Figure 15). The flexed lumbar curvature tended to be more comfortable compared to the lordotic lumbar curvature but this difference was not significant due to the large variability between participants. Furthermore, peak and cumulative spinal loading were similar between a fixed flexed and fixed lordotic curvature.

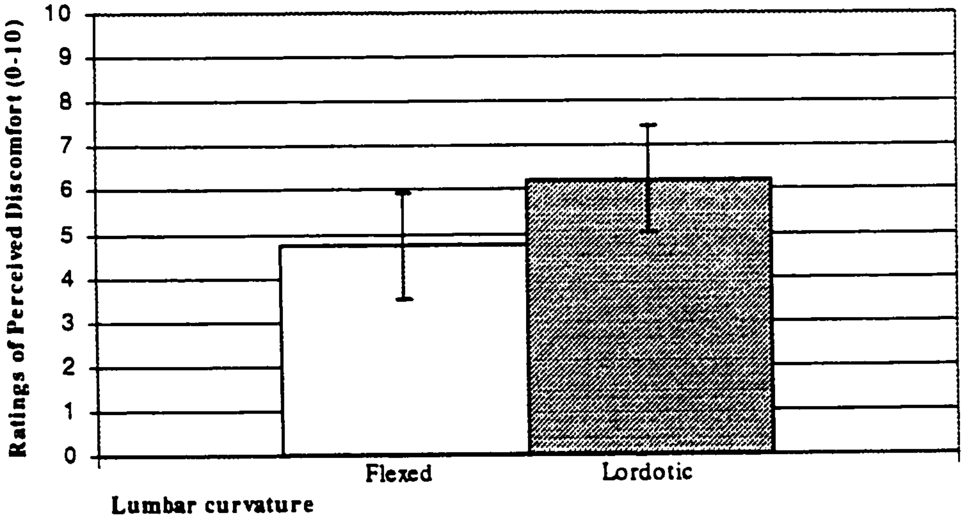


Figure 15. Ratings of perceived discomfort for the fixed flexed and fixed lordotic lumbar curvature were, on average, 4.7 and 6.2 out of 10, respectively. The ratings of perceived discomfort did not differ significantly between the two curvatures after 25 minutes of assembly time ($p<0.31$).

The flexed lumbar curvature required less muscular activation during the assembly time, as measured by the 50th percentile of the APDF: at right L3 ($p<0.001$), left L3 ($p<0.01$), right L5 ($p<0.006$), and left L5 ($p<0.02$) (Figure 16). The difference in EMG amplitude between the two curvatures ranged from 2.6 to 5.1 % of MVC but this difference in activation was not large enough to result in a significant difference in discomfort between the two lumbar curvatures. The difference in average activity might be explained by the moment generating contribution of the passive elastic component of the musculature when under tension due to increased muscle length in the flexed lumbar curvature. McGill and Kippers (1994) showed that the musculature was able to generate a substantial amount of force elastically through stretching during a flexor-relaxation protocol. An additional explanation is a difference in trunk geometry between the two curvatures. The location of the centre of mass of the trunk might have moved posterior in a flexed curvature due to the rounding of the spine. A posterior shift of the centre of mass reduces the extensor moment and the muscular activation required to generate this extensor moment.

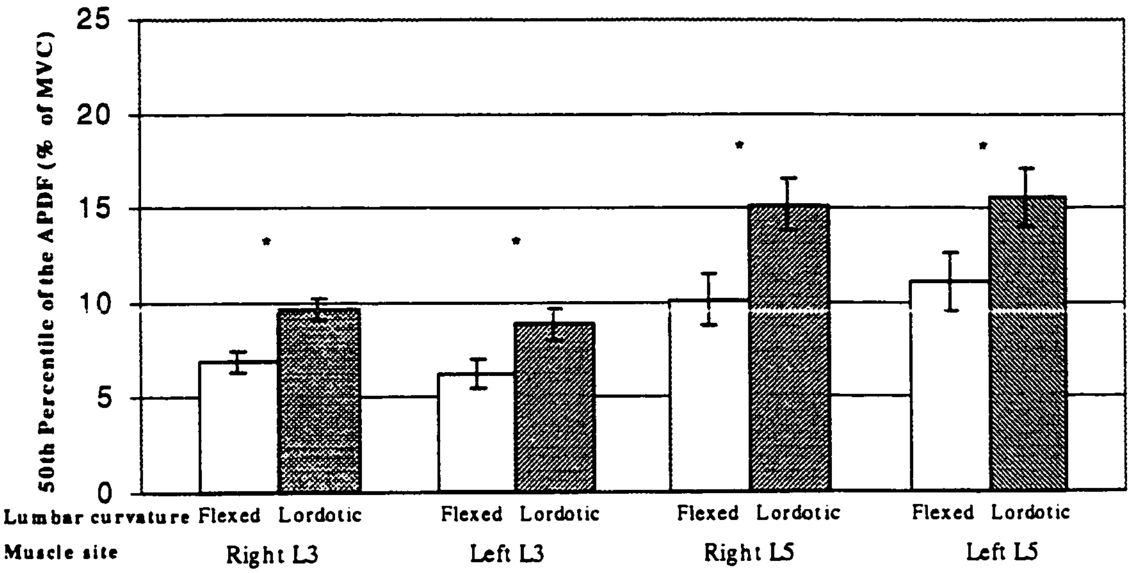


Figure 16. The average muscular activation, measured by the 50th percentile of the APDF and expressed in % of MVC, was significantly lower for the flexed compared to the lordotic lumbar curvature. The difference in activation between the two curvatures is shown for right L3 ($p<0.001$), left L3 ($p<0.01$), right L5 ($p<0.006$), and left L5 ($p<0.02$).

Some participants reduced their back extensor activation below 5% of MVC. However, none of the participants was able to reduce the amplitude of the muscular activation level to noise level at either muscle site (Figure 17). This shows that the flexed lumbar curvature, obtained during 30° of trunk flexion, did not completely unload the musculature that was monitored and remained the dominant contributor to the extensor moment in both lumbar curvature conditions. Maintaining activation of the musculature is important since it reduces anterior joint shear force (McGill and Norman, 1986; Potvin *et al.*, 1991).

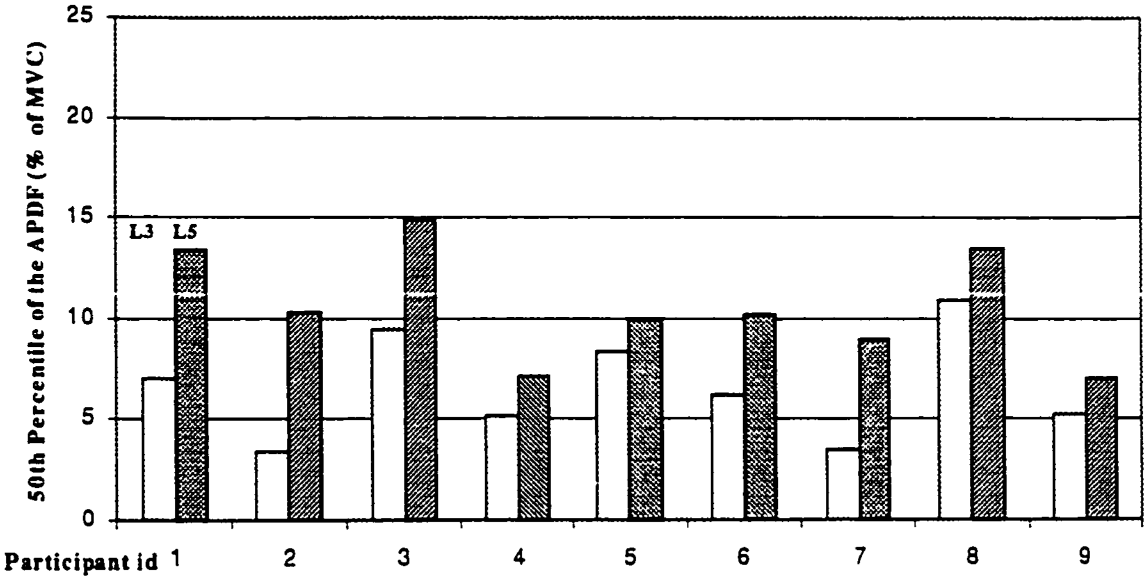


Figure 17. The 50th percentile of the APDF, averaged over left and right electrode sites, is shown for the 3rd and 5th lumbar level for nine participants. None of the participants was able to reduce muscular activity to noise level, below 2 % of MVC, indicating that the monitored musculature was not completely unloaded and remained the dominant contributor to the extensor moment.

Perceived discomfort was expected to be significantly lower in the flexed curvature, but is was not due to the large variability between individuals. Participants were instructed to position their lumbar curvature at the end range of motion in a flexed curvature. Forcing the spine into an extreme position might have caused discomfort for some individuals, by stretching passive tissues, instead of reducing discomfort.

Is the magnitude of risk factors for low back pain reporting of a self-selected lumbar curvature less than a maximally flexed or lordotic curvature?

Yes, ratings of perceived discomfort were significantly lower when a self-selected curvature was adopted by experienced workers (mean of experienced assembly workers=1.4, $p<0.001$), even after a full one hour task duration, compared to 25 minutes of assembly in a fix flexed or fixed lordotic curvature (mean of students=4.7 to 6.2, depending on the lumbar curvature and study). Furthermore, in general, muscular activation was less in the self-selected lumbar curvature compared to a fixed lordotic curvature ($p<0.003$). The change in lumbar curvature was, however, not sufficient to change estimates of cumulative spinal compression force, reaction shear force, extensor moment and muscular fatigue of the back extensor musculature.

The self selection of a lumbar curvature increased the average magnitude of the joint shear force ($p<0.044$) compared to the fixed flexed and fixed lordotic curvature. In these fixed curvatures, all participants maintained extensor muscle activation, thereby reducing the anterior joint shear force. When individuals selected their preferred lumbar curvature, some individuals adopted a large curvature in flexion which increased the joint shear forces from 84N (SD=14) to 383N (SD=84). These joint shear forces, produced by upper body weight only are, however, probably not high enough to be problematic.

Although a self-selected curvature reduced the magnitude of some risk factors for low back pain reporting compared to fixed lumbar curvatures, perceived discomfort increased, on average, to 1.4 over the 1 hour work duration. If this task is performed over a workday or workweek, not just for one hour as in this study, these ratings might further increase and result in low back pain reporting, possibly followed by time off work. It is therefore recommended that workers use a self-selected lumbar curvature during light assembly and introduce changes in work posture when discomfort is perceived. Alterations in work posture by changing trunk angle, lumbar curvature or shifting weight side ways might allow for recovery and result in a beneficial reduction in discomfort.

Discomfort perceived by inexperienced participants, students, (3.8) was significantly higher than the discomfort perceived by assembly workers (1.4) when performing a "light" assembly task with a self-selected lumbar curvature. One explanation is that work experience, possibly affecting physiological and psychological factors, can alter perceptions of discomfort. Work experience might be beneficial due to a training effect. When performing the same task repeatedly over time, individuals become accustomed to the task, possibly followed by a reduction in discomfort. Furthermore, university students and assembly workers are thought to differ in attitude and job expectations. The experienced workers do assembly type of work for a living whereas students seem to expect that their education will result in a more interesting or challenging job, in their eyes a "better" job.

Since inexperienced workers perceive higher discomfort than experienced workers it might be beneficial to provide job training for the inexperienced workers. A possible training strategy for light assembly work is introducing the assembly task to the new workers at a lower work/recovery ratio thereby allowing for more pauses. Once the worker is accustomed to the task the work/recovery ratio could be increased. Another training strategy might be an initial reduction in production rate to allow for recovery breaks within the assembly duration. Again, once the new worker is accustomed to the task, the production rate could be increased.

The rationale for recruiting experienced assembly workers was to improve the applicability of the research findings to the workplace. This work is however limited by the fact that a task simulation in the laboratory was used to collect the data. Assembly workers commented on how clean and quiet the environment was. Their content about the work environment compared to other work places and the attention they received during the data collection might have resulted in lower discomfort ratings than might have been obtained during data collection in the actual workplace. Subjective ratings have been shown to be easily affected by situational factors such as expected work duration, expected performance and possibly the work environment. This has been shown to be true especially during light and moderate exercise intensities (Noble and Robertson, 1996). Although data collection in the workplace is more realistic, it involves additional challenges and often does not allow for use of extensive data collection techniques as are applied in the laboratory.

Can ratings of perceived discomfort replace instrumented measures of risk factors for low back pain reporting?

The answer to this question consists of two parts. Yes, ratings of perceived discomfort, averaged over participants, were significantly higher for the 55/5 second work/recovery ratio compared to the other two work/recovery ratios which were similar after 25 minutes of assembly with a lordotic curvature ($p<0.0001$; study 1). In other words, the difference in demands between the 55/5 and 40/20 second work/recovery ratio was large enough to alter, on average, individuals' perceptions.

No, there was no relationship between perceived discomfort and instrumented measures of risk factors for low back pain reporting when evaluating one and the same work situation. Individuals with high discomfort were compared to those with low discomfort while performing the same assembly task at the 55/5 second work/recovery ratio (study 3). Grouping of individuals into a high and low response group was done based on their discomfort ratings and a cut off of 1.5 was used (Figure 18). Selection of an arbitrary cut off based on data instead of on theory can be problematic when replicating this work. More work should be done on discomfort rating scales to attempt to establish absolute values to identify high risk groups. When using the 1.5 cut off, the low and high discomfort groups did not differ in peak spinal loading, cumulative spinal loading, muscular activation levels or magnitude of local muscular fatigue developed over the work duration.

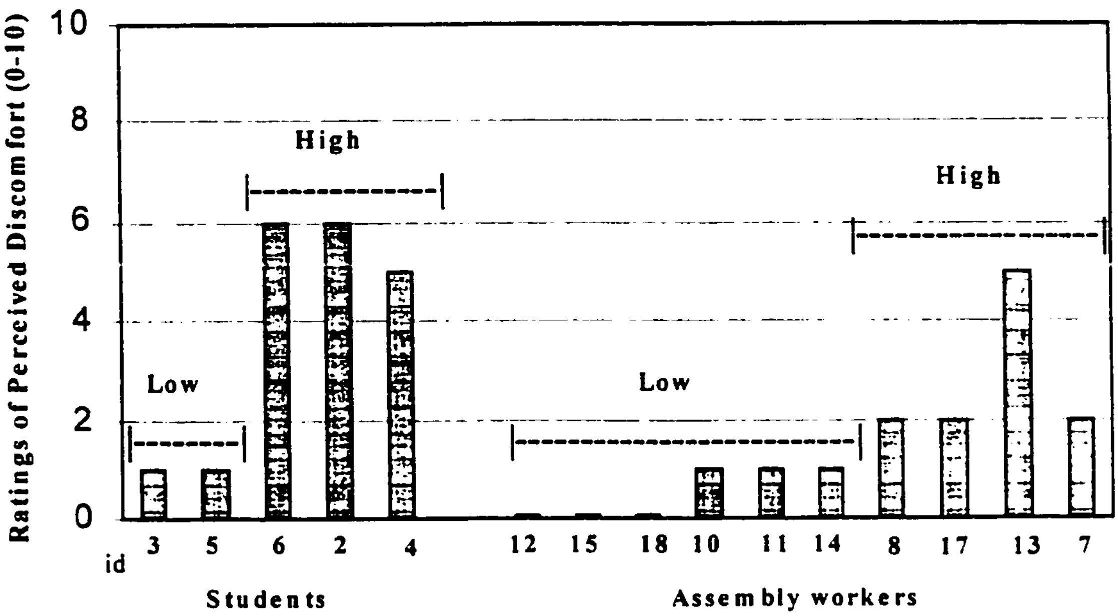


Figure 18. Ratings of perceived discomfort at the end of the assembly task differed among individuals as shown for the five inexperienced workers, students, and ten experienced assembly workers. Within the student and assembly worker group, individuals with ratings below 1.5, low discomfort individuals, and above 1.5, high discomfort individuals, could be identified. The high discomfort individuals rated significantly higher discomfort compared to the low discomfort individuals for both the student ($p<0.0003$) and assembly worker group ($p<0.002$).

Peak spinal loading, such as peak compression force, did not differ among individuals with low and high discomfort (Figure 19). Therefore, individuals did not base their perceptions on known risk factors for low back pain reporting such as spinal loading. This is in agreement with the literature which suggests that ratings of exertion are marginally or not at all based on spinal loading variables (Thompson and Chaffin, 1993; Jorgensen *et al.*, 1999; Davis *et al.*, 2000).

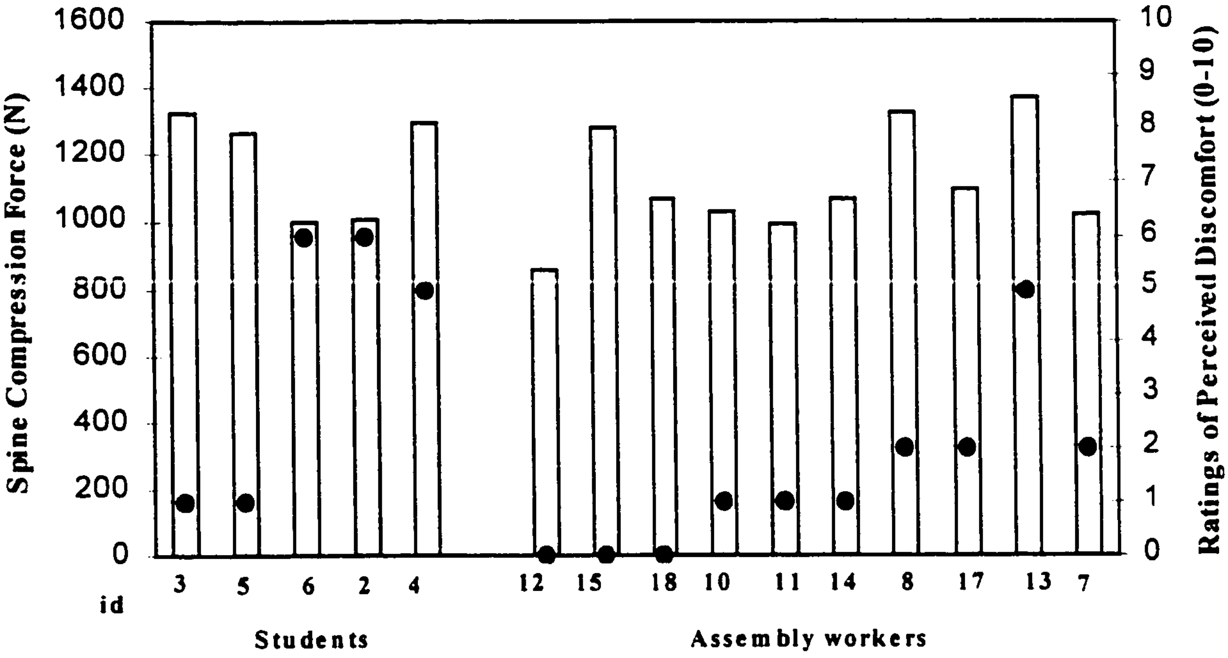


Figure 19. Spinal compression forces, as presented by bars and the left vertical axis, are shown in combination with ratings of perceived discomfort, as presented by dots and the right vertical axis. It can be seen that individuals with high discomfort ratings (participant number 6, 2, 4, 8, 18, 13 and 7) were exposed to a similar magnitude of risk factors for low back pain reporting as individuals with low discomfort ratings within the students group ($p<0.22$) and the assembly worker group ($p<0.15$).

No difference was found in muscular activation level, a measure partly related to muscular force, between high and low discomfort individuals (Figure 20), whereas Davis *et al.* (2000) showed that the selection of acceptable loads for lifting were affected by muscular force and by heart rate when heavy loads were involved. The difference in findings might be due to the low level of activation required in the assembly task. The findings by Davis *et al.* (2000) were obtained from manual material handling involving moderate to high loads, ranging from 9.1 to

41.7 kg. In a higher loading task, muscular force may play a more important role in perception of the demand.

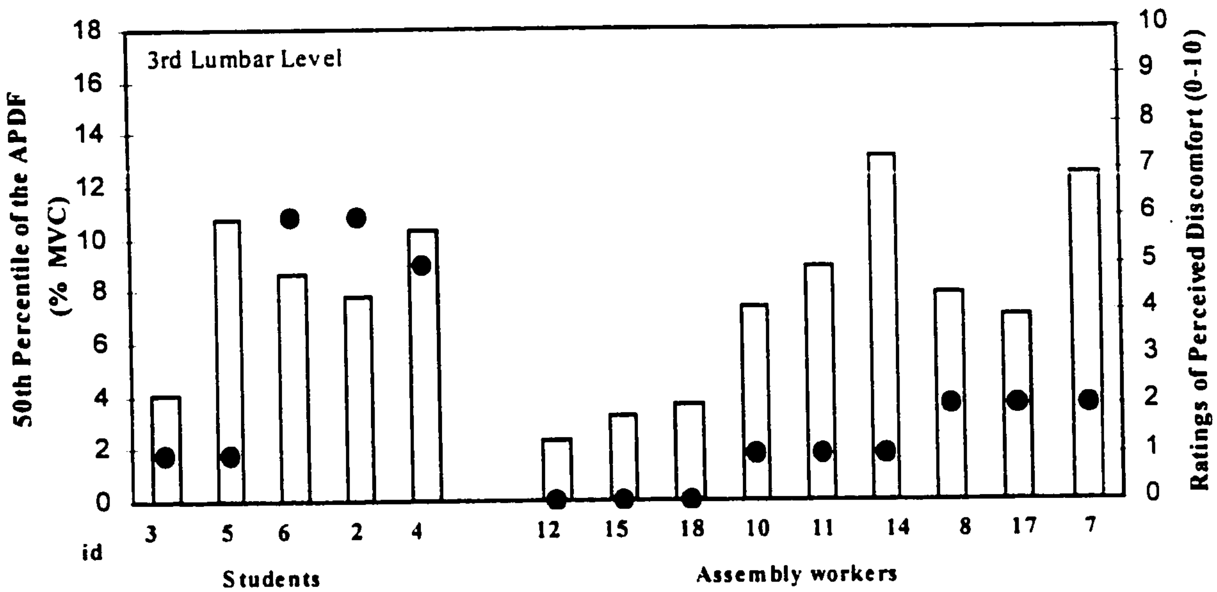


Figure 20. The 50th percentile of the APDF (bars, left axis) at the level of the 3rd lumbar vertebra is shown in combination with discomfort ratings (dots, right axis). Average muscular activation levels were similar between low and high discomfort individuals within the student ($p<0.66$) and assembly worker group ($p<0.36$).

Local muscular fatigue (MPF) did not differ between the low and high discomfort group, whereas, Dedering *et al.* (1999) reported a linear relationship between measures of discomfort and spectral EMG measures and endurance time during a modified Sørensen's test. The discrepancy between the findings in these studies and those of Dedering *et al.* (1999) might be explained by the differences in tasks and muscular activity level. The task in the present study was more complex, involving static and dynamic components, possibly allowing for partial recovery by changing recruitment among muscles. The average muscular activation level of the task in the present study was only 12.5 % MVC which was considerably less than approximately 45-65 % MVC that occurs during a Sørensen's test. It is known that discomfort develops more rapidly at higher intensities. These differences between studies could therefore affect individuals' perceptions of discomfort.

Discomfort ratings were correlated with the initial MPFs to determine whether individual characteristics, such as possible differences in fibre type, affect perceptions of discomfort. A poor correlation between initial MPFs and ratings of perceived discomfort were found ($r=0.31$) indicating that discomfort ratings were not highly related to the initial MPF.

The one variable that was related to discomfort was pain located in the low back (region between the lower part of the rib cage and the pelvis). Individuals who perceived high discomfort also rated high on the pain scale with the low back being the most dominant site of pain ($p<0.0003$). A high correlation between the discomfort and pain ratings obtained after one hour of assembly was found ($r=0.87$; combined data of study 3 and 4). This finding implies that the participants did not distinguish between discomfort and pain. Therefore, instead of using two separate rating scales, a discomfort and pain scale, one scale might be sufficient. Based on this research a ratio scale, with no discomfort at 0 and extreme pain at 10, in combination with a diagram is proposed. The diagram will locate the area of discomfort or pain and this might better target perceptions from physical origin (a location on the diagram) than perceptions from mental/emotional origin. None of the other reported pain locations, shoulders, neck, upper back, thigh, knee and feet, were able to distinguish between individuals with low and high discomfort.

Production rate was similar between the two groups ($p<0.35$) and a slight increase in production rate over time occurred, rather than a decrease with increased discomfort and pain as was expected ($p<0.046$). A decrease in production rate with an increase in discomfort and pain was expected because it was thought that discomfort would distract from the assembly task and that additional postural movements would interfere with the continuation of the task. The increase in production rate is not thought to be a result of an increase in discomfort and pain. The increase in production rate was probably due to a learning effect. Therefore, production rate can not explain differences between high and low discomfort groups.

It can be concluded that ratings of perceived discomfort, averaged over participants, distinguished between the more demanding 55/5 second work/recovery ratio and the other two work/recovery ratios in a similar way as did instrumented measures of risk factors. In other words, average ratings of perceived discomfort can replace instrumented measures when evaluating "light" assembly work with various work/recovery ratios that differ widely in the magnitude of risk factors.

However, there was no relationship between perceived discomfort and instrumented measures of risk factors when evaluating one and the same work/recovery ratio. These findings might imply that perceived discomfort is not sensitive enough to detect changes in instrumented measures of risk factors for low back pain reporting. The opposite could be questioned. Are instrumented measures of risk robust enough to detect changes in discomfort? Data from this research showed that instrumented measures of risk involved less variability than ratings of perceived discomfort. If instrumented measures of risk and discomfort ratings were related, than instrumented measures could be robust enough to detect changes in discomfort ratings. However, the instrumented measures of risk used in this study did not appear to be closely related to discomfort ratings. The instrumented measures of risk obtained in this study were not robust enough to detect differences in discomfort between participants when performing a "light" assembly task at a 55/5 second work/recovery ratio possibly because the instrumented measures may not be relevant in the perception of discomfort.

From this research it is not clear on which risk factors individuals base their perceptions of discomfort. Therefore, when evaluating a "light" assembly task with one work/recovery ratio, ratings of perceived discomfort can not replace instrumented measures of risk factors. This does not mean that perceptions of discomfort are not important. Perceived physical demands was a strong and independent risk factor for the reporting of low back pain in the study of auto workers (Norman *et al.*, 1998; Kerr *et al.*, 2000). Individuals who perceive high discomfort are more likely to report low back pain, possibly followed by time off work. Instrumented measures of risk factors and ratings of perceived discomfort appear to be measuring different phenomena. It is therefore recommended that both, instrumented and subjective measures are obtained when evaluating the risk for low back pain reporting during work.

Do individuals who had had low back pain alter trunk angle and lumbar curvature during the task performance?

No, individuals who had recently had low back pain did not change trunk angle or lumbar curvature more compared to those who had not had low back pain (Table 2). This was surprising since pain in the low back was reported most often and changes in trunk posture and lumbar curvature might have alleviated this pain. The majority of participants reported a shifting of their body weight sideways, from one leg to the other, to reduce discomfort, pain and/or fatigue. Whether individuals moved their body weight side ways or not did not appear to be related to their discomfort or pain level. Only a few individuals described an intentional alteration in their work posture in flexion-extension. The nature of the task seemed to allow for more room for changes in lateral direction than flexion, possibly due to the fixed height of the table on which the assembly task was performed. Perhaps if room for change in posture in flexion-extension was build into the task, this might induce postural relief.

Measure	Students; (n=5)	Assembly workers; (n=10)	Individuals who had had low back pain; (n=9)
Trunk angle (°)	36.5 (8.2)	32.9 (4.3)	30.4 (4.3)
Lumbar curvature (% of ROM)	48.0 (20.9)	56.0 (18.2)	50.5 (12.6)
Change in flexion, SD (°)	1.0 (0.3)	0.9 (0.3)	1.4 (0.8)
Change in lateral bending, SD (°)	0.8 (0.4)	0.7 (0.4)	1.1 (0.5)
Change in twisting, SD (°)	0.7 (0.3)	0.6 (0.3)	0.9 (0.4)

Table 2. No significant differences between the three groups of participants in trunk angle and lumbar curvature measures (lumbar curvature as a percentage of maximum range of motion and standard deviation in flexion, lateral bending and twisting) were found during the assembly duration. The means and standard deviations are shown.

Not finding a difference in postural alterations between those with and without recent low back pain might be explained by the similarity between the two groups in spinal loading, perceived discomfort and local muscular fatigue.

The similarity found in local muscular fatigue between those with and without recent low back pain does not contradict the repeatedly reported differences in spectral measures of the lumbar extensor musculature between back pain patients and healthy individuals (Roy *et al.*, 1989; Biedermann *et al.*, 1991; Peach and McGill, 1998). The difference in the findings in this study compared to the literature might be explained by the difference in participant selection (recurrent or first time back pain patients versus the chronic back pain patients in those studies) and the magnitude of muscular activation during testing (below 20% of MVC in assembly versus between 40 to 80 % of MVC which was used for discriminant analysis).

Although the ratings of perceived discomfort of the individuals who had had low back pain (3.2 out of 10) were not significantly higher than those of the assembly workers (1.4), their ratings were high and similar in magnitude to the ratings of the students in the third study (3.8). The tendency of individuals who had had low back pain and students to perceive higher discomfort is important. Reporting of low back pain is at least in part thought to be preceded by the perception of discomfort or pain. Therefore, individuals with high discomfort and pain are thought to be more likely to report low back pain.

It must be kept in mind that ratings of perceived discomfort and pain, of individuals who had had low back pain, during a particular task might be affected by the location from which the pain originates. For example, low back pain from discogenic origin is known to be aggravated in flexion. Individuals had various diagnoses and levels of low back pain at the time of participation in this study. This might explain the large differences in perceived discomfort found among the participants which exceeded that of the students and assembly workers.

LIMITATIONS

1) Participant selection is important. Individuals with work experience, in this case assembly work, perceived less discomfort during the task than did the students. This implies that, ideally, evaluations of work situations should be done with experienced workers.

2) The selection of the work environment is important. The experienced assembly workers enjoyed the task and commented on the quietness and cleanliness of the environment. Their contentment with the work environment might have reduced their perceptions of discomfort.

3) Assembly task durations of 25 minutes and 60 minutes were used to estimate the magnitude of risk factors for low back pain reporting and these durations might not reflect the demands over a full workday, even though measurable responses to the work occurred in this short time.

CONCLUSIONS

1) The first hypothesis, that an increase in work/recovery ratio would increase the magnitude of risk factors, was supported by the data. Cumulative spinal loading increased and local muscular fatigue and ratings of perceived discomfort increased with an increasingly more adverse work/recovery ratio.

A "light" assembly task was not light during a "55/5 second minute" in terms of cumulative spinal loading, local muscular fatigue and perceived discomfort. This type of task is, however, often interpreted as being light by people such as employers and industrial engineers since it does not involve high peak loading. It should be noted that although the magnitude of risk factors for low back pain reporting during the 25/35 and 40/20 second work/recovery ratio were similar and lower than those of the 55/5 second work/recovery ratio, all three work/recovery ratios might be demanding when performed over a longer duration such as a full workday or workweek.

2) The second hypothesis, that a flexed lumbar curvature would be perceived by participants as less demanding than a lordotic curvature, was not supported by the data. Participants found both lumbar curvatures, a fixed flexed and fixed lordotic curvature, equally uncomfortable and painful after just 25 minutes of assembly time.

3) The third hypothesis, that ratings of perceived discomfort would be lower for a self-selected lumbar curvature, was supported by the data. The self-selected curvature resulted in significantly lower ratings of perceived discomfort, even after a full one hour task duration, compared to 25 minutes of assembly in a fix flexed or fixed lordotic curvature.

4) The fourth hypothesis, that ratings of perceived discomfort could not replace instrumented measures of risk factors, was, depending on the application of this measure, supported by some data and rejected by other data. Ratings of perceived discomfort, averaged over participants,

distinguished between the more demanding 55/5 second work/recovery ratio and the other two work/recovery ratios in a similar way as instrumented measures did. In other words, average ratings of perceived discomfort can replace instrumented measures when evaluating various situations of "light" assembly work that differ substantially in the magnitude of risk factors.

However, there was no relationship between perceived discomfort and instrumented measures of risk factors when evaluating one and the same work situation. It is not clear on which risk factors individuals base their perceptions of discomfort. Therefore, when evaluating one work situation of "light" assembly, ratings of perceived discomfort can not replace instrumented measures of risk factors. This does not mean that perceptions of discomfort are not important since individuals who perceive high discomfort are more likely to report low back pain, possibly followed by time off work with the threat of expensive long-term disability, for some.

5) The fifth hypothesis, that individuals who had recently had low back pain would vary trunk angle and lumbar curvature, was not supported by the data. Individuals who had had low back pain did not change trunk angle or lumbar curvature more than those who had not had low back pain. This was surprising since pain in the low back was reported most often and changes in trunk posture and lumbar curvature might alleviate this pain. The majority of participants reported a shifting of their body weight sideways from one leg to the other, to reduce discomfort, pain and/or fatigue.

RECOMMENDATIONS

1) A "55/5 second minute" of "light" assembly in mild trunk flexion should be avoided.

2) Individuals should be encouraged to adopt a self-selected lumbar curvature.

3) Individuals should be encouraged to introduce changes in trunk posture in flexion-extension since changes in posture might induce postural relief. Instruction to introduce changes in posture after individuals perceive discomfort might be beneficial.

4) Ratings of perceived discomfort can not replace instrumented measures of risk factors of low back pain reporting when evaluating one and the same "light" assembly task. Discomfort ratings should be used in combination with other measures of risk factors.

5) Evaluation of industrial jobs should ideally be done with experienced workers and in the appropriate workplace rather than using inexperienced participants such as students and collecting data in the laboratory.

FUTURE RESEARCH

1) Work/recovery ratios should be evaluated using variables related to risk of injury for a variety of industrial tasks which are performed over longer durations such as a full workday.

2) The understanding of variables that affect perceptions of discomfort and pain should be improved since these perceptions could result in back pain reporting, possibly followed by time off work.

3) The usefulness of a single rating scale, with 0 representing no discomfort and 10 representing

extreme pain, in combination with a diagram to locate the area in which discomfort or pain is felt, should be evaluated.

4) Mechanisms of injury following prolonged low level loading require further examination.

5) The benefits of instruction and practice of strategies, such as alternation in lumbar curvature and movement of the trunk, which can be adopted during "light" assembly tasks should be evaluated.

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Appendix A

The effects of altering work/rest ratios of a prolonged, low peak loading task on risk factors for the reporting of low back pain in industry

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Abstract

The purpose of this study was to improve the understanding of the effects of altering work/rest ratios during simulations of an industrial task, characterized by prolonged loading without high peak load, on risk factors related to the reporting of low back pain. Nine healthy women performed an assembly task with the torso at a 30° flexion angle. The task duration was 25 minutes with a cycle time of 1 minute and three work/rest ratios were performed (25-35, 40-20 and 55-5 seconds), each on a different day. Measures of spinal loading, subjective ratings of discomfort and risk of injury, EMG amplitude and EMG spectral measures were taken at 5 minute intervals during the task. A significant increase in cumulative spinal loading (5 MN s compression force), elevated ratings of perceived discomfort (increase from 1.8 to 3.4 out of 10), continuous muscular activation levels during rest (from 3.1 to 6% MVC) and development of muscular fatigue (18.2% increase in fatigue) occurred from the 40-20 to the 55-5 second work/rest ratio. The 25-35 and 40-20 second work/rest ratios were comparable in terms of subjective ratings and muscular fatigue. Furthermore, the physical demands did increase significantly over the 25 minute work duration, as was measured by subjective ratings and muscular fatigue.

Relevance to industry

Competition in industry has lead to an increase in work/rest ratios. This study showed that, for a simulation of an industrial task, risk factors of reporting low back pain increased exponentially with an increase in work/rest ratio. This work is an initial step towards the development of guidelines for acceptable work/rest ratios in industry from a biomechanical

perspective. Further research is required to achieve this goal.

Keywords: Work/rest ratio; Risk factors; Low back pain; Cumulative loading; Industrial task simulation; Female workers

1. Introduction

High peak forces on the lumbar spine have long been known to be a risk factor for low back injury (Kelsey *et al.*, 1984; Marras *et al.*, 1993; Norman *et al.*, 1998) and efforts have focused on reduction of this type of loading. Cumulative loading has also been identified as potentially injurious to the back in epidemiological studies (Norman *et al.*, 1998; Kumar, 1990) and in *in vitro* studies (Adams and Hutton, 1985).

Many industries have attempted to reduce or eliminate high peak forces on the low back by improving job design. However, it appears that adverse effects of cumulative loading, as a result of prolonged or repetitive tasks of "lighter" jobs, have not been recognized as problematic in the workplace. Competition in industry is high and has lead to a reduction of the workforce and an increase in production rates. These changes result in a larger amount of work done by fewer workers. In other words, the amount of time allocated to work increases and the time allocated to rest decreases, thereby, possibly increasing cumulative loading. For example, some companies in the automobile industry are working towards a work/rest ratio up to 55-5 (55 seconds of work, 5 seconds of rest in a 60 second cycle). Moreover, women have increasingly become a larger part of the workforce in recent decades but physical ergonomics research on the female population has been sparse.

Perceptions of pain by workers often result in absence from the workplace. It is widely accepted that physical work results in muscular fatigue and that this fatigue may result in perceptions of discomfort or even pain by the worker. A linear relationship between measures of subjective discomfort and measures of fatigue such as spectral EMG and endurance time, during a modified Sørensen test, was found by Dedering *et al.* (1999). This finding suggests that rating scales, which are inexpensive and easy to use, can replace instrumented measures of fatigue but whether this is true for tasks other then the Sørensen test must be examined. Furthermore, since the link between fatigue and the risk of low back injury is unclear, ratings of perceived risk of injury instead of ratings of discomfort might result in a better estimate of risk factors related to low back pain. Whether individuals are able to estimate sizes of risk factors associated with a particular task must also be evaluated. This paper addresses the effects of various work/rest ratios up to 55-5 seconds on the physical demands in women during simulated work, in terms of cumulative spinal loading, discomfort rating, muscular activation level, and fatigue, some of which have been shown to be related to the risk of low back injury.

The task that was analyzed in this study was selected to represent a working posture that occurs in the automobile industry. The task can be characterized by its quasi-dynamic nature and prolonged loading without high peak loading. The 30° trunk flexion angle used in this study was described by Punnett *et al.* (1991) as mild trunk flexion with an odds ratio of 4.9, meaning that cases (workers who had reported low back pain) were 4.9 times as likely to work with the trunk in moderate flexion (20°-45°) for any length of time compared to referents (those who had not reported pain). During preliminary data collection in the present study a large variation in lumbar curvature was found between individuals. To reduce the variability, lumbar posture was constrained to a hollow curvature (lordosis) which requires back extensor muscle activation, thereby reducing anterior shear force (McGill and Norman, 1987; Potvin *et al.*, 1991). Both peak and cumulative shear force have been identified as risk factors for low back pain (Norman *et al.*, 1998) and a reduction in shear force is expected therefore, to reduce the risk of injury of the experimental task. A lordotic curvature can be seen as a posture at the outer edge of an envelope of lumbar postures that people use while working.

Work-rest models have been developed to be able to select the duration and frequency of rest pauses with the intent to increase productivity and reduce muscular fatigue and risk of injury. Various work-rest models have been developed using endurance and recovery data from a combination of muscle groups and these models have been proposed to be applicable to multiple body parts (Rohmert, 1960; Dul *et al.*, 1991; Rose, 1992). However, later work by Rohmert *et al.* (1986) suggests that different models should be used for upper extremity postures versus trunk postures since the endurance times of the muscle groups involved differ. This suggests that the use of one work-rest model may not be feasible and a more complicated approach of body part specific evaluation is required. To our knowledge only one work-rest model addressing the trunk has been developed which was based solely on endurance data from a stooped trunk posture (Milner, 1985). However, this model was developed on four repeated bouts of exercise only. The duration of exercise was limited to 33%, 66% and 100% of maximum holding time (MHT) and rest durations of 25%, 50% and 100% MHT. The exercise bouts were interspersed with MHTs to determine recovery at multiple intervals. Therefore, this model does not appear to reflect repeated exercise for durations below MHT and further evaluation of the model for a larger number of repetitions and a wider range of work/rest ratios is desired.

Work-rest models are based on measures of maximum holding time and/or number of repetitions until exhaustion (Milner, 1985; Rose, 1992; Dul *et al.*, 1991; Rohmert, 1960) but the reliability of these measures is questionable. Maximum holding time has been shown to be highly variable, especially at activation levels below 15% MVC due to participant motivation (Sjøgaard, 1986). Furthermore, most models address the issue of muscular fatigue with the underlying idea that fatigue limits performance and leads to the development of musculoskeletal disorders. Fatigue has been hypothesized to reduce motor control and predispose the spine to injury (Parnianpour *et al.*, 1988; Potvin, 1992; McGill *et al.*, 1995). However, to our knowledge, the development of muscular fatigue during cumulative loading has not been epidemiologically linked to risk of low back injury. Therefore, variables related to risk of injury should be measured to address the effects of work-rest schedules on back injury risk.

Many variables have been proposed to be related to risk of low back injury (Garg and Moore, 1992; Frank *et al.*, 1996) but few have been proven. Cumulative spinal loading has been shown to be a risk factor for low back injury as shown by Norman *et al.* (1998) based on data from a large automobile industry. Furthermore, elevated subjective ratings of perceived exertion which are used to reflect the perception that one's job is physically demanding on the body have been shown to be related to the risk of low back injury (Kerr, 1998). Since the present study involved a quasi-dynamic task without peak loading, rating of perceived discomfort was used instead of exertion which was developed for tasks that strain the cardiovascular and/or respiratory system (Borg, 1982). Static loading during repetitive assembly work for, on average, 16 years has been shown to be a risk factor for muscular disorders such as trapezius myalgia (Larsson *et al.*, 1988); whether this finding can be extended to the back musculature is not known.

The purpose of this study was to improve the understanding of the effects of altering work/rest ratios during simulations of an industrial task, characterized by prolonged loading without high peak load, on risk factors related to the reporting of low back pain. It was hypothesized that: 1. an increase in work/rest ratio results in an exponential increase in measures of risk factors and that risk factors increase over the work duration and 2. subjective ratings of perceived discomfort and perceived risk of injury can not replace instrumented measures of risk factors and that the two rating scales are not comparable.

2. Methods

2.1. Participants

Nine healthy women (height 1.70 m, SD = 0.1; body mass 63.7 kg, SD = 8.6; age 20.2, years, SD = 2.6) were recruited from an undergraduate university population. None of the participants had experienced low back pain in the year preceding testing. All participants read and signed the informed consent form approved by the Office of Human Research at the university.

2.2. Experimental task

An assembly task was performed in upright standing with the trunk flexed forward 30° from vertical. Participants returned to an upright posture at set intervals in which they were allowed to move their torso freely. The time spend in the flexed forward posture will be referred to as work and the upright standing posture as rest. This task involved low peak loading since upper body weight was the only load that had to be supported. The posture was constrained by instructing the participants to position their lumbar spine in a lordosis and to maintain this curvature during the task. The task was performed in the sagittal plane and no changes in posture were allowed during assembly which consisted of building a car/helicopter/boat model using small building blocks which were located on a table in front of the participant.

The cycle time was 1 minute with three work/rest ratios of 25-35, 40-20 and 55-5 seconds. Each work/rest ratio was performed on a different day and the total duration of the task was 25 minutes.

2.3. EMG fatigue test

Participants held a chain with a 10 kg load just above the floor with the trunk at a 30° flexion angle from vertical and the low back in a lordosis. This static posture under sub-maximal loading was maintained for 5 seconds at the beginning of testing and at 5 minute intervals during the task (total of 6). After completion of the task, a fatigue test was done in which the participants held the load until they were unable to maintain the static posture (average 3 minutes 43 seconds; range 32 seconds - 7 minutes 28 seconds). Data were recorded during the first and last 5 seconds during this EMG fatigue test with the last recording representing maximal fatigue.

2.4. Normalization test

Maximum voluntary contractions (MVC) of the back extensor musculature, for EMG normalization purposes, were performed at the beginning of data collection. Participants were asked to lie on their stomachs and lean over the edge of a bench with the legs restrained. A maximum back extensor effort was performed against manual resistance. This test was repeated 3 times.

2.5. Data acquisition and reduction

Biomechanical model: A biomechanical model (4DWATBAK, University of Waterloo) was used to estimate peak and cumulative spinal loading. A detailed description of the 2 dimensional version of this model can be found in work by Andrews *et al.* (1997) and Norman *et al.* (1998). Furthermore, the model has been risk-validated, meaning that it has been shown to be able to produce an epidemiological estimate of risk reporting of low back pain (Norman *et al.*, 1998; Kerr *et al.*, 2000). Video was used to position the model's moveable manikin in the posture obtained during the task. The manikin provided joint coordinate data which, in combination with gender, height and weight of the participants, were used to estimate peak spinal compression force, reaction shear force, and extensor moment. Cumulative loading was obtained by extrapolating single estimates taken at 5 minute intervals to a total of 25 minutes. Data were multiplied to obtain cumulative loading estimates over a 7 ½ hour workday for literature comparison purposes. Although the model allows for a 3 dimensional analysis, a 2 dimensional analysis was performed due to the nature of the task (sagittal plane, quasi-dynamic).

Electromyography: Surface EMG was collected to obtain amplitude and spectral measures. EMG electrodes were placed bilaterally, 3 cm lateral to the 3rd lumbar vertebra representing the lumbar Erector Spinae and 1-2 cm lateral to the 5th lumbar vertebra representing the Multifidus. Signals were prefiltered to obtain a bandwidth of 5 to 500 Hz, amplified with a differential amplifier (CMRR 80dB @ 60 Hz) to produce signals between 2 and 8 V and A/D-converted at 1024 Hz.

During the normalization tests, EMG was collected for a 5 second duration. Data were full-wave-rectified and low pass filtered (Butterworth) at a cutoff frequency of 2.5 Hz. The peak of each record was identified and the highest value of the three repeats was selected for EMG normalization purposes.

EMG was collected for a duration of 1 minute (1 cycle) at the beginning of the task and at 5 minute intervals for a total of 5, one minute, data collections. The data were full-wave-rectified, low pass filtered (Butterworth with cutoff of 2.5 Hz) and normalized to MVC. The 1) average EMG of the signal was calculated and 2) the signal was transformed into an Amplitude Probability Distribution Function (APDF). The 5th percentile of the APDF was calculated to obtain a measure of rest. The 90th percentile was calculated to obtain peak muscular activity.

Mean Power Frequencies (MPF) of the EMG fatigue tests were calculated. Each 5 second record was clipped into 10, half second pieces. The MPF of each clipping was calculated and the MPFs of the middle 8 clippings were averaged to obtain 1 MPF per EMG fatigue test. The change in MPF over the task duration was quantified by taking the difference between the MPF obtained after the first 5 minutes of task performance and the average of two MPFs obtained during the last 5 minutes of the task. The maximum change in MPF was quantified as the difference between the MPF obtained after the first 5 minutes during the task ("unfatigued") and the MPF obtained at the end of the maximal holding trial ("maximum fatigue"). The change in MPF during the task was expressed as a percentage of the maximum change (drop) in MPF.

Rating scale and pain diagram: A 10 point scale was used to obtain ratings of perceived discomfort and ratings of perceived risk of injury: zero was defined as "no perceived discomfort" or " no perceived risk of injury" and 10 was defined as "extreme perceived discomfort" or "extreme perceived risk of injury". Ratings were taken during and after testing (total of 5). A pain diagram, showing a front and back view of the entire body, was completed before and after task performance. Participants were asked to circle body areas in which pain was felt. Pain experienced in each body part was quantified using a 10 point scale with the zero point defined as "no pain" and the 10 was defined as "extreme pain".

2.6. Statistical analysis

One-way ANOVAs were used to determine whether spinal loading, EMG spectral and amplitude measures, and rating scales differed significantly between work/rest ratios. Additional one-way ANOVAs with repeated measures on time were used to determine whether peak spinal loading and rating scales changed significantly over the duration of the task. For EMG amplitude measures one-way ANOVAs with repeated measures on time and muscle were used. The strength of the relation between ratings scales and spectral fatigue measures was determined using Pearson Correlation Coefficients; a level of significance of 0.05 was chosen.

3. Results

3.1. Peak loading

The task was characterized by low peak loading. For example, on average, peak compression force was 1085N which is well below the NIOSH action limit of 3433N. The 3 work/rest ratios did not differ significantly in peak spinal compression force, shear force and extensor moment as is shown in figure 1. Peak muscular activation was measured using the 90th percentile of the APDF and was, on average, 14.9% MVC. Again, no significant differences were found in peak values between the 3 work/rest ratios (figure 2).

3.2. Cumulative loading

Cumulative loading during the task was large and, in general, exceeded control (individuals who did not report low back pain) and case data (individuals who did report low back pain) described by Norman *et al.* (1998) as is shown in figure 3. Work/rest ratios differed significantly ($p<0.0001$) with the highest work/rest ratio resulting in the largest cumulative loading, as was expected.

3.3. Rest time

An increase in work/rest ratio resulted in a reduction in upright standing time (rest). The 5th percentile of the APDF of the EMG was used to determine whether the participants were able to return to and maintain upright standing. All 3 work/rest ratios differed significantly, with the 5th percentile of the APDF of the 55-5 second work/rest ratio exceeding 5% of MVC ($p>0.0001$; figure 4).

3.4. Rating scales

Ratings of perceived discomfort and ratings of perceived risk of injury, averaged over the task duration, were significantly higher for the 55-5 second work/rest ratio compared to the other two work/rest ratios (p<0.0001; figure 5).

3.5. Muscular activation levels

The average EMG was obtained over a 1 minute cycle which includes work and rest. The average activation levels were low and a step-wise increase over the three work/rest ratios occurred from 7.4% to 10.5% and to 12.7% of MVC. All three work/rest ratios were significantly different (p<0.0001; figure 6).

3.6. Muscular fatigue

The increase in work/rest ratio affected muscular fatigue. Spectral measures (MPF) were used to quantify muscular fatigue and a large amount of fatigue (28.1% drop in MPF with respect to rest) was found during the 55-5 second work/rest ratio whereas the 25-35 and 40-20 second work/rest ratios showed comparable magnitudes of fatigue, a 8.3% and 9.9% drop in MPF with respect to rest, respectively (figure 7). A large variability between participants occurred as is reflected in the large standard error bars.

3.7. Rating scales and EMG spectral measures of fatigue

Correlation between the ratings of perceived discomfort/risk of injury and the change in MPF as a percentage of maximum drop in MPF was poor. The magnitude of the correlation coefficients for the 3 work/rest ratios and 4 lumbar muscle sites ranged from 0.49 to -0.7, with only 1 correlation being significant (40-20 second work/rest ratio at the 5th lumbar level on the right side).

3.8. Changes over time

Changes in the performance of the task over time were evaluated. A significant decrease in peak spinal loading ($p<0.0001$) was found from the first 5-10 minutes to the following 15-20 minutes (figure 8). For the 90th percentile of the APDF, a significant decrease was found from the first 5 to the following 10 minutes ($p<0.0016$). During the last 10 minutes of the task the AEMG increased (figure 9).

Ratings of perceived discomfort increased more steeply over time in the 55-5 second work/rest ratio compared to the other 2 work/rest ratios. Rating of perceived risk of injury also showed a steep increase during the 55-5 second work/rest ratio compared to the other two work/rest ratios in which a significant increase from only the initial to the final one or two ratings was found (figure 10). In general, the ratings of the two scales run parallel, with perceived discomfort being rated higher than perceived risk of injury. Ratings of perceived discomfort and perceived risk of injury correlated significantly for the 25-35 (0.92, $p<0.0004$) and 55-5 (0.82, $p<0.007$) second work/rest ratio. The high correlation for the 25-35 second work/rest ratio is partly due to two participants rating a 3 or more for perceived discomfort and risk of injury, whereas all other values are at or below 2. This distribution resulted in a high correlation which should be interpreted with care. For the 40-20 second work/rest ratio all ratings are spread below 3 resulting in a poor correlation. At the 55-5 second work/rest ratio a range of ratings between 0 and 9 was found which was reflected by the high correlation. This finding indicates that a sufficiently large stimulus is required (eg. 55-5 second work/rest ratio) to cause a change in measures, which could then result in a high correlation.

The pain diagram and pain scale were used to locate and quantify pain developed during the task. The upper back, lower back and posterior side of the thighs were rated most often (4 to 6 participants out of 9) and showed the highest average magnitudes (ranging from 3.3 to 5.5) amongst the participants who rated these body parts. The above findings suggest that participants straightened up over time due to discomfort and/or pain.

4. Discussion

Moving from a 40-20 second work/rest ratio to a 55-5 second work/rest ratio resulted in a substantial increase in physical demands and adverse changes in low back injury risk factors as was determined by high cumulative spinal loading, elevated subjective ratings, continuous muscular activation levels during rest, and the development of muscular fatigue. The physical demands associated with the 25-35 and 40-20 second work/rest ratio were comparable. This finding indicates that, for the task performed in this study, there is a "breakpoint" located between the 40-20 and 55-5 second work/rest ratio. However, when interpreting these results it must be kept in mind that the task was performed for a 25 minute duration, not a full workday. The physical demands of the 25-35 and 40-20 second work/rest ratio were lower compared to the 55-5 second work/rest ratio, but all three work/rest ratios might be demanding when performed over a workday or workweek.

The demand of the task in terms of cumulative loading was high when compared to an epidemiological study performed in a large automobile plant (Norman *et al.*, 1998). Cumulative spinal loading (compression, shear and moment) of all 3 work/rest ratios exceeded that of mean case data from Norman *et al.* (1998) except cumulative compression for the 25-35 second work/rest ratio. The probability of being classified as a case, when using the Norman *et al.* study, ranged from 0.51 to 0.79 for cumulative spinal loading of the 40-20 and 55-5 second work/rest ratios. The authors of this paper acknowledge that cumulative loading can not distinguish between the underlying injury mechanisms which probably differ for prolonged loading (e.g. tissue creep) and repetitive loading (e.g. tissue micro tears). Furthermore, participants experienced the task as being demanding as is shown by the increase in rated discomfort and pain over the 25 minute task duration.

Average ratings of perceived discomfort and perceived risk of injury could distinguish between work/rest ratios in a comparable manner to measures of spectral and amplitude EMG and cumulative spinal loading. This does not necessarily mean that average discomfort ratings can replace instrumented measures of fatigue and known risk factors. The perceived discomfort scale, in contrast to the perceived exertion scale, has not been validated. Perceived exertion has been shown to vary, depending on, for example, time of the day, psychological state, and lack of sleep. It would not be surprising if discomfort ratings could also be affected by various factors. Furthermore, on an individual basis within a condition, our study did not show a good correlation between ratings of discomfort and spectral EMG measures. This is in contrast to Dedering *et al.* (1999) who found a linear relationship between measures of subjective discomfort and spectral EMG measures/endurance time during a modified Sørensen test. The discrepancy between our findings and those of Dedering *et al.* (1999) might be explained by the different scales used: a rating scale versus a category scale, respectively. Our task was more complex, involving static and dynamic components, and our task involved an average muscular activation level of 12.5% MVC which was considerably less than the approximately 45-65% MVC used by Dedering *et al.* (1999). These discrepancies could change how individuals perceive discomfort.

Ratings of discomfort and ratings of risk of injury were highly correlated when exposed to a large enough stimulus, indicating that measurement of one of these variables will provide sufficient information. In other words, participants did not distinguish between the two concepts of discomfort and risk of injury in this type of task. Moreover, the ratings of risk of injury were low for the 25-35 and 40-20 second work/rest ratios (on average 1.9 on a 10 point scale) and less than 5.3 for the 55-5 second work/rest ratio. The use of average values of discomfort in this type of task is recommended since discomfort ratings were more sensitive to differences between conditions and changes over time.

Another risk factor is the static EMG level. It has been proposed that the static level during continuous work should not exceed 2-5% MVC (Jonsson, 1978) for up to 10% of the work time. Static low loading during repetitive assembly work, involving the upper extremities, which was performed for an average of 16 years has been identified as a risk factor for myalgia of the trapezius muscle (Larsson *et al.*, 1988). If these findings are extended to the back extensor musculature, then the 55-5 second work/rest ratio could increase the risk of injury since the muscular activity was at or below 6% MVC for up to 5% of the time only.

There is some controversy regarding the use of spectral measures to measure fatigue at low levels of muscular activation. Physiological variables such as muscular temperature (Petrofsky, 1971; Petrofsky and Lind, 1980) and change in recruitment pattern can move the EMG spectrum in different directions. It has been suggested that spectral measures taken below 50% of MVC could be problematic (Sjøgaard, personal communication). In this study, spectral measures were taken during a fatigue test in which a 10 kg load in addition to upper body weight was lifted. The addition of a 10 kg load to the upper body weight resulted in a small increase in muscular activation level, on average, from 12.5% to 18.3% of MVC. This small increase in activation level is thought to have a minor affect on the power spectrum. Furthermore, our data did show a shift in power spectrum to lower frequencies, indicating that the magnitude of fatigue was large enough to dominate the overall shift of the spectrum to lower frequencies. Muscle length affects spectral measures with greater lengths resulting in higher frequencies, meaning that the muscle length must be kept constant during repeated measurements (Nargol *et al.*, 1999; Potvin *et al.*, 1997). In this study, the length of the back extensors was controlled by trunk posture. However, minor changes in trunk posture and lumbar curvature, not visible to the researcher or intentional on the part of the participant, could have occurred thereby increasing the variability in spectral EMG measures.

Risk factors are thought to increase over the work duration. Due to simple summation, cumulative loading increased over time indicating that moderate sustained trunk flexion for prolonged periods of time elevated the risk of injury above case levels from Norman *et al.* (1998). Rating scales of both, discomfort and risk of injury, increased over time. However, concerns regarding these rating scales remain. Fatigue of the back extensor muscles developed over time and could possibly have further increased with a prolonged task duration. However, muscular fatigue has not yet been shown to be related to injury. It has been hypothesized that injury might follow fatigue due to a reduction in motor control as measured by an increase in coupled spinal rotations (Parnianpour *et al.*, 1988) or by a shift in loading to weaker tissues as a result of loss of lordosis (Potvin, 1992). Another possible pathway is that discomfort and fatigue cause adjustments that might be loading smaller fascicles of the spine which are not normally used for the task and which are perhaps more vulnerable. Furthermore, the motor control system can be compromised when challenged by, for example, the ventilatory system (McGill *et al.*, 1995).

5. Conclusions

It can be concluded that the physical demands and risk factors of low back injury, of a quasi-dynamic task involving prolonged loading without high peak loading, increased substantially between the 40-20 and 55-5 second work/rest ratio and that these risk factors increase over the work duration. Average ratings of perceived discomfort could distinguish between the various work/rest ratios in a similar manner to instrumented measures of fatigue and known risk factors. However, due to the large variability in ratings of discomfort between individuals it must be questioned how applicable this measure is in obtaining estimates of fatigue and risk of injury. Furthermore, ratings of perceived discomfort and perceived risk of injury were comparable and the use of discomfort ratings is recommended due to its increased sensitivity to different conditions and changes over time. Further research is required to evaluate work-rest schedules, using variables related to risk of injury, for a variety of tasks which are performed over longer durations such as a full workday.

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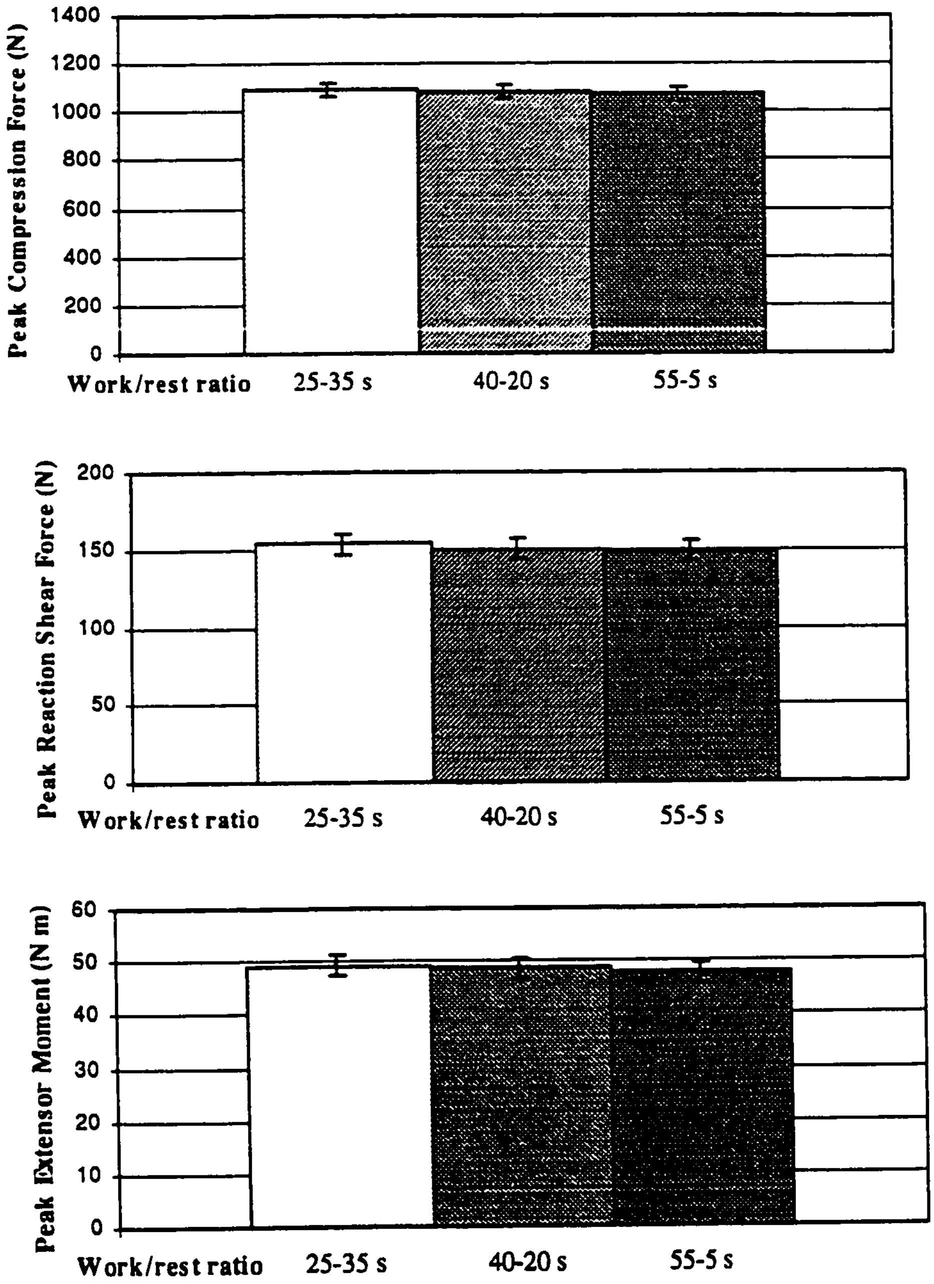

Figure 1. The three work/rest ratios did not differ in peak spinal loading: compression force, reaction shear force and extensor moment (peak value and standard error of the difference). Furthermore, the magnitude of peak spinal loading was small; for example, peak compression force was, on average, 1085N, which is well below the NIOSH action limit of 3433N.

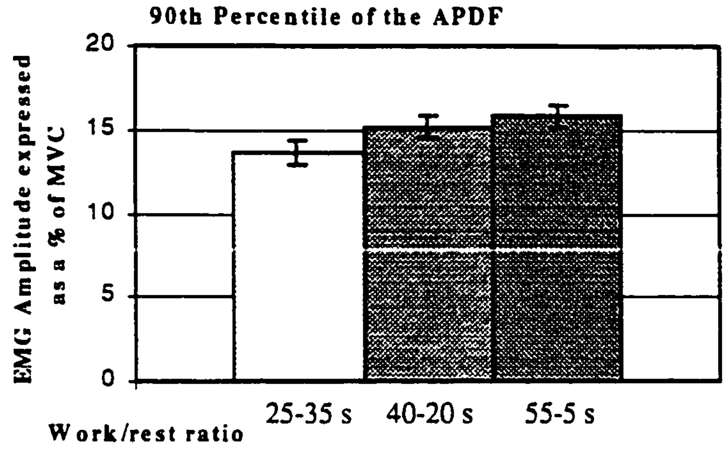

Figure 2. No significant differences were found between the three work/rest ratios at the 90th percentile of the APDF which reflects peak muscular activity. The magnitude of the muscular activation is a small percentage of MVC, on average 14.9%, indicating that the task involves low peak loading only.

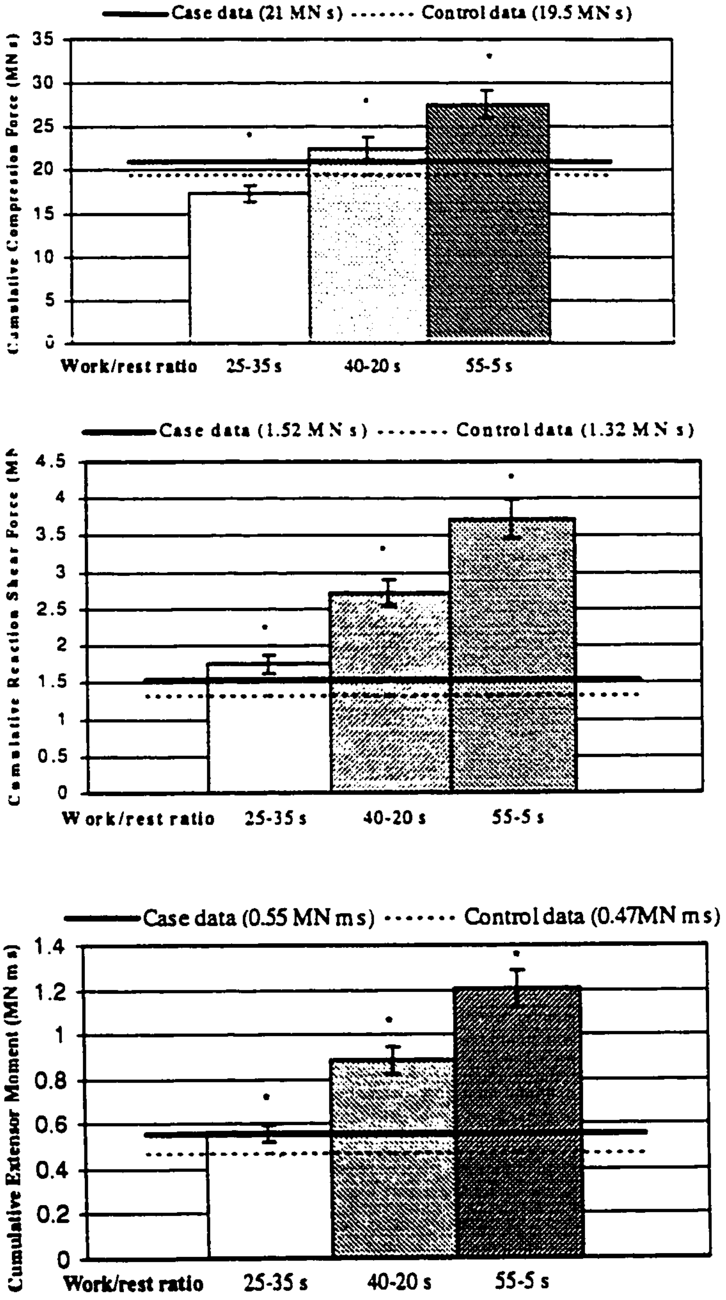

Figure 3. Cumulative spinal loading (compression force, shear force and extensor moment) differed significantly between the three work/rest ratios with the highest work/rest ratio resulting in the largest cumulative loading, as was expected. Cumulative spinal loading is high when compared to data from Norman *et al.* (1998).

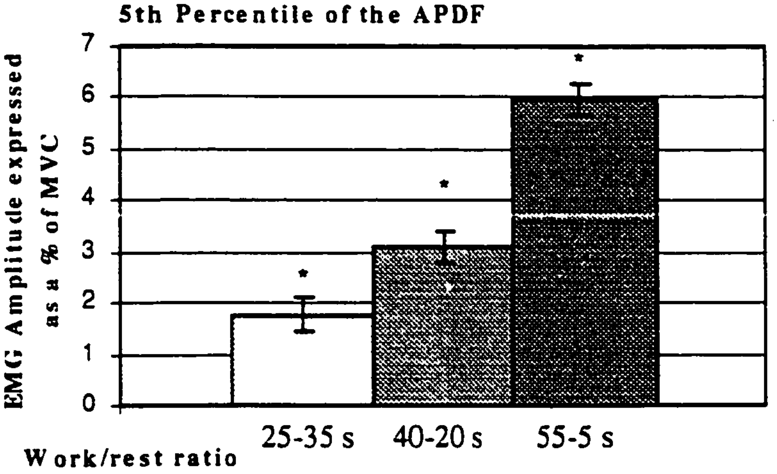

Figure 4. The 5th percentile of the APDF represents the time in upright standing (rest). Significant differences between work/rest ratios were found with the 55-5 second work/rest ratio exceeding 5% MVC.

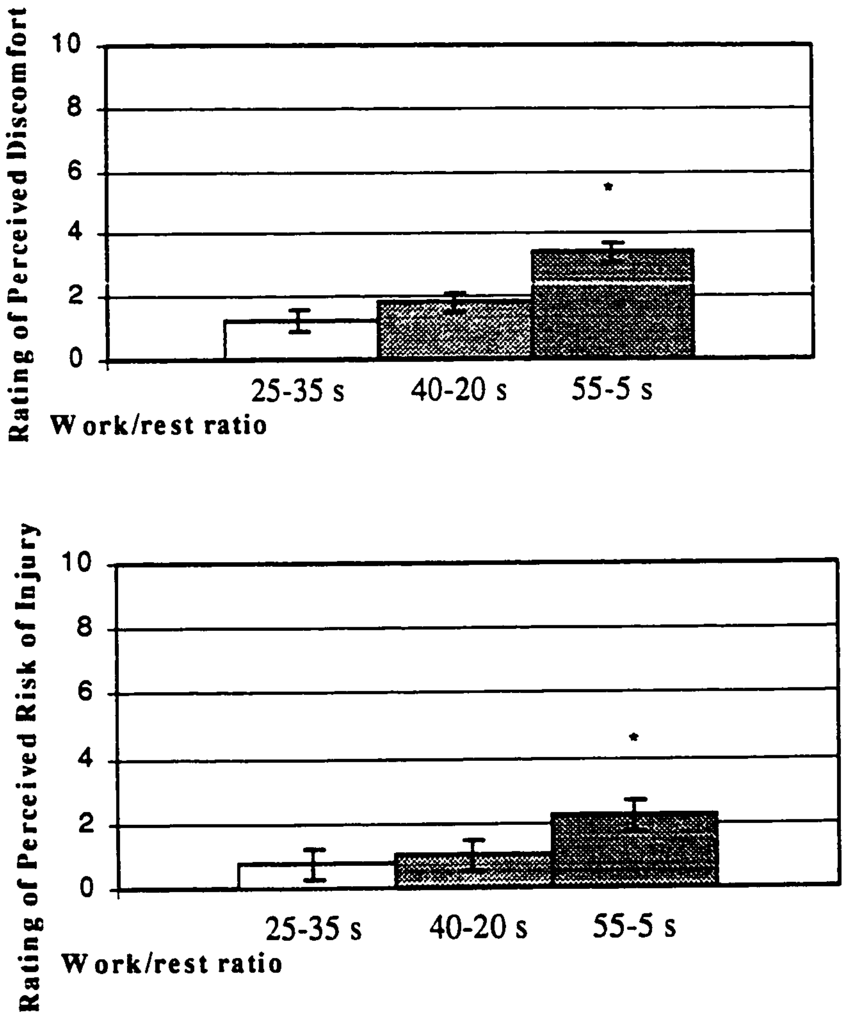

Figure 5. Ratings of perceived discomfort and ratings of perceived risk of injury were significantly higher for the 55-5 second work/rest ratio compared to the other two work/rest ratios.

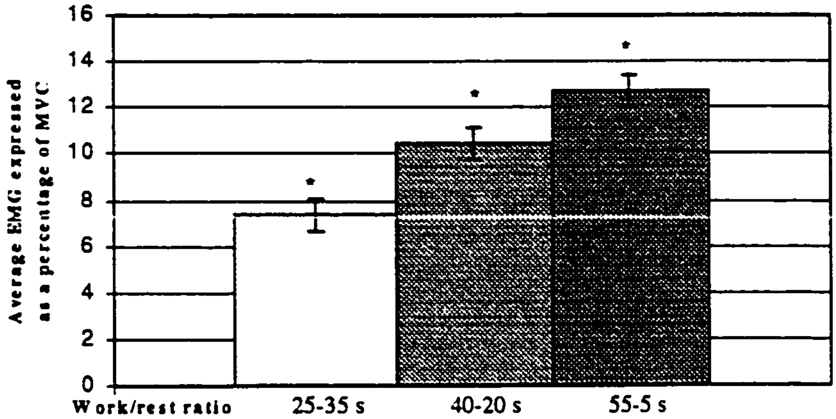

Figure 6. The average EMG obtained during a 1 minute cycle comprising work and rest, showed a significant stepwise increase from the 25-35 to the 55-5 second work/rest ratio. The average magnitude is low since work and rest are combined.

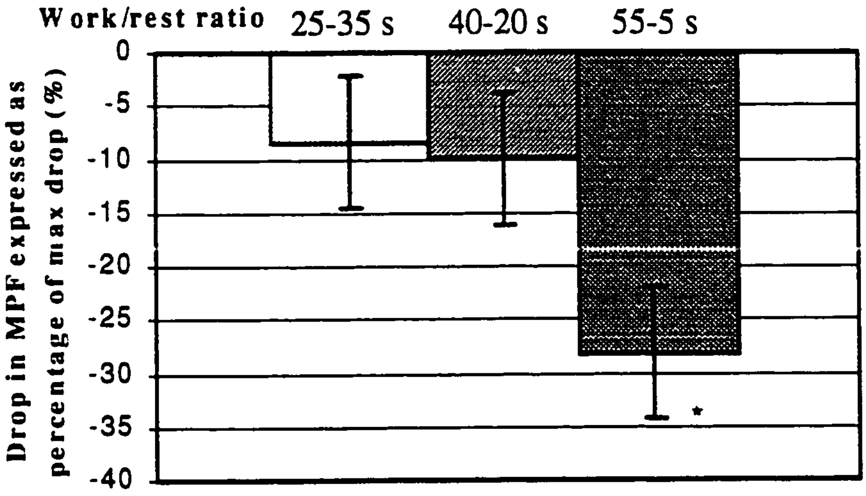

Figure 7. Fatigue was measured as a drop in MPF expressed as a percentage of the maximum change in MPF during exhaustion. Fatigue developed in all three work/rest ratios with the 55-5 second work/rest ratio resulting in a 27% drop in MPF which differed significantly from the other 2 work/rest ratios.

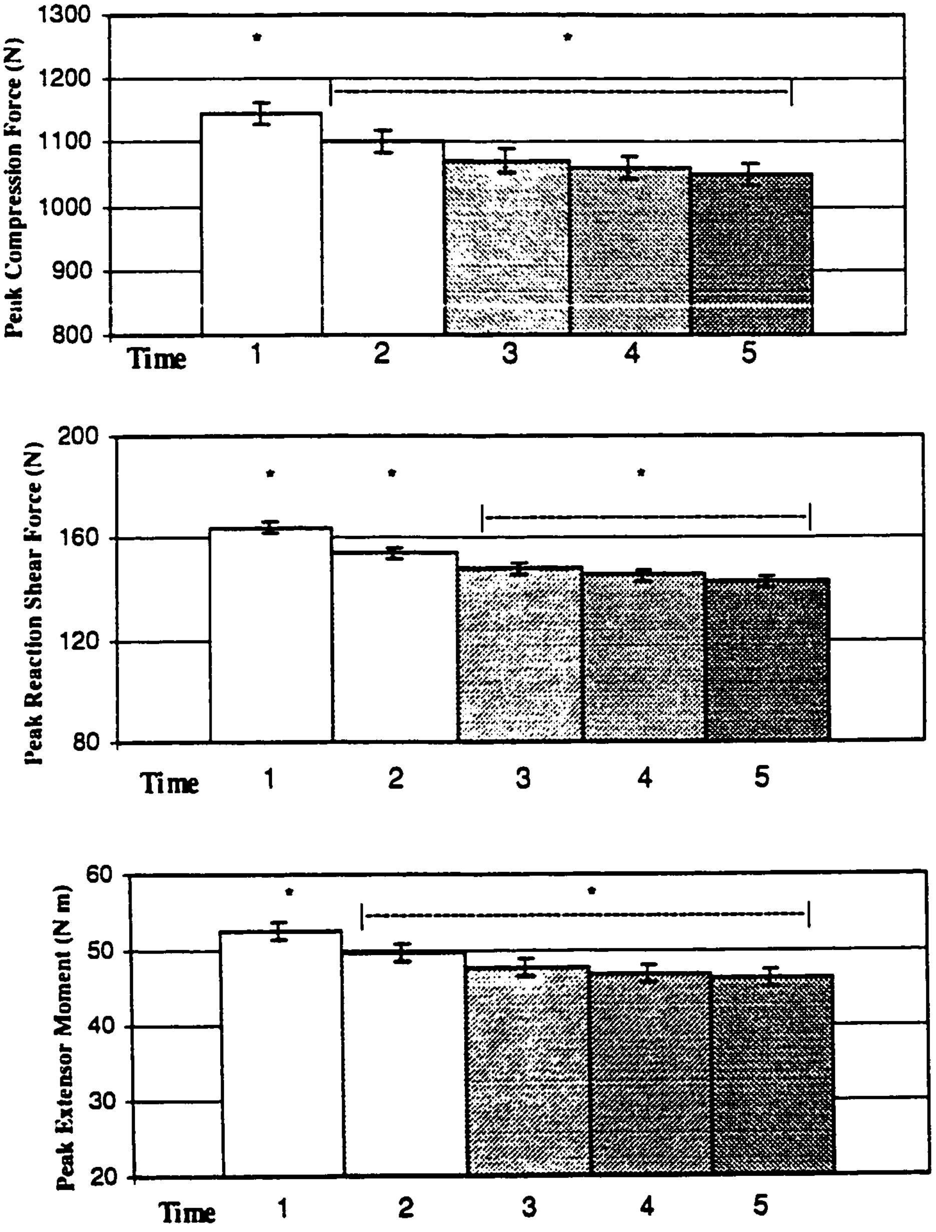

Figure 8. A significant decrease in peak spinal loading occurred from the first 5-10 minutes during the task to the following 15-20 minutes.

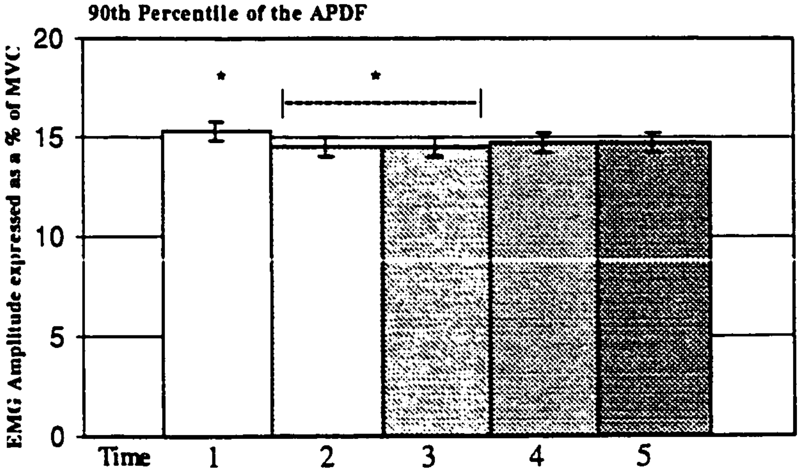

Figure 9. The 90th percentile of the APDF, reflecting peak muscular activity, decreased from the first 5 minutes to the following 10 minutes during the task. During the last 10 minutes of the task the amplitude increased, possibly due to fatigue.

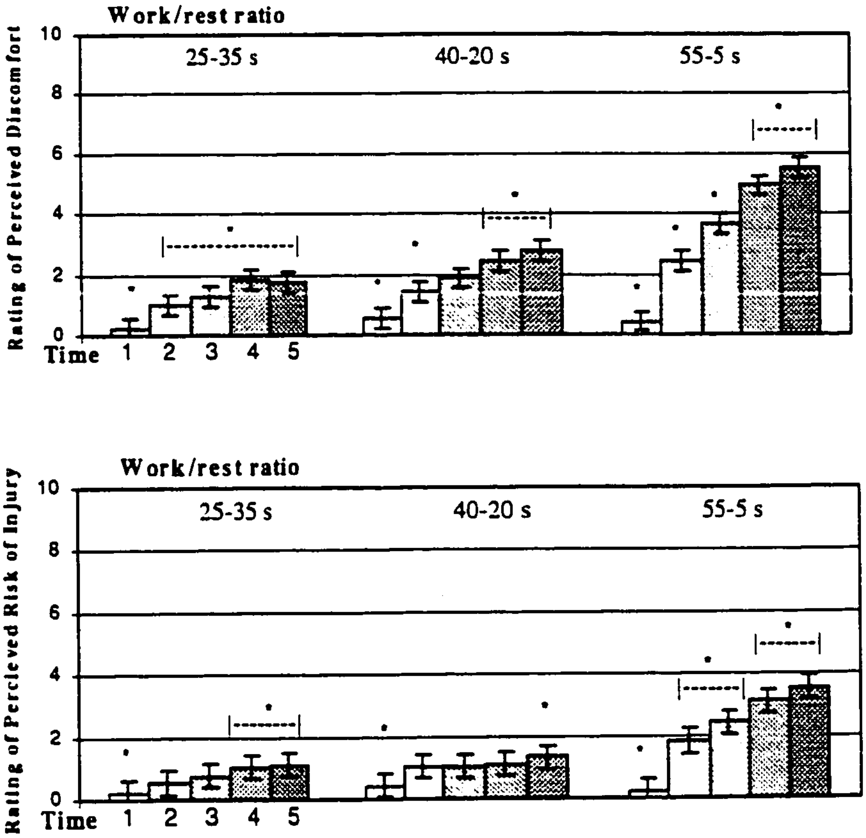

Figure 10. Ratings of perceived discomfort and ratings of perceived risk of injury increased significantly over time. The rate of increase was dependent on the demand of the task (work/rest ratio). In general, ratings of both scales ran parallel, with perceived discomfort being rated higher than perceived risk of injury.

Appendix B

The effect of lumbar curvature on risk factors for the reporting of low back pain in industry during a prolonged, low peak loading task

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Abstract. This paper addresses the effects of changes in lumbar curvature by women, on known risk factors for the reporting of low back pain, during a prolonged, low peak loading task with a work/recovery ratio of 55/5 seconds. Nine healthy women performed an assembly task with their trunk at a 30° inclination angle and the task involved torso weight only. Their lumbar spine was maintained in a lordotic curvature (hollow back) or flexed curvature (rounded back) which is often obtained voluntarily. The lumbar curvature conditions did not differ in peak and cumulative spinal loading and in ratings of perceived discomfort. A flexed curvature required, on average, less back extensor muscle activity compared to lordosis (difference of up to 5.1 % MVC) but both curvatures did require activation of the musculature during assembly thereby minimizing passive tissue recruitment. Discomfort ratings at the end of the 25 minute task duration were high (up to 6.2 out of 10) and cumulative loading over a full workday was high (cumulative compression force exceeded 25 MN s). It can be concluded that the physical demands of a prolonged low peak loading task are comparable between a flexed and lordotic curvature and this task exposes individuals to a high risk of low back pain reporting in both lumbar curvatures.

Keywords: Lumbar spine; Prolonged loading; Women; Risk factors; Back pain; Industrial task simulation

1. Introduction

High peak forces on the lumbar spine have been long known to be a risk factor for low back pain [7, 12] and many workplaces have made attempts to reduce or eliminate tasks which involve high peak loading. The nature of work has, therefore, been altered to low peak loading tasks which are sustained or repeated over prolonged periods of time. For example, these new tasks often require workers to support the weight of the head, arms and trunk in mild forward-inclined trunk postures. However, the type of loading involved in these tasks, cumulative loading, has been shown to be a risk factor for the reporting of low back pain in a large automobile company by Norman *et al.* [19]. They found that cumulative compression, moment and shear were significantly higher in cases, defined as individuals who reported low back pain, compared to controls, people who did not report low back pain. Kumar [11] reported that cumulative compression and reaction shear forces were higher in male nurses who reported back pain compared to nurses who did not report back pain. This was, however, not true for female nurses. A different risk factor for the reporting of low back pain is the perception that one's job is physically demanding on the body as measured by subjective ratings of perceived exertion [8].

Competition in industry has had a major impact on the workplace. The total number of workers has been reduced and work is being done at a faster pace. In addition, jobs have become more "dense", meaning that more tasks have to be performed in the same job, resulting in more time allocated to work and less time allocated to recovery. Some automobile industries are working towards a "55 second minute", which means 55 seconds of work and 5 seconds of recovery in a 60 second job cycle. Previous work from our laboratory [18] has shown that a simulation involving a "55 second minute" job cycle is physically demanding when participants performed an assembly task for 25 minutes using a mildly inclined trunk posture. Participants in that study were instructed to preserve a lordotic curvature, a body manouevre that has been estimated to reduce shear force supported by passive tissues of the lumbar spine [15, 20]. This job simulation was demanding as shown by the high cumulative spinal loading, the elevated ratings of perceived discomfort at the end of the task duration, and the inability to deactivate the back extensor musculature during the entire job cycle involving both work and recovery.

People appear to alleviate muscular fatigue and discomfort in jobs like this by making adjustments in their spinal curvature. From observation in the workplace and previous testing in our laboratory, a flexed curvature, and not a lordotic curvature, is commonly adopted by individuals, voluntarily. This might suggest that individuals perceive a flexed curvature to be more comfortable and that this curvature induces less pain. We questioned what the effects of changes in lumbar curvature by women were on known risk factors for the reporting of low back pain during a prolonged, low peak loading task with a work/recovery ratio of 55/5 seconds.

The loss of the lordosis has been shown to be disadvantageous from a biomechanical point of view during heavy lifting tasks [15, 16, 20]. When the lumbar spine is positioned in an extremely flexed curvature, the extensor moment is generated much less by active tissues (musculature) and much more by passive tissues (ligaments and disc). The inter-spinous ligament has been shown to dominate ligamentous resistance to flexion and recruitment of the inter-spinous ligament increases anterior joint shear force due to the orientation of this ligament [15]. When maintaining a lordotic lumbar curvature, however, the musculature is the main contributor to the extensor moment and passive tissues are not recruited. In this case, the anterior joint shear force will be minimized by the action of the extensor musculature [16, 20]. The force vectors of the Longissimus Thoracis pars lumborum and the Iliocostalis Lumborum pars lumborum are angled posterior and inferior [3]. This vector orientation opposes the anterior joint shear force acting on the spine, thereby minimizing or eliminating the anterior joint shear force [16].

A distinction must be made between *reaction shear force* and *joint shear force*. Reaction shear force is calculated from the weight of the load being handled, torso weight and their accelerations and is not affected by lumbar curvature. Joint shear force calculations include the action of active and passive tissues in addition to the weight of the load being handled, torso weight and their accelerations. Estimation of joint shear force, although more realistic biomechanically, is more complex than reaction shear force, especially in a workplace environment where determination of lumbar curvature is difficult because of clothing.

The contribution of active and passive tissues in generating the required extensor moment directly affects the magnitude of muscular activation. In the most extreme case of a flexor-relaxation manouevre (fully flexed), the extensor musculature is electrically silent [5]. In this extreme posture, the extensor moment is generated by ligament recruitment and passive stretch of the musculature [14]. Only a small range of motion, close to full flexion, allows for interplay in moment generation between ligamentous tissue and the musculature. This is caused by the large flexion angle needed to recruit ligaments (12-13° for L4/L5) and the steep load-deformation curve of the inter-spinous ligament [13]. When the L4/L5 flexion angle is less than 10°, the musculature is the main contributor to the extensor moment. Measurement of muscular activation will reveal if the musculature contributes to the extensor moment or if passive tissues generate the moment. Whether the loss of lordosis is biomechanically disadvantageous during a task that requires a mildly inclined trunk posture involving upper body weight only, instead of heavy load handling, remains unknown.

The purpose of this work was to assess the effects of changes in lumbar curvature by women on known risk factors for the reporting of low back pain during a prolonged, low peak loading task with a work/recovery ratio of 55/5 seconds. It is hypothesized that: 1. peak and cumulative spinal compression force, reaction shear force and extensor moment are similar between both curvatures, thus, risk of low back injury reporting from these factors will not be affected by changes in lumbar curvature, 2. a flexed curvature will be perceived by participants as less demanding, thereby lowering this risk factor for the reporting of low back pain and 3. a flexed lumbar curvature requires less back extensor muscle activation compared to a lordotic curvature.

2. Methods

2.1. Participants

Nine healthy women (height 1.68 m, sd = 0.1; body mass 62.9 kg, sd = 4.9; age 24.7 years, sd = 2.2), who were university students, participated in this study. The exclusion criterion was the experience of low back pain in the year preceding testing. All participants read and signed the informed consent form approved by the Office of Human Research at the university.

2.2. Industrial assembly task

The task consisted of 55 seconds of *assembly work* in a 30° inclined forward trunk posture and 5 seconds of *recovery* in upright standing. The inclined forward posture was constrained by instructing the participants to position their lumbar spine in a lordotic (hollow back) or flexed (rounded back) lumbar curvature and they were told to obtain a curvature as close to the end range as possible. During recovery, the participants were allowed to move their torsos freely and shuffle their feet but they were not allowed to step away from the work station. The task was performed in the sagittal plane and no change in posture was allowed during the assembly of a car / helicopter / boat model using small building blocks which were located on a table in front of the participant. The task involved essentially zero external forces on the hands and in most plants would be considered to be a low loading job since the only load that had to be supported was upper body weight in a mild inclined posture.

The task consisted of 1 minute cycles with a 55/5 second work/recovery ratio. Both lumbar curvatures were performed on the same day allowing for re-use of data recording instrumentation without removal. The task was performed for 25 minutes in each lumbar curvature condition and the second condition would be started after a minimum of 30 minutes recovery in between curvature conditions and the rating of perceived discomfort had to be zero. If discomfort had not yet reached zero, the recovery period was prolonged. This was done to minimize the effect of the first testing session on the second testing session. The order of the lumbar curvature, lordotic or flexed, was randomly assigned to each participant.

2.3. Normalization test

Maximum Voluntary Contractions (MVC), to normalize the EMG signal, were performed at the beginning of data collection. The back extensor musculature was maximally activated by having participants lie on their stomachs and lean over the edge of a bench with the legs restrained. In this position a maximum back extensor effort was performed against manual resistance. Each normalization test was repeated 3 times.

2.4. Data acquisition and reduction

2.4.1. Biomechanical model

A biomechanical model (4DWATBAK, University of Waterloo) was used to estimate peak and cumulative spinal loading. A detailed description of the 2 dimensional version of this model can be found in work by Andrews *et al.* [2] and Norman *et al.* [19]. The model has been "risk validated" meaning that its outputs have been shown to be able to produce an epidemiological estimate of risk of reporting of low back pain [19, 9]. Video was used to guide the positioning of the model's moveable manikin to the posture obtained during the task. The manikin provided joint coordinate data which, in combination with gender, height and weight of the participants, were used to produce estimates of peak spinal compression force, reaction shear force, joint shear force and extensor moment. Cumulative loading was obtained by extrapolating single estimates taken at 5 minute intervals to a total of 25 minutes. Data were multiplied to obtain cumulative loading estimates over a 7 ½ hour workday for literature comparison purposes.

2.4.2. Electromyography

EMG electrodes were placed bilaterally, 5 cm lateral to the 9th thoracic vertebra representing the Longissimus Thoracis and thoracic portion of the Iliocostalis Lumborum, 3 cm lateral to the 3rd lumbar vertebra representing the lumbar portion of the Iliocostalis Lumborum and 1-2 cm lateral to the 5th lumbar vertebra representing the Multifidus. All these muscles support moments about L4/L5. Signals were prefiltered to obtain a bandwidth of 5 to 500 Hz, amplified with a differential amplifier (CMRR 80dB @ 60 Hz) to produce signals between 2 and 8 V and A/D-converted at 1024 Hz.

During the normalization tests, raw EMG was collected for a 5 second duration. Data were full-wave-rectified and low pass filtered (Butterworth) at a cutoff frequency of 2.5 Hz to produce a linear envelope of the signal. The peak of each record was identified and the highest value of the three repeats was selected for EMG normalization purposes.

Raw EMG was collected for a duration of 1 minute (1 cycle) at the beginning of the task and at 5 minute intervals for a total of 5, one minute, data collections. The data were full-wave-rectified, low pass filtered (Butterworth with cutoff of 2.5 Hz) and normalized to MVC. The 1 minute data record was transformed into an Amplitude Probability Distribution Function

(APDF). The 5th and 90th percentile of the APDF were calculated to obtain a measure of low level muscular activity and peak muscular activity, respectively. The low level activity was of interest to measure the ability to deactivate the back extensor musculature during the entire job cycle involving both work and recovery. The average activity during the assembly time was obtained by windowing the middle 45 seconds of the 55 second assembly time. This was done to eliminate the transition from upright standing to the forward-inclined trunk posture. This 45 second data record was transformed into an APDF and the 50th percentile was calculated.

2.4.3. Perceptions of physical demands

Perceptions of physical demands of the tasks were recorded using two 10 point rating scales: ratings of perceived discomfort and ratings of pain. For the discomfort scale the zero point was defined as "no perceived discomfort" and 10 was defined as "extreme perceived discomfort". Ratings were taken during and after testing (total of 5). A pain diagram, front and back view of the entire body, was completed before and after task performance. Participants were asked to circle body areas in which pain was felt. Pain experienced in each body part was quantified using a 10 point scale with the zero point defined as "no pain" and 10 was defined as "extreme pain".

2.5. Statistical analysis

One-way ANOVAs were used to determine whether cumulative spinal loading and discomfort ratings differed significantly between the two lumbar curvatures. One-way ANOVAs with repeated measures on time were used to determine whether peak spinal loading differed significantly between lumbar curvatures over time. One-way ANOVAs with repeated measures on time and muscle site were used to determine whether EMG amplitudes differed between lumbar curvatures. Significance of repeated measures was determined using the Greenhouse-Geiser p-values and the degrees of freedom were adjusted using the Greenhouse-Geiser epsilon to account for non-random allocation violation [23]. Paired comparisons were done using the protected least significant difference (protected LSD) [4]. A level of significance of 0.05 was chosen.

3. Results

3.1. Peak spinal loading

The assembly task performed in this study, for either lumbar curvature condition, involves low risk for the reporting of low back pain in terms of peak spinal loading. Peak compression, reaction shear and extensor moment are less than half of those of the control data (workers who did not report low back pain) and approximately one third of the case data (workers who did report low back pain) reported by Norman *et al.* [19].

A lumbar curvature by time interaction revealed a significant decrease over time in peak spinal loading for the lordotic but not for the flexed curvature. This decrease occurred from the first measure taken at the beginning of the task to the following measures taken over time (compression force $p<0.004$; reaction shear force $p<0.025$; moment $p<0.005$; Fig. 1). Further analysis was done to compare the two lumbar curvatures at the reduced trunk angle (repeated measures from time 2 to 5) and the difference in curvatures was significant or close to significant (compression force $p<0.034$; reaction shear force $p<0.071$; extensor moment $p<0.038$).

This decrease in peak loading, when performing a task with a lordotic curvature, can be explained by a reduction in trunk inclination angle, on average 7.3°, that took place over time due to straightening up by the participants. Although the curvature by time interaction was not significant ($p<0.089$), the difference between curvatures from time 2 to 5, thereby excluding time 1, was close to significance ($p<0.063$). Further analysis revealed that the flexed curvature data showed a larger variability than the lordotic curvature data. This variability in the data did not allow for detection of a significant decrease in trunk angle during lordosis. Therefore, both curvatures were analyzed separately and a significant decrease in trunk inclination angle was found for lordosis from the first to the following measures taken over time ($p<0.0004$; Fig. 2). The 30° trunk inclination angle was maintained during the flexed lumbar curvature.

Peak joint shear forces are shown for the lordotic curvature which requires the back extensor musculature to generate the entire extensor moment (Fig. 3). The peak joint shear forces, which include muscular activation, are approximately half of the peak reaction shear forces. A significant decrease in joint shear force occurred from the first measure to the following measures taken over time ($p<0.011$) which can be explained by the change in trunk angle during lordosis as discussed above.

3.2. Perception of physical demands

None of the participants rated any discomfort at the beginning of the task. At the end of the task, the ratings of perceived discomfort were, on average, lower for the flexed curvature compared to lordotic curvature, a rating of 4.7 versus 6.2, but this difference was not statistically significant indicating that both lumbar curvatures were equally uncomfortable ($p<0.31$; Fig. 4).

The participants did not report any pain at the beginning of the task. After completion of the task some participants reported pain in the shoulders, upper back, lower back, back of the thighs, back of the knees and/or feet (Table 1). The majority of the complaints were located in the upper and lower back with 3 to 6 participants, out of 9, identifying these pain locations. The average magnitude of pain ranged from 0 to 3 depending on the location. No significant differences in pain magnitude were found between the flexed and lordotic curvature for any of the pain locations ($p<0.88$). The pain magnitude, averaged over participants and curvatures, was significantly higher for the lower back compared to the upper back and both were significantly higher compared to all other pain locations ($p<0.007$).

3.3. Muscular activation levels

The lordotic spinal curvature condition was expected to require higher lumbar and thoracic muscular activation levels than the flexed curvature condition. Passive tissues can support the moment of force when muscles are disabled in extreme loss of lordotic curvature. The average muscular activation during the assembly time (50th percentile of the APDF) showed that the lordotic curvature did require significantly higher levels of muscular activation compared to a flexed curvature for left T9 ($p<0.03$), right L3 ($p<0.001$), left L3 ($p<0.01$), right L5 ($p<0.006$), and left L5 ($p<0.02$) (Fig. 5). At right T9 the difference in 50th percentile of the APDF between the two curvatures was close to significance ($p<0.059$). This muscle site was not significant due to increased variability possibly introduced by the dominant use of the right hand/arm during assembly. The difference in EMG amplitude between the two curvatures ranged from 2.6 to 5.1 % of MVC for different muscle sites, and the amplitude of the flexed curvature was higher than initially expected, ranging from 5.9 to 11.1 % of MVC for different muscle sites.

Low average muscular activation levels for some of the participants were found during the flexed curvature. However, none of the participants was able to reduce the amplitude of the muscular activation level to noise level during assembly time for any of the muscle sites (Fig. 6). These findings indicate that the flexed curvature obtained in this study did not disable the musculature and therefore the musculature remained a contributor to the extensor moment in both lumbar curvature conditions. A larger trunk inclination angle, than the 30° in this study, appears to be required before passive tissues will be recruited.

The 5th percentile of the APDF, which reflects the ability to deactivate the back extensor musculature during the entire job cycle including work and recovery, is similar between the two curvatures at either the 3rd lumbar and 5th lumbar level. Significantly lower activity levels were found for the flexed curvature compared to the lordotic curvature for right T9 ($p<0.037$) and left T9 ($p<0.022$). The absolute magnitude of muscular activation ranged from 2.8 % to 5.4 % of MVC for all muscles and curvatures and noise level was never reached (Fig. 7).

The peak muscular activity (90th percentile of the APDF) was significantly lower in the flexed curvature compared to the lordotic curvature during a full work/recovery cycle for the majority of sites (Left T9 $p<0.046$; Right L3 $p<0.001$; Left L3 $p<0.018$; Right L5 $p<0.004$; Left L5 $p<0.016$) except right T9 which was close to significance ($p<0.07$). Overall, the peak muscular activity was below 19 % of MVC (Fig. 8).

3.4. Cumulative loading

No significant differences between the two lumbar curvatures were found in cumulative spinal loading as was expected since the same work/recovery ratio was used for both conditions (Fig. 9). When comparing the cumulative spinal loading found in this study to estimates reported by Norman *et al.* [19] it can be seen that the task, in both lumbar curvature conditions, is demanding even though the trunk inclination angle was mild (30°) and there was essentially no load in the hands.

4. Discussion

The physical demands of a lordotic and flexed lumbar curvature, during a prolonged low peak loading task, were determined. The peak and cumulative compression force, reaction shear force, joint shear force and extensor moment to which the participants were exposed, were the same between both curvatures. Peak spinal loading was small but cumulative loading appeared to be high. The hypotheses, that individuals prefer a flexed curvature above a lordotic curvature must be rejected. Participants found both lumbar curvatures quite uncomfortable and painful after just 25 minutes of task performance. The hypothesis that a flexed curvature is, on average, less demanding in terms of muscular activation holds. Overall, the average and peak muscular activation was lower in a flexed compared to lordotic curvature. Both curvatures did allow for similar low level muscular activation at both lumbar levels during a full cycle including work and recovery, but not at thoracic level.

In this study, a limited work duration was used and the task was performed in a posture involving two selected lumbar spinal curvatures. Even though the task was performed for 25 minutes only, instead of a 7½ hour work shift, this is a considerable amount of data collection time that allows for estimation of peak loading which is commonly done and also for cumulative loading estimates. Furthermore, data collection beyond 25 minutes was not necessary since even from our 25 minute data collection it could be concluded that the task was physically demanding. Participants were instructed to position their spine in one of two extreme lumbar curvatures at the outer edge of the envelope, flexed or lordotic, and this curvature had to be maintained during the entire task performance. These restrictions to the work posture, especially lumbar spinal curvature, are not common in the workplace where individuals can select their preferred work posture and possibly rotate between postures. However, individuals often adopt a flexed curvature voluntarily indicating that this curvature is a preferred work posture for some people. Furthermore, restriction of the curvature reduced variability between participants allowing for group analysis.

Peak spinal compression force was found to be comparable between the two lumbar curvatures. This is in agreement with Potvin *et al.* [20] who reported no change in compression force when changing the lumbar spinal curvature from flexed to lordotic in a inclined posture while holding a 22 kg load. The magnitude of peak spinal loading during the assembly task was small. The probability of being classified as a case, when using data from the Norman *et al.* [19] study, is 0.26 for peak compression, 0.24 for peak reaction shear and 0.27 for the peak moment.

From the literature it is known that the opposing action of the activated back extensor musculature reduces or eliminates the anterior joint shear force [16, 20]. Since the back extensor musculature in this study was activated in both lumbar curvatures, the anterior joint shear force in both curvatures is probably similar. Either lumbar curvature can be used without compromising the risk of low back injury due to anterior joint shear force during this prolonged, low peak loading task. This is, however, not true for heavy lifting tasks in which maintenance of a lordotic curvature is recommended. Potvin *et al.* [20] showed a large increase in anterior joint shear force when altering a lordotic curvature to a flexed curvature. The task evaluated by Potvin *et al.* [20] involved a forward-inclined trunk posture while holding a heavy load, 22 kg, above the floor. This inclined trunk posture, at the end range of motion, and the addition of the external load did disable the back extensor musculature and recruited passive tissues resulting in elevated anterior joint shear force.

The magnitude of the peak anterior joint shear force in the current study was small, on average 75 N (sd 13). This is considerably less than the 700 N (range 39-1272 N) reported by McGill and Norman (1986), during squat lifts involving weights ranging from 27.3 to 90.9 kg, and the 200 N of anterior joint shear force reported by Potvin *et al.* [20], again involving squat lifting but using lower weights, ranging from 5.8 to 32.4 kg. Furthermore, tissue tolerance values for reaction shear force, by far, exceed the magnitudes of reaction shear forces found in our study [10, 24]. The peak anterior reaction and joint shear forces acting on the spine during a 30° inclined trunk posture, when the back extensor musculature is active, did not result in a high risk of injury. Prolonged low peak shear loading could, however, result in irritation of already inflamed spinal tissues that support shear forces [19].

A change in work posture over the 25 minute task duration was found for the lordotic curvature. Participants straightened up during the first 5 minutes of the work duration which resulted in the decrease in peak spinal loading estimates over time. This reduction in trunk angle was not intentionally done by the participants or visibly noticeable by the experimenter. No change in trunk angle occurred during the flexed curvature. Since ratings of perceived discomfort nor pain ratings differed significantly between the two curvatures, these can not explain the difference in behavior over time. Participants did, however, express that they felt awkward in the lordotic curvature and they might have straightened up to move into a less awkward posture.

Discomfort developed over the task duration in both lumbar curvature conditions. The development of discomfort during lordosis was expected as a result of the activation of the back extensor musculature to generate the extensor moment. During the flexed curvature the stretch of passive tissues might have caused the development of discomfort. Both curvatures resulted in pain which developed mainly in the upper and lower regions of the back.

All participants activated their back extensor musculature even when the task was performed using a flexed curvature in which they were instructed to round their lumbar spine as far as possible. This indicates that the musculature is a contributor to the extensor moment in both lumbar curvatures when the trunk is positioned at a 30° trunk inclination angle. The first ligaments to fail in flexion are the supra-spinous and inter-spinous ligaments and these do not come into play until at least half-way through the range of motion in spinal flexion [1]. A mathematical model of the lumbar motion segment at L4/L5 showed that the joint is quite unrestricted between 0 to 10° of spinal flexion and the resistance provided by ligaments increased drastically around 12 to 13° of spinal flexion [13]. This rapid increase is caused by the steep load-deformation curve of the inter-spinous ligament which means that ligaments are either fully recruited or not. Potvin *et al.* [20] found a lumbar spinal flexion angle of 39.9° during squat lifts involving loads with weights varying from 5.8 to 32.4 kg. These squat lifts were found to have only minimal moment contributions from passive tissues. In our study, the inclination angle of the entire trunk, from L4/L5 to the shoulder, was only 30°. Therefore, the flexion angle of the isolated lumbar spine during the assembly task must have been less than 30° which was most likely not sufficient to recruit the ligaments.

Activation of the musculature during the task performance might have been maintained in both curvatures due to a protective action of the back extensor musculature by restriction of the flexion angle in full flexion and avoiding ligament recruitment [1]. A similar avoidance strategy for passive tissue loading by the motor control system has been described by Potvin *et al.* [21]. They found that an increase in the weight lifted resulted in higher muscular activation levels and that this increase in weight did not affect the contribution of passive tissues to the extensor moment. This strategy allowed for a constant and small amount of passive tissue recruitment and a safe level of joint shear force.

Although the musculature was activated in both lumbar curvatures, a significant or close to significant, lower average muscular activation was found for the flexed compared to the lordotic curvature. This difference in average muscular activity could not be attributed to the a difference in the 30° trunk inclination angle since the task was performed at the same trunk inclination angle or even at a reduced inclination angle in the lordotic curvature, not in the flexed curvature. The difference in average activity might be explained by the moment-generating contribution of the passive elastic component of the musculature when under tension due to increased muscle length in the flexed curvature. McGill and Kippers [14] showed that the musculature was able to generate a substantial amount of force elastically through stretching during a flexor-relaxation maneuver.

An additional explanation could be a difference in trunk geometry between the two curvatures. The location of the centre of mass of the trunk might have moved posterior in a flexed curvature due to the rounding of the spine. A posterior shift of the centre of mass reduces the extensor moment and the muscular activation required to generate this extensor moment. However, the latter explanation is thought to have a small effect on the extensor moment only. The biomechanical model used in this study did not account for these small changes in trunk geometry.

The musculature was unable to reduce its activity to noise level during a full work cycle. Low levels of muscular activation, below 15-20% of MVC as found in our study, might induce muscle damage if sustained or repeated over prolonged periods of time [22]. A possible pathway for musculoskeletal illness is a reduction in muscle oxygenation. Jensen *et al.* [6] showed that the oxygen supply of the back extensor musculature was maintained at a contraction level of 5% of MVC, but the supply was reduced at and above 20 % of MVC. Whether the supply of oxygen is sufficient at contraction levels between 5 and 20 % of MVC was not evaluated in that study. McGill *et al.* [17] showed a reduction in muscle oxygenation at activity levels as low as 2 % of MVC of the back extensor musculature.

The 5th percentile of the APDF reflects low level muscular activity during the full work cycle, including work and recovery. At thoracic level, the flexed curvature during assembly allowed for lower muscular activation levels than those that took place during recovery when the musculature had to be activated for postural stability. Individuals were allowed to move their torsos during recovery to relieve discomfort and this requires trunk muscular activation. The flexed curvature therefore resulted in less activation at the 5th percentile of the APDF at thoracic level compared to lordosis, thereby possibly prolonging the onset of muscular fatigue.

The demands of this task, in terms of cumulative spinal loading are high for both lumbar curvatures. The probability of being classified as a case is as high as 0.62 for cumulative compression, 0.83 for cumulative shear and 0.82 for the cumulative extensor moment. These findings show that even though the peak spinal loading is low, the cumulative spinal loading is high and that the assembly task is physically demanding.

5. Conclusions

The physical demands of a prolonged low peak loading task, when performed using a flexed or lordotic lumbar curvature, are comparable in peak and cumulative spinal loading and in the individuals' perception of discomfort. Loss of lordosis in a posture involving a mild trunk inclination angle and torso weight only did not affect the peak joint shear force and did, therefore, not increase the risk of injury as occurs during heavy, manual, material-handling tasks. Although peak spinal loading was low, cumulative loading and discomfort ratings were high, thereby, exposing the worker to a high risk of low back pain reporting. The flexed lumbar curvature condition did, in general, require less average and peak muscular activation compared to the lordotic condition, possibly due to recruitment of the passive elastic component of the musculature and an alteration in trunk geometry. Even though the muscular activation was below 19% of MVC, a risk of muscular damage is still present due to the prolonged static nature of the task. It can be concluded that a prolonged low peak loading task, with a mild trunk inclination angle, is physically demanding when performed using either the flexed or lordotic lumbar curvature.

Acknowledgments

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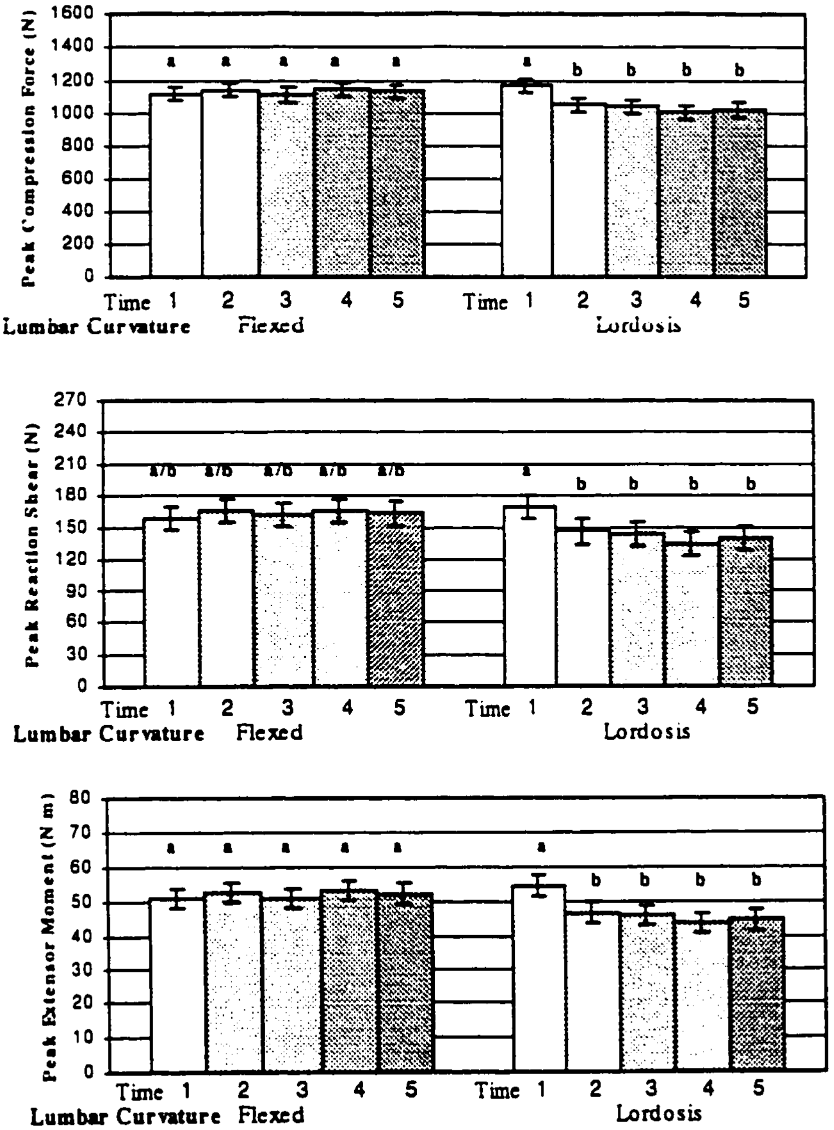

Fig. 1. Peak spinal loading estimates, compression force, reaction shear force and extensor moment, are shown for the flexed and lordotic curvature for five measurements over a 25 minute work duration. Standard errors are shown and bars with different letters are significantly different. A significant decrease in all peak biomechanical model estimates occurred over time after 5 minutes in the task performance during the lordotic curvature but not during the flexed curvature.

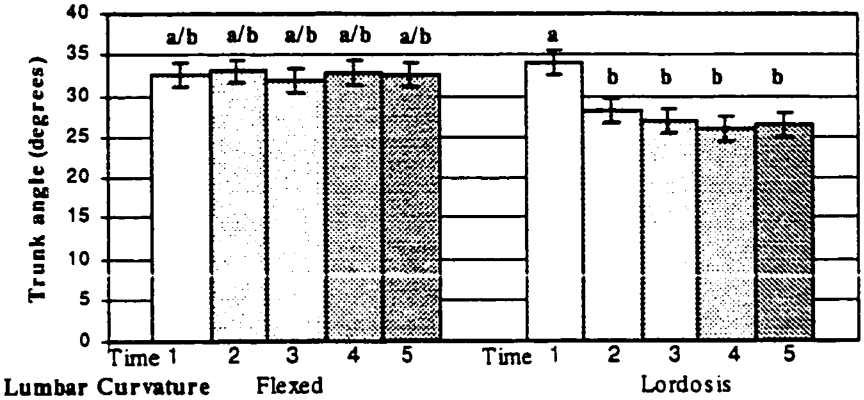

Fig. 2. The trunk inclination angle was set to 30° at the beginning of the task. This trunk angle was maintained during the flexed curvature, but during lordosis a significant decrease in trunk angle occurred after 5 minutes in the task performance ($p<0.0004$). This reduction in trunk angle can explain the decrease in peak spinal loading estimates that occurred over time.

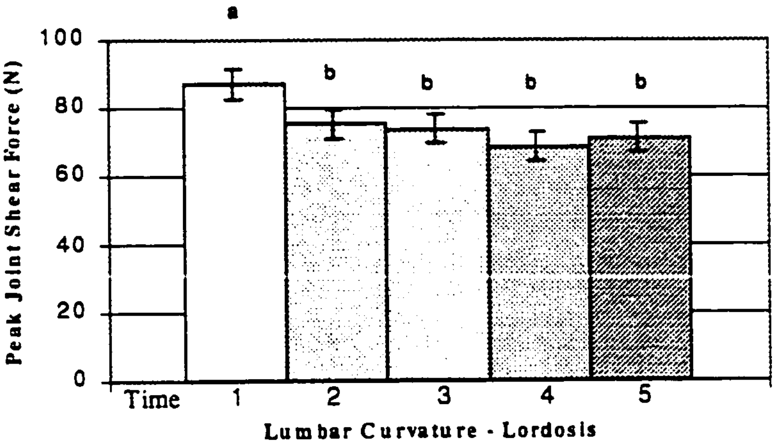

Fig. 3. Peak joint shear forces are shown for the task with a lordotic curvature during which the back extensor musculature generated the entire extensor moment. The magnitude of the joint shear forces are small, approximately half of the reaction shear forces, and a significant decrease occurred during the first 5 minutes of the work duration ($p<0.011$).

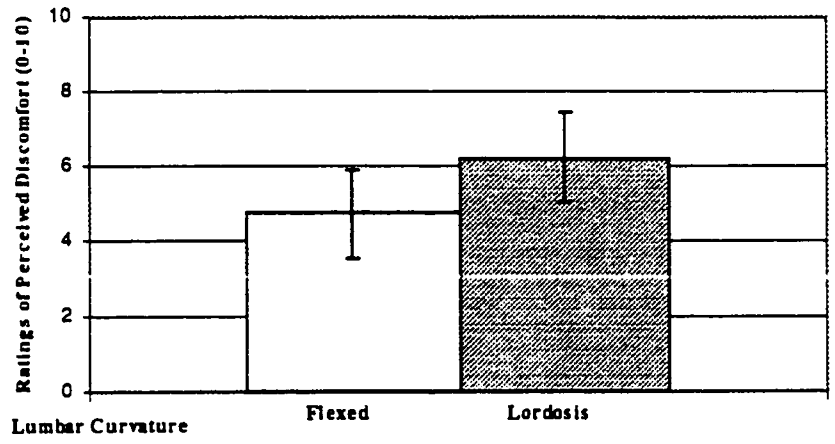

Fig. 4. Perceived discomfort was rated on a scale from 0 to 10. The ratings of perceived discomfort at the end of the task are shown (time 5). The ratings were slightly lower for the flexed curvature (final average rating of 4.7) compared to the lordotic curvature (final average rating of 6.2), but this difference was not significant (p<0.31).

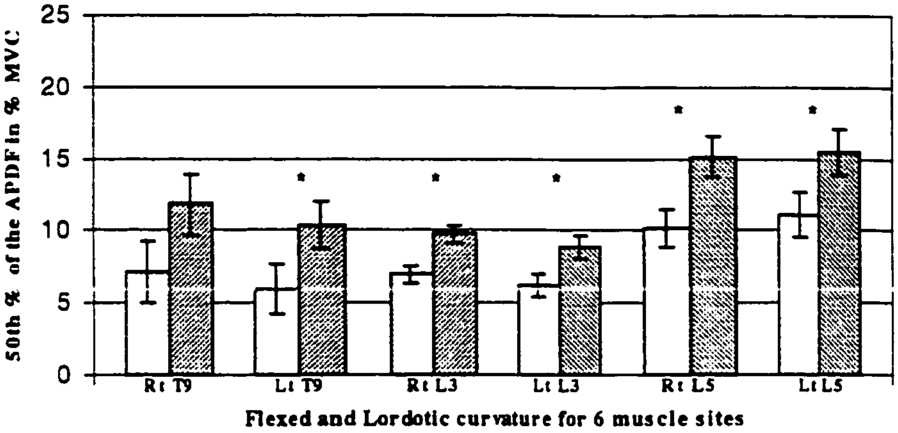

Fig. 5. The 50th percentile of the APDF, in percent of maximum voluntary contraction, is shown for muscle sites at the right and left side of the body at the 9th thoracic vertebra, the 3rd lumbar vertebra and the 5th lumbar vertebra. The flexed posture is shown in lightly shaded bars and the lordotic curvature is shown in darkly shaded bars. Significant differences between lumbar curvature conditions are indicated by asterisks. In general, the muscular activation level during lordosis was significantly higher compared to the flexed curvature, between 2.6 to 5.1 % of MVC, depending on muscle site.

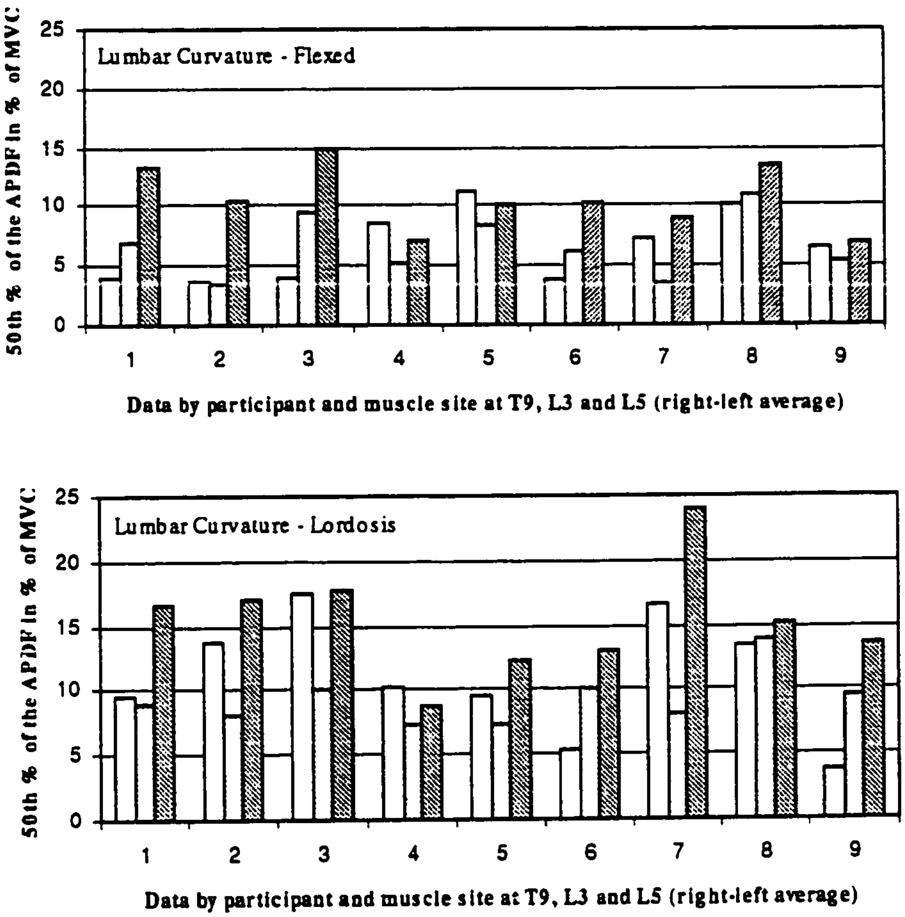

Fig. 6. The 50th percentile of the APDF for the thoracic and two lumbar levels, averaged over the right and left side of the body and averaged over time, is shown for all 9 participants. It is apparent that none of the participants was able to reduce the activity of any of the muscle sites to zero in both lumbar curvatures during the assembly time.

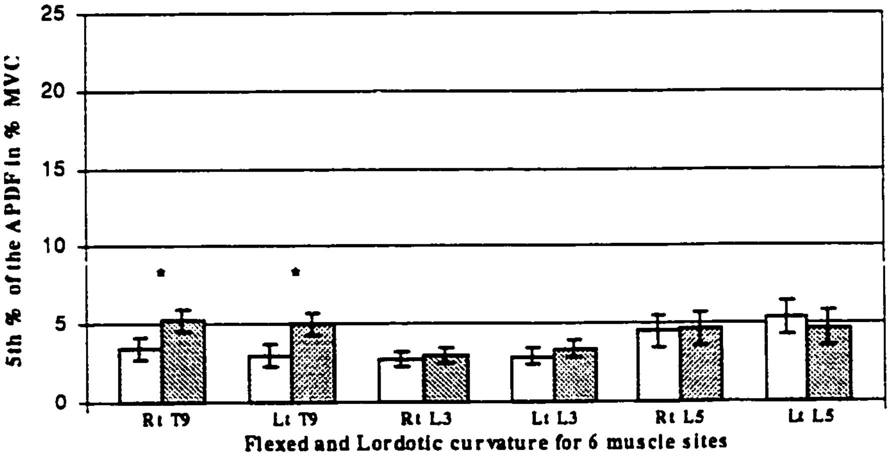

Fig. 7. The 5th percentile of the APDF is shown for the flexed (lightly shaded bars) and lordotic (darkly shaded bars) lumbar curvature for all 6 back extensor muscle sites. The two curvatures did differ significantly at the 9th thoracic level for the left and right side of the body. No significant difference between the two lumbar curvatures was found at either lumbar level, 3rd or 5th lumbar vertebrae. This task did not allow for a reduction in muscular activation to zero during assembly or recovery.

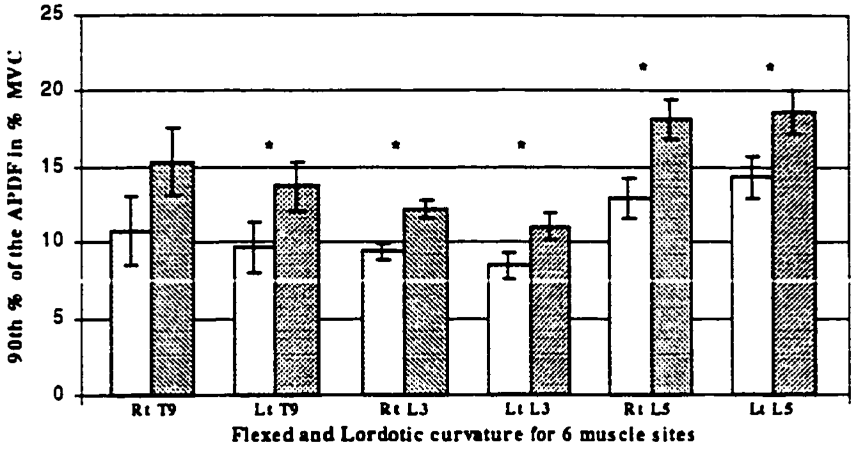

Fig. 8. The 90th percentile of the APDF, representing peak muscular activity, is shown for the flexed (lightly shaded bars) and lordotic (darkly shaded bars) lumbar curvature for all 6 back extensor muscle sites. Overall, the lordotic curvature required higher activation levels compared to the flexed curvature. The peak estimates for all muscle sites recorded were below 19 % of MVC.

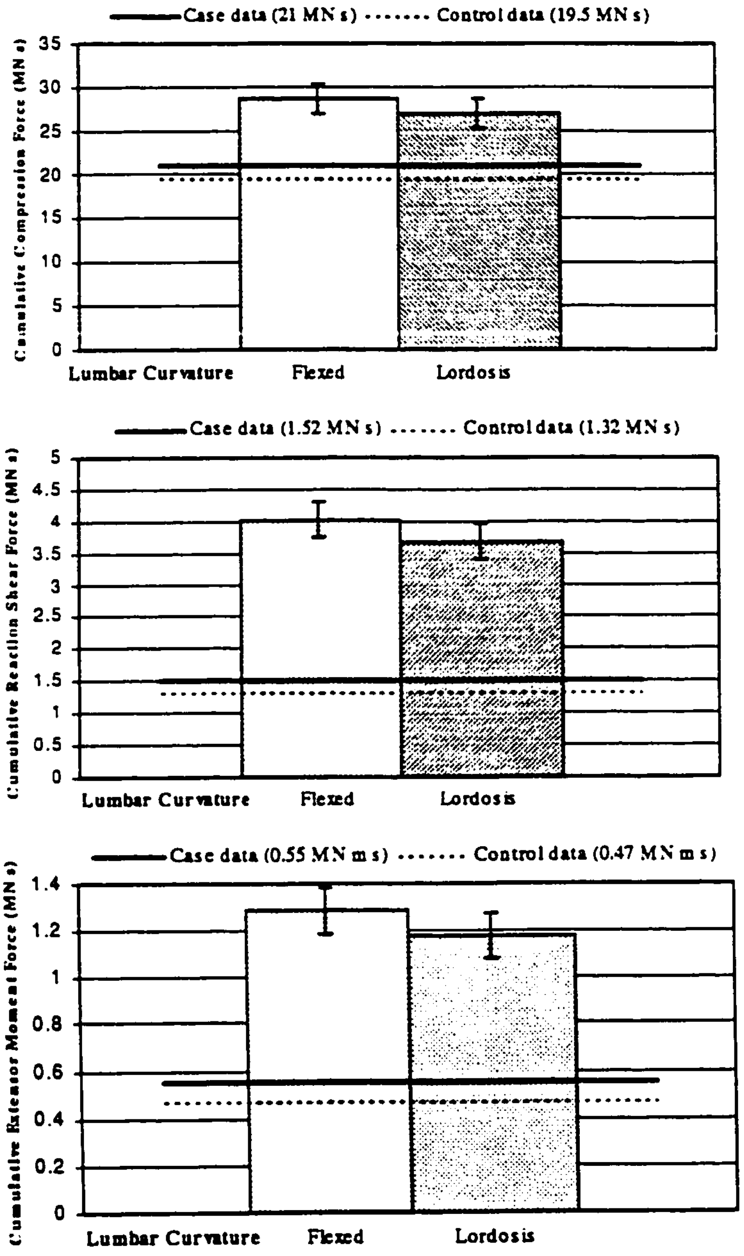

Fig. 9. Cumulative spinal loading, spinal compression force, reaction shear force and extensor moment, are shown for the flexed (lightly shaded bars) and lordotic (darkly shaded bars) curvature. The two lumbar curvatures did not differ in cumulative spinal loading. However, cumulative spinal loading was high when compared to data by Norman *et al.* [19].

Table 1. The locations where pain developed over the task duration are shown. None of the participants reported any pain (zero) at the beginning of each testing session. The number of occurrences are the number of participants (out of 9) that reported pain at a specific location; the average pain magnitude was taken over all participants. The pain magnitude located in the back, averaged over participants and lumbar curvatures, exceeded that of the other pain locations ($p<0.007$). No significant differences between the flexed and lordotic curvature were found in pain magnitude at any of the pain sites ($p<0.88$).

	Lumbar Curvature: **Flexed**		Lumbar Curvature: **Lordosis**	
Pain Site	**# of Occurrences**	**Average**	**# of Occurrences**	**Average**
Shoulders	1	0.8	1	0.7
Upper Back	3	1.0	4	2.5
Lower Back	6	3.0	5	2.6
Back of the Thighs	1	0.9	0	0.0
Back of the Knees	0	0.0	1	0.4
Feet	2	1.0	1	0.9

Appendix C

Effects on low back pain risk factors of a simulated industrial "light" assembly task performed by women

M.I.V. Mientjes and R.W. Norman

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Keywords: Lumbar spine; Prolonged loading; Women; Risk factors; Back pain; Lumbar curvature; Light assembly

The purpose of this study was 1) to quantify the physical demands on the low back of a simulated industrial "light" assembly task in terms of spinal loading, perceived discomfort, back muscle activation and local muscular fatigue, 2) to determine whether individuals who perceived higher discomfort were exposed to higher measured physical demands, and 3) to determine whether individuals who perceived higher discomfort adopted measurable strategies to reduce their discomfort. Ten experienced assembly workers and five inexperienced participants performed a "light" assembly task. They bent forward with the trunk at a 30° flexion angle, for one hour, in one minute cycles of 55 seconds of work followed by 5 seconds of recovery in upright standing. Workers were allowed to select and vary their lumbar curvature but were required to maintain an approximately constant production rate. Results showed that participants were not able to perform an hour of this "light" assembly task without adverse effects such as elevated perceived discomfort (on average 2.2 out of 10), constant muscular activation levels (average of 2.9% MVC at L3 and 4.5% MVC at L5) and development of muscular fatigue (decrease in MPF of 4.7 Hz at L3 and 5.9 Hz at L5). This task was not light from the perspective of cumulative spinal loading (average cumulative compression force of 28.7 MN s), a known risk factor for low back pain reporting. Workers who selected their preferred lumbar curvature perceived lower discomfort (reduction of 3.3 out of 10) and reduced muscular activation levels (by 2.9 - 5 % MVC) compared to those who maintained a lordotic lumbar curvature. Individuals with relatively high discomfort (ratings exceeding 1.5) were

exposed to the same demands as individuals with low discomfort ratings (below 1.5). Furthermore, individuals who perceived high discomfort did not alter their trunk posture, lumbar curvature or other variables measured in this study to reduce their discomfort. Experienced workers perceived significantly less discomfort compared to inexperienced participants, once again indicating that, to allow for application of the findings to the workplace, recruitment of participants from the workforce of interest is desired. From this study it is, therefore, not clear on which variables individuals base their perceptions of discomfort, aside from pain located in the low back.

1. Introduction

Competition in industry has resulted in changes in the workplace. The number of workers has been reduced but the production rate has remained constant or has increased. This has been achieved by adding tasks to existing jobs. Some industries are working towards a 55/5 second work/recovery ratio which has been referred to as a 55 second minute of value-added work. The effects of this change in the nature of the work environment on risk factors which have been proven or proposed to be related to low back pain reporting must be evaluated.

Many variables have been proposed to be risk factors for low back pain but only a few have been proven and some will be addressed here. Peak spinal loading, as occurs during heavy lifting, is a risk factor for low back pain (Kelsey *et al.*, 1984, Marras *et al.*, 1993, Norman *et al.*, 1998) and awareness of this risk factor has led to a reduction of peak loading in the workplace. Cumulative spinal loading, which is a summation of sustained or repeated loading during a workday, has been shown to be a risk factor for low back pain reporting (Norman *et al.*, 1998; Kumar, 1990). Furthermore, from spinal tissue examination, it was concluded that prolonged low level loading is related to low back disorders (Videman *et al.*, 1990). Adverse effects of cumulative spinal loading, however, has not been given as much consideration in the workplace as peak loading, particularly in jobs considered to be light assembly.

At the muscle level, even low levels of static muscular load have been linked to trapezius myalgia (Westgaard, 1988; Veiersted *et al.*, 1990). A possible pathway is the continuous activation of low threshold, "Cinderella" fibers (Hagg, 1991) resulting in pathologic changes in these fibers (Larsson *et al.*, 1988). As well, muscular fatigue has been shown to develop at activation levels as low as 5% of MVC (Sjogaard, 1986). The development of muscular fatigue has been shown to reduce motor control as measured by an increase in motion in secondary planes (Parnianpour *et al.*, 1988) and fatigue has been proposed to predispose the spine to injury due to shifting of loading to more injury-susceptible tissues (McGill, 1995; Cholewicki and McGill, 1996). Furthermore, there is evidence to suggest that fatigue reduces the ability to respond appropriately to sudden loading (Jorgensen, 1997; Parnianpour *et al.*, 1988).

Previous studies from our laboratory evaluated the physical demands of a prolonged, low peak loading task. A "light" assembly task was performed at a moderate trunk flexion angle using a lordotic (hollow) or flexed (rounded) lumbar spinal curvature and a 55/5 second work/recovery ratio (Mientjes and Norman, submitted). This prolonged task, although "light" with respect to negligible forces on the hands and low peak forces on spinal structures, was shown to be demanding in terms of cumulative spinal loading, ratings of perceived discomfort, static muscular loading and muscular fatigue.

Initially the light assembly task was performed using a lordotic spinal curvature (Mientjes and Norman, submitted A) because of its advantageous reduction/elimination of anterior joint shear force due to the action of the back extensor muscles (McGill and Norman, 1986; Potvin *et al.*, 1991). However, continuous activation of the back extensor musculature to maintain a lordotic curvature can result in fatigue and possibly muscular pain/damage, even at low levels of muscular activation (Sjogaard and Jensen, 1999; Westgaard, 1988; Veiersted *et al.*, 1990). In a second study, the assembly task was performed using a maximally flexed lumbar spinal curvature which potentially allows for interplay between passive and active tissues in generating the trunk extensor moment, thereby reducing the magnitude of muscular activation. As was expected, reduction in low back extensor muscle activation was found for a flexed curvature compared to a lordotic curvature. However, this change in curvature did not significantly reduce perceived discomfort ratings. These remained high, exceeding a rating of 4 out of 10 after just 25 minutes of the task performance (Mientjes and Norman, submitted B). This work demonstrated that maintaining either a lordotic or fully flexed lumbar curvature, which are both extremes at the end range of lumbar curvatures, was demanding and not advised.

Besides instructing participants to use a specific lumbar curvature, lordotic or flexed, they were also told to maintain this curvature over the work duration. The static nature of the task most likely resulted in loading of the same tissues over the work duration. Variation in work postures has been proposed to reduce the demands on tissues (Sjogaard and Jensen, 1999). Performance of the task using a self-selected lumbar curvature, and allowing for changes in curvature over time, might reduce both the measured and perceived physical demands.

High ratings of perceived physical demands have been shown to be a strong risk factor for the reporting of low back pain in industry (Kerr *et al.*, in press). However, what measurable and modifiable variables people perceive is unclear. This uncertainty makes intervention in the workplace difficult. It would be helpful to identify variables on which individuals base their perceptions.

Ratings of perceived exertion were developed for tasks that strain the cardiovascular and/or respiratory systems (Borg, 1982) which is common in physical exercise but these systems may not be strained during occupational tasks. MacKinnon (1999) found a fairly good correlation (r=0.73) between ratings of perceived exertion and heart rate during a box-carrying (20% of body weight) and sweeping task which both involved substantial whole body movement. Taksic (1986), however, evaluated the demands of 7 different static trunk postures and concluded that heart rate could not distinguish between the demands of the different postures but that subjective ratings of discomfort were able to explain 50% of the variance. Jorgensen *et al.* (1999) and Davis *et al.* (2000) also concluded that heart rate did not contribute to perceptions of exertion when handling weights that were below the maximally acceptable weight of lift. Furthermore, perceptions of exertion appear moderately or not to be related to risk factors for low back pain such as spinal loading (Thompson and Chaffin, 1993; Jorgensen *et al.*, 1999) but perceptions of exertion have been shown to be related to muscle force (Davis *et al.*, 2000). The use of ratings of perceived discomfort, instead of exertion, might be more appropriate when evaluating a static or quasi-dynamic occupational task which involves local sensations such as muscle force but does not involve strain to the cardiovascular and/or respiratory systems.

The purpose of this study was 1) to quantify the physical demands on the low back of a simulated industrial "light" assembly task, in terms of spinal loading, perceived discomfort, back muscle activation and local muscular fatigue, 2) to determine whether individuals who perceived higher discomfort were exposed to higher measured physical demands, and 3) to determine whether individuals who perceived higher discomfort adopted measurable strategies to reduce their discomfort.

The two previous studies performed in our laboratory and the literature suggest the following hypotheses: 1) ratings of perceived discomfort will be lower for a self-selected lumbar curvature compared to a forced lordotic or flexed curvature, 2) ratings of perceived discomfort are related to activation levels of the musculature, and 3) individuals who perceive discomfort will vary trunk angle and lumbar curvature during the task.

2. Methods

2.1. *Participants*

Fifteen women participated in this study. Ten women (height 1.64 m, SD =6.4; body mass 61.2 kg, SD =8.9; age 29.8 years, SD =7.1) with assembly experience were recruited through an employment agency and 5 women, who did not have assembly experience (height 1.65 m, SD =4.2; body mass 61.7 kg, SD =5.3; age 21.4 years, SD =1.5), were recruited from a university population.

All individuals reported to be in good to excellent health and they were physically active. Activities ranged from daily walking to playing basketball and running, with the students being more active than the assembly workers. Twelve of the fifteen participants had not experienced low back pain in the 6 months preceding testing. Three participants, 2 assembly workers and 1 student, did report a pain level of "mild" or "moderate" in the past 6 months. The two assembly workers experienced back pain every 6 months or more, whereas, the student experienced back pain one or more times per month. The duration of back pain for all three individuals was short, ranging from 1 hour to 1 day. No diagnosis for these individuals was available. Fortunately, the previous back complaints of the 2 assembly workers did not result in any pain perceptions over the 1 hour task duration. However, the student (id 2) with a previous back complaint did report development of pain located in the low back during the task duration (pain rating of up to 6 out of 10). All participants read and signed an informed consent form approved by the Office of Human Research at the university.

2.2. *Industrial assembly task*

The task consisted of 55 seconds of *assembly work* in a 30° inclined forward trunk posture and 5 seconds of *recovery* in upright standing (55/5 second work/recovery ratio). The task was performed for a 1 hour duration. During the 5 second recovery, the participants were allowed to move their torsos freely and shuffle their feet but they were not allowed to step away from the work station. The task consisted of assembly of small plastic building blocks which were located on a table in front of the participant resulting in dominant trunk motion in the sagittal plane. To perform the task, participants used their preferred working posture and they could alter their posture over time. The task involved negligible external forces on the hands and in most plants would be considered to be a low loading or "light" job since the only load that had to be supported was upper body weight in a mildly inclined posture.

2.3. *Spinal maximum range of motion test*

Participants moved their torsos through their maximum range of motion for spinal movement normalization purposes. The participants started in upright standing, slowly flexed forward as far as possible aiming to touch the floor and then returned to upright standing. This maximum range of motion test was performed at the end of the data collection session, instead of at the beginning, to simplify EMG data collection since movement through the maximum range of motion often loosens the EMG electrodes due to the stretching of the skin.

2.4. *EMG normalization test*

Maximum Voluntary Contractions (MVC), to normalize the EMG signal, were performed at the beginning of data collection. The back extensor musculature was maximally activated by having participants lie on their stomachs and lean over the edge of a bench with the legs restrained. In this position a maximum back extensor effort was performed against manual resistance. Each normalization test was repeated 3 times.

2.5. *EMG fatigue test*

EMG fatigue tests were performed in a standing position with the trunk flexed forward 30° from vertical. The low back was positioned in a lordosis (hollow back). A handle with a length adjustable chain was held in the hands and the end of the chain had to be kept just above the floor to allow for the 30° trunk angle thereby improving replication of this trunk angle. This static posture, involving sub-maximal loading, was maintained for 5 seconds at the beginning of testing and at set intervals during the task (total of 8).

2.6. *Data acquisition and reduction*

2.6.1. *Biomechanical model*

A biomechanical model (4DWATBAK, University of Waterloo) was used to estimate peak and cumulative spinal loading. A detailed description of the 2 dimensional version of this model can be found in work by Andrews *et al.* (1997) and Norman *et al.* (1998). The model has been "risk-validated" meaning that its outputs have been shown to be able to produce an epidemiological estimate of risk of reporting of low back pain (Norman *et al.*, 1998; Kerr *et al.*, 2000). Video was used to estimate the trunk flexion angle to guide the positioning of the model's moveable manikin to the body posture obtained during the task. The manikin provided joint coordinate data which, in combination with gender, height and weight of the participants, were used to produce estimates of peak spinal compression force, reaction shear force, joint shear force and extensor moment. Cumulative loading was obtained by extrapolating single estimates taken at 8 set intervals during the 1 hour task performance to a 7 ½ hour workday for literature comparison purposes.

2.6.2 *Spinal Kinematics*

The 3SPACE isotrak (Polhemus Inc.) was used to measure spinal kinematics in three dimensions. The 3SPACE is an electromagnetic device and consists of a source, which was placed over the sacrum, and a sensor, which was placed over the spinous process of the 12th thoracic vertebra. The accuracy and viability of the 3SPACE isotrak has been evaluated by McGill *et al.* (1997). The 3SPACE was calibrated to zero in upright standing. Data collection was done for a duration of 1 minute during the maximum range of motion test and during the 1 hour task performance at set time intervals (total of 8 data collections). A sampling frequency of 20.5 Hz was used.

The angle of spinal curvature in flexion during the maximum range of motion test and during the task performance were obtained. The angle of spinal curvature in flexion during the task performance was expressed as a percentage of the maximum range of motion in flexion. This allowed for estimation of the contribution of active and passive tissues to the extensor moment. The variation in spinal curvature, in flexion, lateral bend and twisting, during the middle 45 seconds of assembly time was quantified using the standard deviation.

2.6.3. *Electromyography*

EMG electrodes were placed bilaterally, 3 cm lateral to the 3rd lumbar vertebra representing the lumbar portion of the Iliocostalis Lumborum and 1-2 cm lateral to the 5th lumbar vertebra representing the Multifidus. These muscles support moments about L4/L5. Signals were prefiltered to obtain a bandwidth of 5 to 500 Hz, amplified with a differential amplifier (CMRR 80dB @ 60 Hz) to produce signals between 2 and 8 V and A/D-converted at 1024 Hz.

During the EMG normalization tests, raw EMG was collected for a 5 second duration. Data were full-wave-rectified and low pass filtered (Butterworth) at a cutoff frequency of 2.5 Hz to produce a linear envelope of the signal. The peak of each record was identified and the highest value of the three repeats was selected for EMG normalization purposes.

Raw EMG was collected for a duration of 1 minute (1 cycle) at the beginning of the task and at set intervals during the task for a total of 8, one minute, data collections. The data were full-wave-rectified, low pass filtered (Butterworth with cutoff of 2.5 Hz) and normalized to MVC. The 1 minute data record was transformed into an Amplitude Probability Distribution Function (APDF), an analysis technique described by Jonsson (1978). The 5th, 50th and 90th percentile of the APDF were calculated to obtain a measure of low level muscular activity, average muscular activity and peak muscular activity, respectively.

EMG fatigue test data were used to calculate Mean Power Frequencies (MPF). Each 5 second record was clipped into 10, half second pieces. The MPF of each clipping was calculated and the MPFs of the middle 8 clippings were averaged to obtain 1 MPF per EMG fatigue test. The change in MPF over the task duration was quantified by taking the difference between the MPF obtained before the task was started and the MPF obtained after 58 minutes of task performance.

2.6.4. *Perceptions of physical demands*

Perceptions of physical demands of the tasks were recorded using two 10 point rating scales; ratings of perceived discomfort and ratings of pain. For the discomfort scale the zero point was defined as “no perceived discomfort” and 10 was defined as “extreme perceived discomfort”. Ratings of perceived discomfort were taken during the task performance (total of 9). A pain diagram, front and back view of the entire body, was completed before, during and after the task performance (total of 3). Participants were asked to circle body areas in which pain was felt. Pain experienced in each body part was quantified using a 10 point scale with the zero point defined as “no pain” and 10 was defined as “extreme pain”.

2.6.5. *Questionnaires*

A task performance questionnaire was completed at the end of the testing session. The questions addressed the individuals perception of their work posture in terms of whether they altered their work posture over time and why.

2.6.6. *Measure of productivity*

Participants were instructed to place as many assembly blocks onto a base as they could do comfortably and they were instructed to maintain this assembly pace for the full 1 hour task duration. The number of assembly blocks was counted at set time intervals (total of 20) during the 1 hour task duration to quantify productivity and monitor changes in productivity over time.

2.7. *Statistical analysis*

To determine whether the physical demands of various lumbar curvatures was significantly different, a one-way ANOVA was performed and the LSD post hoc test was used. A two way ANOVA with repeated measures on time was performed to evaluate differences in physical demands between groups (student versus assembly worker and low discomfort versus high discomfort) and to evaluate the significance of changes in the physical demands over time. Significance of repeated measures was determined using the Greenhouse-Geiser p-values and the degrees of freedom were adjusted using the Greenhouse-Geiser epsilon to account for non-random allocation violation (Winer, 1971). Paired comparisons were done using the protected least significant difference (protected LSD) (Choi, 1978). The Pearson correlation coefficient was used to determine the strength of the relation between trunk flexion angle and lumbar curvature. A level of significance of 0.05 was chosen.

3. Results

3.1. *Physical demands of a light assembly task using a self-selected posture*

The magnitudes of the physical demands, averaged over all 15 participants, are shown in table 1. Ratings of perceived discomfort increased, on average, 2.2 out of 10 during the 1 hour of task performance. Increases in ratings were, however, individual dependent and ranged from no discomfort (zero) to a rating of 6 by two individuals.

Peak spinal loading, in terms of compression force, reaction shear force, joint shear force and extensor moment, was low when compared to cases (individuals who reported back pain) and controls (individuals who did not report back pain) from a study by Norman *et al.* (1998). The probability of being classified as a case based on peak spinal loading is low, ranging from 0.24 to 0.27 depending on the mode of loading. Cumulative spinal loading, however, was high compared to data by Norman *et al.* (1998) resulting in a high probability of being classified as a case (ranging from 0.62 to 0.84 depending on the mode of loading).

The 5th percentile of the APDF was, on average, 2.9 and 4.5 % MVC at the 3rd and 5th lumbar vertebrae level, respectively. The 50th percentile was 7.7 and 9.9 % MVC and the 90th percentile was 10.1 and 12.8 % MVC for the two lumbar levels. The muscular activation required during the 1 hour task performance resulted, on average, in the development of fatigue as measured by a significant 4.7 Hz drop in mean power frequency at the 3rd lumbar level ($p<0.01$) and a significant 5.9 Hz drop at the 5th lumbar level ($p<0.034$).

3.2. *Do the physical demands depend on lumbar curvature?*

The physical demands of this study, in which participants selected their preferred lumbar curvature and were allowed to change their lumbar curvature over time, were compared to results from two previous studies (Mientjes and Norman, submitted A and B) in which the same task was performed, but the selection of lumbar curvatures was constrained. In one study a lordotic lumbar curvature had to be maintained (hollow back; study A) and in study B participants performed the task twice, once using a lordotic lumbar curvature and once using a maximally flexed (rounded) lumbar curvature. Variables that differed significantly between the various working postures (lumbar curvatures) are presented in table 2.

Ratings of perceived discomfort were significantly lower for the current study (mean=2.2, SD=2.2; $p<0.001$), even after a full 1 hour task duration, compared to previous work by the same authors in which the task was performed for 25 minutes only but a lordotic or fully flexed lumbar curvature had to be maintained (mean values ranging from 4.7 to 6.2, depending on the lumbar curvature).

The average magnitude of the joint shear force, which is affected by lumbar spinal curvature, was significantly higher in the self-selected curvature ($p<0.044$) compared to the other curvatures in which the participants maintained extensor muscle activation, thereby offsetting the anterior joint shear force. In the current study the preferred lumbar curvature of some individuals, 4 out of 15, involved a substantial lumbar curvature in flexion in which the joint shear forces were elevated up to 383N (SD=84).

The 5th, 50th and 90th percentile of the APDF, at the level of the 3rd lumbar vertebra, were comparable between the current study, involving self-selected lumbar curvatures, and previous work evaluating a flexed versus lordotic lumbar curvature. However, these APDF measures were significantly lower ($p<0.003$) compared to estimates obtained from the study involving a lordotic curvature only (Mientjes and Norman, submitted A). The 50th percentile of the APDF was significantly lower for a self-selected and flexed lumbar curvature (study B) compared to a lordotic curvature (5^{th} lumbar vertebra).

No Significant differences between the self-selected, lordotic and flexed lumbar curvature were found for peak and cumulative spinal compression force, reaction shear force and extensor moment, nor for the trunk angle, the 5th and 90th percentile of the APDF at the 5th lumbar level and muscular fatigue of the back extensor musculature.

3.3. *Student versus assembly worker comparison*

The participants in this study consisted of 5 female university students and 10 women who had assembly experience. These 2 groups differed significantly in their ratings of perceived discomfort with the students reporting more discomfort, average of 3.8 out of 10, and the assembly workers reporting an average discomfort of 1.4 ($p<0.039$; Figure 1). Due to this significant difference between the two groups further analysis was performed on both groups separately. In the physical demand analysis presented above the combined data of the 2 groups was presented to simplify data presentation. This was possible because data analysis performed on the individual groups showed that this separate group analyses lead to the same findings as presented above.

3.4. *High versus low discomfort individuals*

3.4.1. *Ratings of perceived discomfort*

Differences, not only between the student group and the assembly worker group were found but also within each group, classified as "low" and "high" discomfort individuals (Figure 2). A discomfort rating of 1.5 or less was operationally considered low discomfort and a rating exceeding 1.5 was considered high discomfort. This cutoff was consistent with a division in pain ratings of the low back at the end of the work duration. Individuals with pain ratings between 2 to 7 were high discomfort individuals and individuals who did not experience any pain in the low back or rated up to a 1 were low discomfort individuals. Furthermore, a perceived discomfort rating of 1.5 and a pain rating for the low back of 2 after 1 hour of the task performance might result in even higher ratings after a full workday. Furthermore, this cutoff allowed for a grouping of 4 assembly workers as high discomfort individuals. A cutoff above a discomfort rating of 2 would allow for just 1 worker to be classified as a high discomfort individual which is too small a number to be able to make any data comparisons between low and high discomfort individuals.

Two out of 5 students perceived their discomfort as low as 1 out of 10 at the end of the 1 hour task duration. Whereas 3 students developed substantial discomfort with ratings of 5 and 6 which were significantly higher compared to the low discomfort individuals ($p<0.0003$). The low discomfort individuals ($n=6$) within the assembly worker group rated no discomfort or a 1, whereas the high discomfort group rated a 2 or 5 ($n=4$). The high and low discomfort individuals differed significantly ($p<0.002$).

3.4.2. *Pain ratings*

Pain locations that were identified by the participants were the area of the shoulder, neck, upper back, lower back (defined by the lumbar region of the spine), the back of the thigh, back of the knee and the feet (Table 3). The magnitude of pain located in the low back was significantly higher compared to ratings at all the other pain sites for the high discomfort individuals ($p<0.0003$). Furthermore, the pain rating regarding the low back was able to distinguish between high and low discomfort individuals within the student ($p<0.001$) and assembly worker group ($p<0.0003$). None of the other pain locations with accompanying pain ratings were able to distinguish between the low and high discomfort individuals.

3.4.3. *Estimates of spinal loading*

Spinal compression force estimates are shown in figure 3 for all individuals and are presented in combination with the perceived discomfort ratings for each individual. It can been seen that there are no significant differences between the high and low discomfort individuals within the student group ($p<0.22$) or within the assembly worker group ($p<0.15$). These findings are consistent for the trunk angle and for peak and cumulative compression force, reaction shear force and extensor moment since all these estimates were based on the same posture data obtained from video.

3.4.4. *Lumbar spinal curvature*

No significant differences in lumbar curvature in flexion, as measured using the lumbar motion monitor, were found between the high and low discomfort individuals within both the student ($p<0.49$) and the assembly worker group ($p<0.64$) as shown in figure 4.

Lumbar spinal curvature, measured by the lumbar motion monitor, was compared to the trunk angle, which was obtained from video. A significant correlation of 0.64 was found ($p<0.01$) showing that the trunk flexion angle and the angle of lumbar curvature in flexion were related and explained 41% of the variance. However, 59% of the variance remained unexplained indicating that a set trunk angle, in this case 30°, allowed for differences in spinal curvature ranging between a lordotic and flexed curvature.

Variation in spinal curvature during the assembly time was measured by the standard deviation. For the student group the variation in lumbar curvature occurring in lateral bending was significantly higher for the high discomfort individuals compared to the low discomfort individuals ($p<0.025$) and variation in flexion and axial twisting was close to significant ($p<0.069$ and $p<0.06$, respectively; Figure 5). No significant differences in spinal curvature variation were found between the low and high discomfort individuals in the assembly worker group.

3.4.5. *Muscular activation and spectral measures*

The low and high discomfort individuals within the student group did not show any significant differences in muscular activation levels at the 5th, 50th or 90th percentile of the APDF at either the level of the 3rd or 5th lumbar vertebrae. For the assembly worker group the difference between the low and high discomfort individuals was close to significant at the 5th percentile of the APDF obtained from the 3rd lumbar level ($p<0.058$). However, visual inspection revealed that the muscular activation levels of the high discomfort individuals was not consistently higher compared to low discomfort individuals (Figure 6). No significant differences between low and high discomfort individuals within the assembly worker group were found for any of the other APDF measures at either lumbar level.

No significant differences in MPF reduction between the low and high discomfort individuals within both the student ($p<0.47$) and assembly worker group ($p<0.42$) were found.

3.4.6. *A work posture involving minimum discomfort*

Three individuals, all assembly workers, did not experience any discomfort during the 1 hour work duration (Figure 2). These three assembly workers (id 12, 15 and 18), as well as 1 student (id 3), adopted a larger lumbar curvature in flexion compared to other individuals (Figure 4) and their average muscular activation was reduced compared to the other individuals (Figure 7; data of ID 15 is missing at L5). These findings indicate that these individuals recruited passive tissues, in combination with active tissues, to generate the required extensor moment. This has consequences for the joint shear forces acting on the spine which increase when the shear reducing action of the back extensor musculature decreases. This increase in joint shear force compared to other individuals is shown in figure 8.

3.5. *Changes over the 1 hour work duration*

Ratings of perceived discomfort increased significantly over time for the high discomfort individuals of the student ($p<0.063$) and assembly worker group ($p<0.046$). No significant changes in discomfort over time were reported by the low discomfort individuals.

Changes in biomechanical model, lumbar motion device and muscular activation estimates over the work duration were evaluated according to categorization as student or assembly worker group and as low or high discomfort individuals. High discomfort individuals did not change any of the variables over time that were measured in this study. Low discomfort individuals within the worker group did show a significant decrease in the 5th percentile of the APDF, from 5.7 % of MVC during the first minute of the task to 3.8 % of MVC during the last minute of the task, which is possibly beneficial regarding recovery ($p<0.029$). No significant changes in any of the other measures were found over the 1 hour work duration.

3.6. *Measurement of productivity*

Production rate, measured by the average number of small assembly blocks put onto a base, was the same between the student and assembly worker group ($p<0.35$) with 21 blocks per 55 seconds of assembly time. The rate of production over the 1 hour task duration was constant for the students ($p<0.16$) and increased slightly, 3 additional blocks, for the assembly workers ($p<0.046$) possibly due to a leaning effect.

4. Discussion

4.1. *Quantification of physical demands*

Individuals were not able to perform an hour of this "light" assembly task without adverse effects such as elevated perceived discomfort, sustained muscular activation levels and development of muscular fatigue. This task was not light from the perspective of cumulative spinal loading, a known risk factor for low back pain reporting (Norman *et al.*, 1998). These findings did not depend on the selection of spinal curvature since the same conclusions were true for a lordotic, flexed or self-selected lumbar curvature. However, as hypothesized, the physical demands during the self-selected lumbar curvature were more favorable regarding discomfort ratings compared to a fixed lordotic or flexed curvature, and sustained muscular activation levels were reduced in the self-selected lumbar curvature compared to a fixed lordotic curvature.

After 1 hour of assembly the average perception of discomfort increased up to 2.2 out of 10. However, on an individual basis the discomfort ratings differed. Some individuals did not experience any discomfort and some individuals experienced high discomfort with a magnitude of 5 or 6. The latter individuals are thought to be more likely to report low back pain. The pain scale and diagram identified the low back as the most prominent location for pain development in this type of task. This pain site was also the only pain location which could separate low from high discomfort individuals in the same way as discomfort ratings did. The discomfort rated by the individuals was therefore related to their dominant pain sensation which was located in the low back.

4.2. *Physical demands of low versus high discomfort individuals*

It was questioned why some individuals experienced higher discomfort compared to others while performing the same task. The physical loading of individuals with high discomfort ratings was compared to individuals with low discomfort ratings. There were no differences between these two groups in peak and cumulative spinal loading, lumbar curvature, muscular activation levels or magnitude of fatigue development of the back extensor muscles. Inexperienced workers with high discomfort ratings did vary their lumbar curvature more compared to inexperienced workers who perceived low discomfort. This is not true, however, for experienced workers who show a reversed trend which was not significant. For the experienced workers, variation of lumbar curvature occurred in combination with low discomfort ratings. Due to opposite findings for the two different groups it is not clear whether variation in lumbar curvature is beneficial regarding discomfort or not.

Since the physical demands of the high discomfort individuals did not differ from the low discomfort individuals, it appears that individuals did not base their perceptions on known risk factors for low back pain reporting such as spinal loading. The psycho-physical approach has been used to select acceptable loads based on the individual's perceived exertion (Snook, 1978). This technique assumes that individuals can perceive when a load is safe and when it reduces the risk of injury (Herrin *et al.*, 1986). Jorgensen *et al.* (1999) showed that the individuals selection of acceptable loads for lifting is only marginally based on spinal loading variables such as shear force and the extensor moment. Selection of acceptable loads for lifting appear to be more affected by muscle force than spinal loading or by heart rate when lifting high loads

(Davis *et al.*, 2000). We hypothesized to find a difference in muscular activation level, a measure partly related to muscle force, but we did not find a difference between high and low discomfort individuals. This might be due to the low level of activation required in the assembly task. The findings by Davis *et al.* (2000) were obtained from manual material handling involving moderate to high loads, ranging from 9.1 to 41.7 kg. In a higher loading task, muscle force may play a more important role in perception of the demand.

The back extensor muscle fatigue that developed over the work duration was similar between low and high discomfort individuals. Dedering *et al.* (1999), however, reported a moderate correlation of 0.41-0.50 between subjective ratings of fatigue (Borg scale) and the mean power frequency during a modified Sorensen's test. Reasons why we did not find a relation between subjective ratings and spectral fatigue measures compared to Dedering *et al.* (1999) might be the differences in the task constraints and the muscular activation level that was required. The assembly task allowed for 5 seconds of recovery during every minute but there was no rest in the modified Sorensen's test. The back extensor activation level during the assembly task with a 30° flexed trunk posture is less than during the modified Sorensen's test due to the required extensor moment. The assembly task is therefore a less demanding task compared to the Sorensen's test and this possibly diminishes the relation between subjective ratings and fatigue.

4.3. *Strategies involving low perceived discomfort*

A lumbar curvature that did not result in perceptions of discomfort or in a discomfort rating of 1, consisted of a large spinal curvature in flexion, on average 78.4 % of ROM in flexion, in combination with low activation levels, on average 1.7 and 3.3 % of MVC for the back extensor musculature at L3 and L5, respectively. This large spinal curvature in flexion results in recruitment of passive tissues which can generate approximately 50 % of the extensor moment as measured from cadavers (Adams and Dolan, 1991). Furthermore, passive stretch of the musculature can contribute to the extensor moment (McGill and Kippers, 1994). Contribution of passive tissues to the generation of the extensor moment allowed for reduction in muscular activity. The four individuals who adopted this posture successfully minimized their discomfort and although this lumbar curvature, in combination with low muscular activation levels, increased anterior joint shear force (383 N; SD=84), this magnitude is believed to be below injurious levels.

We did not find this relationship between low discomfort ratings, large spinal flexion and low muscular activation levels in our second study in which individuals were instructed to flex their lumbar spine as far as possible during the assembly duration (Mientjes and Norman, submitted B). The higher discomfort ratings found in study 2 (up to 4.7) compared to the current study might be due to forcing the lumbar curvature to the end range in flexion, thereby increasing and not decreasing discomfort.

It was hypothesized that individuals who develop discomfort over the work duration would adopt strategies to reduce this discomfort. Since discomfort was highly related to pain located in the low back, changes in trunk angle and lumbar curvature were expected. However, we did not find any changes in trunk posture (trunk angle and lumbar curvature) over the 1 hour work duration for the high discomfort individuals. This type of task did leave some room for individuals to obtain a different lumbar curvature at a set trunk angle as shown by the 59 % of variance that was unexplained in the relation between trunk angle and lumbar curvature. But individuals did not choose to use the ability to alter spinal curvature in flexion. When the individuals were asked if and how they altered their task performance over time, 11 out of 15 individuals, some with low discomfort and some with high discomfort, reported movement in medial-lateral direction and they elected to alternate the support of their body weight from one leg to the other. The development of discomfort did not affect the task performance since individuals maintained a constant work rate, or even increased their work rate, over the full 1 hour work duration.

4.4. *Sustained low loading*

Static loading of the musculature, even at low levels, has been related to muscular pain of the trapezius musculature (Westgaard, 1988; Veiersted et al., 1990). Aaras (1994) found that a reduction of trapezius muscle activation below 1-2 % of MVC was associated with a reduced incidence of musculoskeletal illness. A possible pathway for musculoskeletal illness is the reduction in muscle oxygenation which occurs at activity levels as low as 2 % of MVC of the back extensor musculature (McGill *et al.*, 2000). These are very low levels of muscular activation which only few participants in the current study obtained. The average activity level was higher, 2.6 and 4.9 % of MVC, for L3 and L5 respectively. Therefore, a change in the assembly task to allow for a reduction in static loading is thought to be beneficial.

4.5. *Measurement of muscular fatigue*

Various authors have shown that muscular fatigue can develop at activation levels below the 15 % of MVC threshold which was initially proposed by Rohmert (1973) (Sjogaard *et al.*, 1988; Jorgensen *et al.*, 1988; Fallentin *et al.*, 1985). However, the ability to measure muscular fatigue by changes in the EMG power spectrum, at muscular activation levels below 10% of MVC, has been questioned. An average reduction in MPF of 4.7 Hz at L3 and 5.9 Hz at L5 was measured over the 1 hour assembly task duration which involved an average activation level of 7.7 and 9.9 % of MVC at L3 and L5, respectively. This is in agreement with Hansen *et al.* (1998) and Kim *et al.* (1994) who were able to measure a decrease in MPF of the back extensor musculature during 2 hours of standing work which involved low muscular activation levels, between 4-6 % of MVC.

4.6. *Other considerations*

The discomfort of individuals with assembly experience and students without assembly experience were compared. The students' perceptions of their discomfort levels was significantly higher compared to the assembly workers. From observation, the experienced workers enjoyed this assembly task compared to other jobs they had done in the past. In general, the students were easily bored. This indicates that when evaluating a task, it is preferred to recruit individuals who are experienced with that particular task.

Assembly workers were recruited to participate in this study to improve the applicability of the research findings to the workplace. This work is, however, limited by the fact that a task simulation in the laboratory was used to collect data. Assembly workers commented on how clean and quiet the environment was. Their content about the work environment compared to other work places and the attention they received during the data collection might have resulted in lower discomfort ratings than might have been obtained during data collection in the actual workplace. Although data collection in the workplace is more realistic, it involves additional challenges and often does not allow for use of extensive data collection techniques as are applied in the laboratory.

4.7. *Conclusions*

1. The hypothesis that ratings of perceived discomfort would be lower for a self-selected lumbar curvature compared to a forced lordotic or flexed curvature was supported by the data. Ratings were reduced, therefore, the use of a self-selected lumbar curvature can be recommended as a strategy for reducing discomfort.
2. The hypothesis that ratings of perceived discomfort were related to muscular activation was not supported by the data. Individuals who experienced discomfort exceeding 1.5 out of 10 recruited their back extensor musculature at a similar activation level as individuals who experienced discomfort below 1.5.
3. The hypothesis that individuals who perceived higher discomfort would vary trunk angle and lumbar curvature during the task was not supported by the data. Changes in trunk angle and lumbar curvature during working cycles were similar between individuals with high discomfort and those with low discomfort.

A "light" assembly task with a 55/5 second work/recovery ratio was not light as seen by the adverse effects on perceived discomfort, muscular activation and local muscular fatigue. Moreover, this task was not light from the perspective of cumulative loading, a known risk factor for low back pain reporting. Individuals who experienced discomfort exceeding 1.5 out of 10 were exposed to the same physical demands as individuals who experienced discomfort below 1.5. From this study we can therefore not conclude on which variables, aside from pain, individuals base their perceptions of discomfort. Further research is required to evaluate which variables affect discomfort and pain since these perceptions can result in back pain reporting that may lead to work absence.

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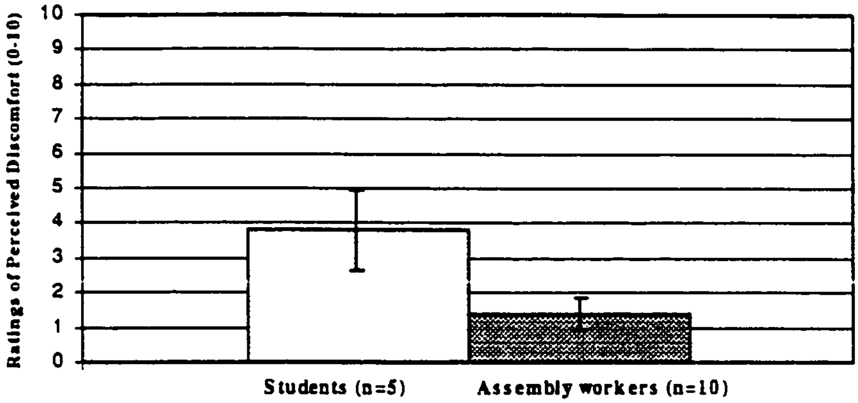

Figure 1. Perceived discomfort ratings of the students was significantly higher than the ratings of the assembly workers at the end of the 1 hour assembly task ($p<0.039$). The average values and standard errors are shown for all 5 students and all 10 assembly workers.

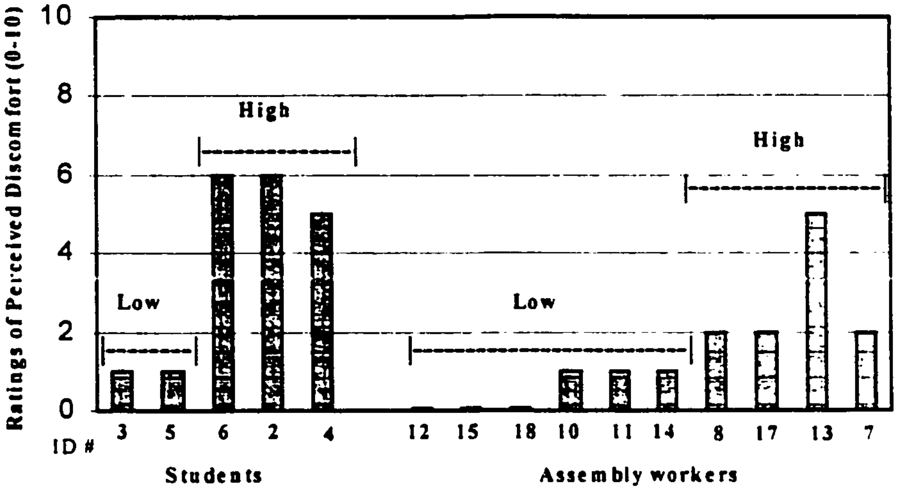

Figure 2. Ratings of perceived discomfort at the end of the 1 hour assembly task differed between individuals as shown for the 5 students and 10 assembly workers. Within the student and assembly worker group, individuals with ratings below 1.5, low discomfort individuals, and above 1.5, high discomfort individuals, could be identified. The high discomfort individuals rated significantly higher discomfort compared to the low discomfort individuals for both the student ($p<0.0003$) and assembly worker group ($p<0.002$).

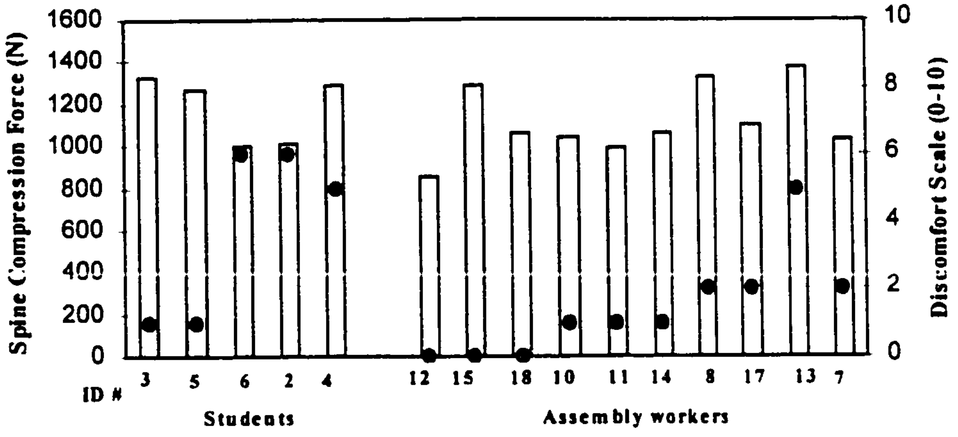

Figure 3. Spinal compression forces, as presented by bars along with the left vertical axis, are shown in combination with ratings of perceived discomfort, as presented by dots and the right vertical axis. It can be seen that individuals with high discomfort ratings (participant number 6, 2, 4, 8, 18, 13 and 7) were exposed to similar physical demands as individuals with low discomfort ratings within the students group ($p<0.22$) and the assembly worker group ($p<0.15$).

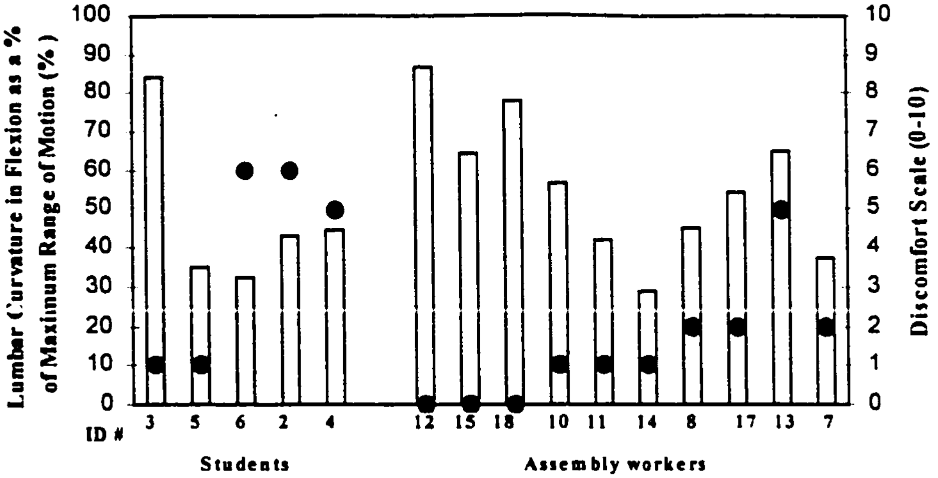

Figure 4. Lumbar curvature in flexion was expressed as a percentage of maximum range of motion in flexion. Lumbar curvature (bars, left axis) is presented in combination with discomfort ratings (dots, right axis). No differences in lumbar curvature in flexion were found between individuals with low and high discomfort ratings within the student group ($p<0.49$) and the assembly worker group ($p<0.64$).

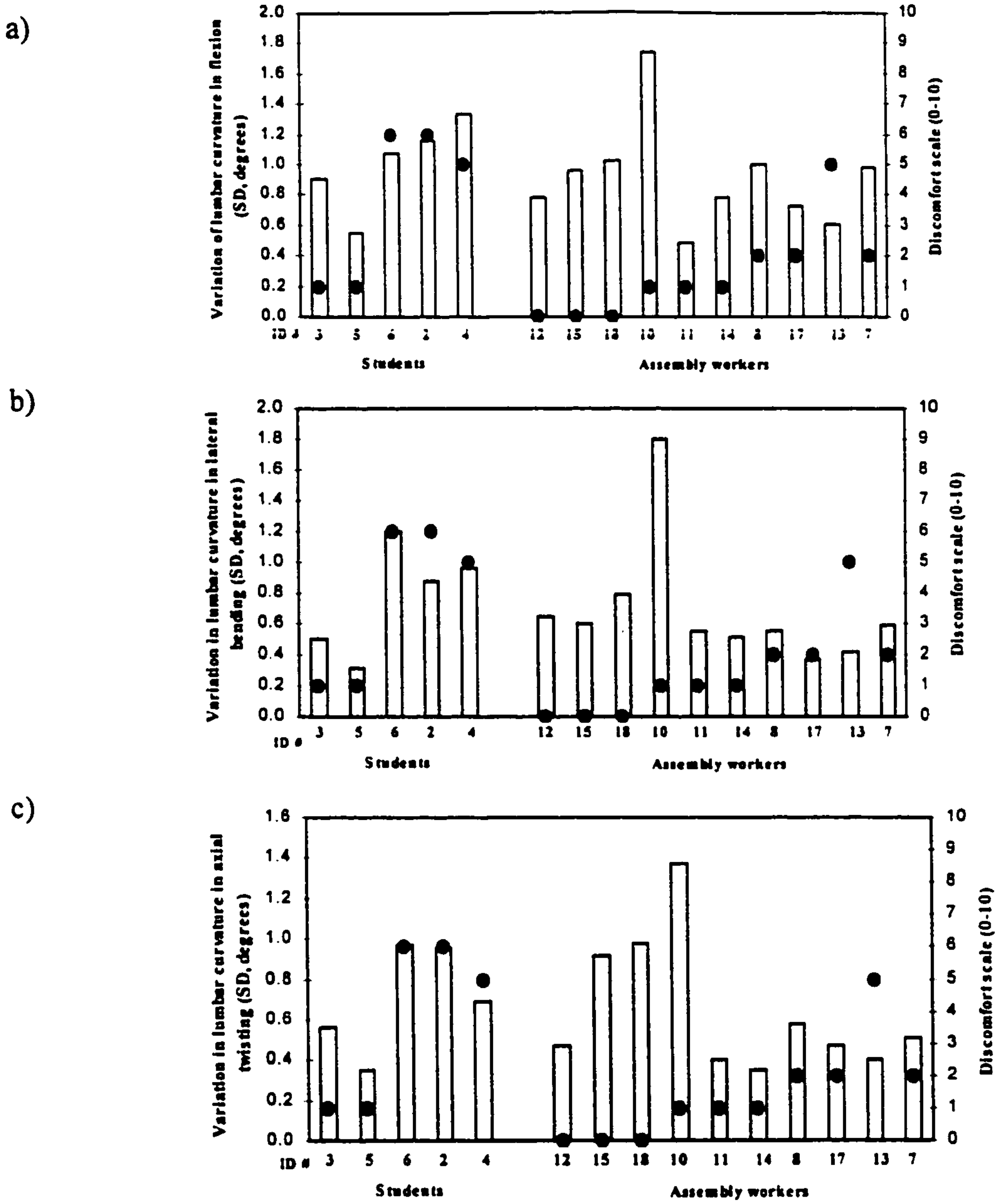

Figure 5. Variation of the lumbar curvature, measured by the standard deviation and expressed in degrees, is shown for (a) flexion, (b) lateral bending and (c) twisting. Lumbar curvature (bars, left axis) data are presented in combination with discomfort ratings (dots, right axis). The variation in lumbar curvature was significantly higher for the high discomfort individuals in lateral bending ($p<0.0025$) and close to significant in flexion ($p<0.069$) and twisting ($p<0.06$). No differences between low and high discomfort individuals were found within the assembly worker group for any of the variables.

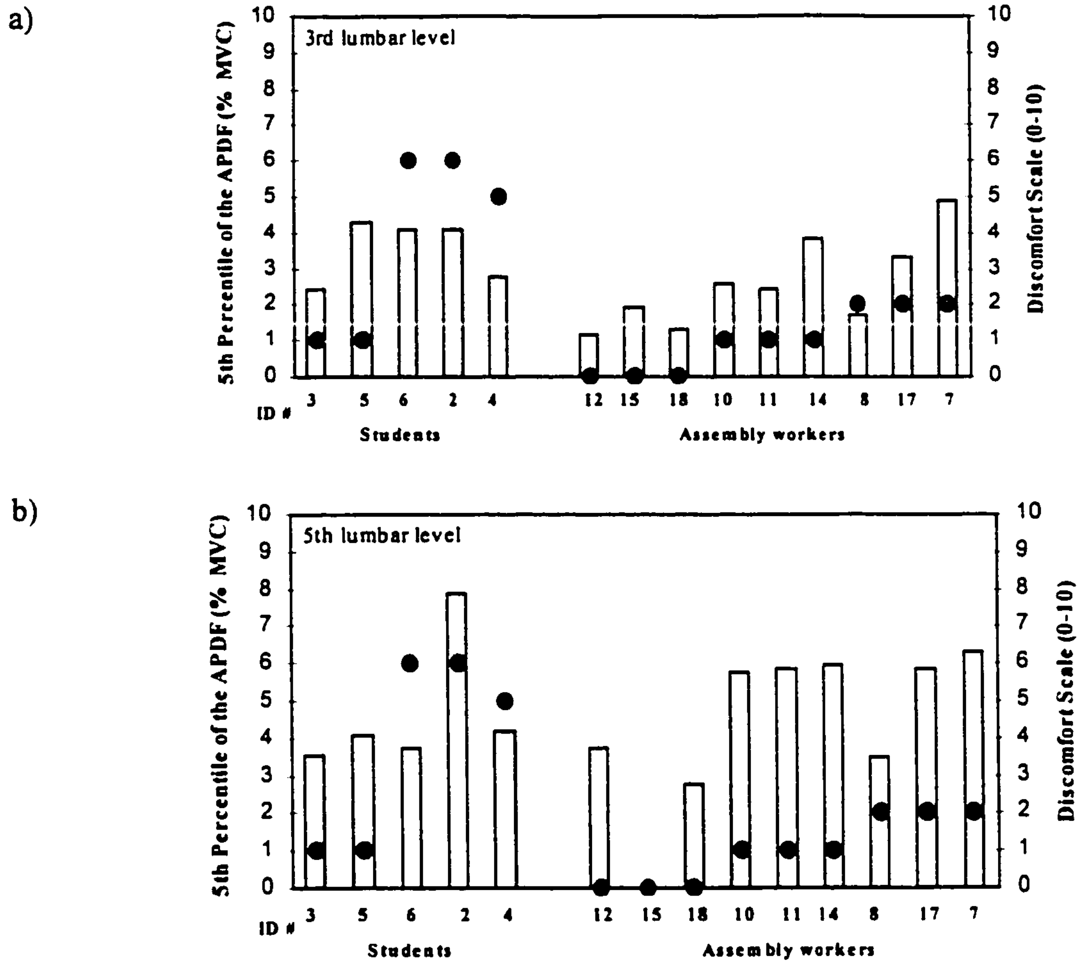

Figure 6. The 5th percentile of the APDF (bars, left axis) at the level of the (a) 3rd and (b) 5th lumbar vertebrae is shown in combination with discomfort ratings (dots, right axis). A close to significant difference between the low and high discomfort individuals was found for the assembly workers at the 3rd lumbar level ($p<0.058$). Visual inspection, however, showed that high discomfort individuals were not consistently higher at the 5th percentile than low discomfort individuals. No other differences were found between low and high discomfort individuals.

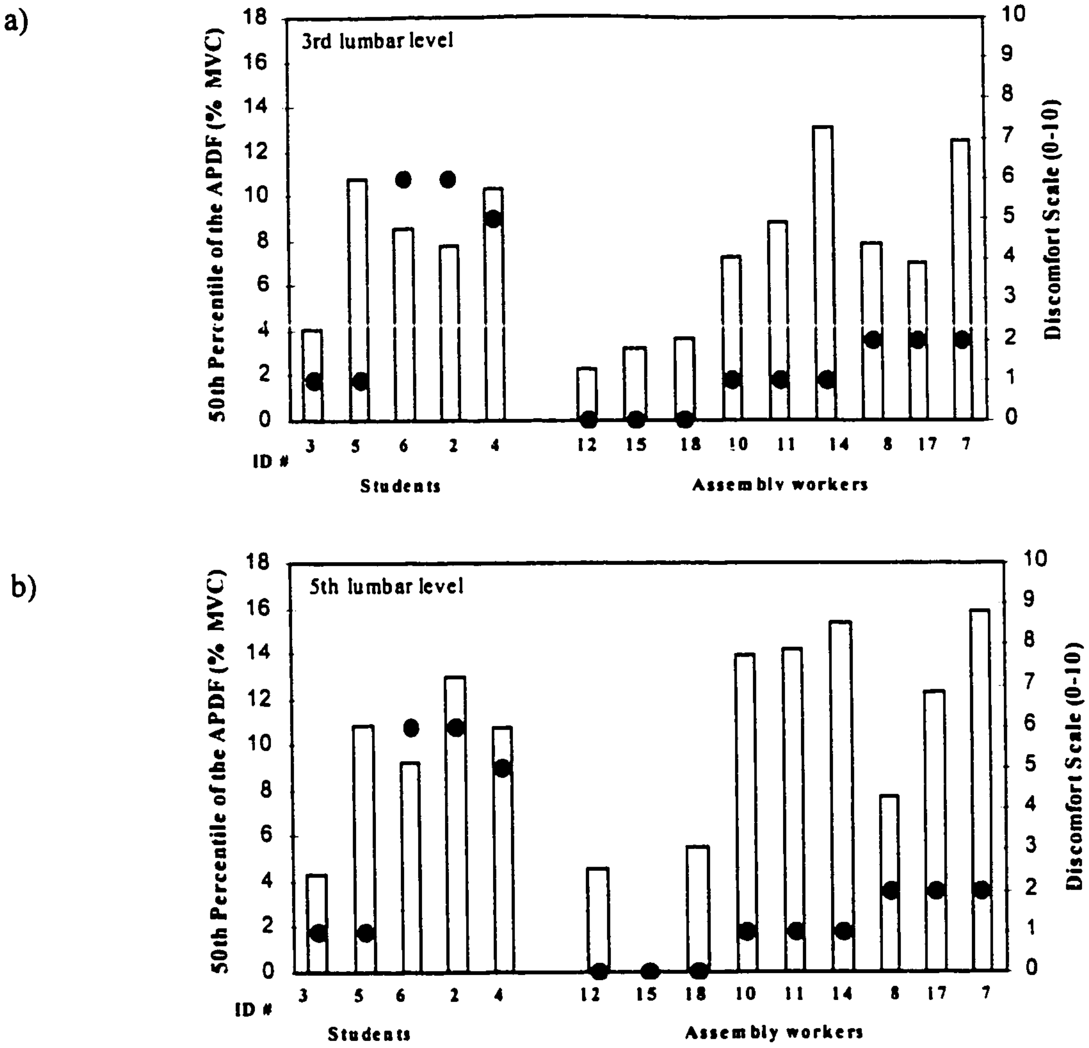

Figure 7. The 50th percentile of the APDF (bars, left axis) at the level of the (a) 3rd and (b) 5th lumbar vertebrae is shown in combination with discomfort ratings (dots, right axis). Average muscular activation levels were similar between low and high discomfort individuals within the student and assembly worker group at the 3rd and 5th lumbar vertebrae. Four individuals, number 3, 12, 15 and 18, adopted a strategy requiring low muscular activation levels compared to the other individuals (data for individual number 15 is missing at L5).

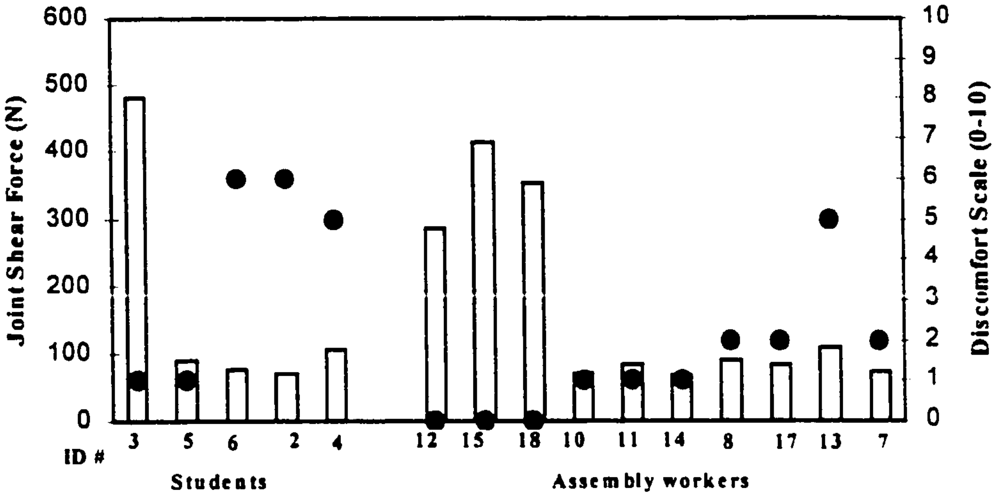

Figure 8. Joint shear forces (bars, left axis) are shown in combination with discomfort ratings (dots, right axis). Three assembly workers, who did not perceive any discomfort, and one student, who perceived a discomfort of 1, obtained a large lumbar flexion angle in combination with low muscular activation levels resulting in higher joint shear forces compared to other individuals who did not use this strategy. The elevated joint shear forces did, however, remain below shear levels which are thought to be injurious.

Table 1. The physical demands to which individuals were exposed while performing a "light" assembly task in a self-selected lumbar curvature are shown. RPD = ratings of perceived discomfort; Fc = spinal compression force; Fsj = joint shear force; Fsr = reaction shear force; M = extensor moment; Cum = cumulative spinal loading; L3 = 3rd lumbar vertebra level, left-right average; L5 = 5th lumbar vertebra level, left-right average.

Measure	Mean (SD)	**Measure**	Muscle site	Mean (SD)
RPD (0-10)	2.2 (2.2)	5th percentile of the APDF (% MVC)	L3	2.9 (1.3)
Peak Fc (N)	1134 (159)		L5	4.5 (2.3)
Peak Fsj (N)	163 (88)	50th percentile of the APDF (% mVC)	L3	7.7 (3.4)
Peak Fsr (N)	168 (29)		L5	9.9 (5.1)
Peak M (N m)	52.9 (8.7)	90th percentile of the APDF (% mVC)	L3	10.1 (4.3)
Cum Fc (MN s)	28.7 (4.1)		L5	12.8 (6.7)
Cum Fsr (MN s)	4.1 (0.7)	MPF (Hz)	L3	- 4.7 (5.9)
Cum M (MN m s)	1.3 (0.2)		L5	- 5.9 (8.4)

Table 2. The physical demands that differed significantly between lumbar curvatures are presented. The values averaged over all participants and standard deviations that are shown in *italics* were significantly lower compared to estimates obtained during other lumbar curvatures. RPD = ratings of perceived discomfort; Fsj = joint shear force; L3 = 3rd lumbar vertebral level, left-right average; L5 = 5th lumbar level, left-right average.

	Lumbar spinal posture			
Measure	Self-selected (current study)	Lordotic lumbar curvature (study a)	Lordotic lumbar curvature (study b)	Flexed lumbar curvature (study b)
RPD (0-10)	*2.2 (2.2)*	5.5 (2.5)	6.2 (2.7)	4.7 (2.3)
Fsj (N)	164 (143)	*75 (17)*	*75 (13)*	*85 (16)*
5th % APDF L3 (% mVC)	*2.9 (1.3)*	5.8 (1.9)	3.2 (1.3)	*2.8 (1.8)*
50th % APDF L3 (% mVC)	*7.7 (3.4)*	12.7 (2.5)	*9.3 (2.1)*	*6.5 (2.6)*
90th % APDF L3 (% mVC)	*10.8 (4.3)*	15.4 (3.0)	*11.6 (2.9)*	*8.9 (3.0)*
50th % APDF L5 (% mVC)	*9.9 (5.1)*	13.4 (3.1)	15.4 (4.3)	*10.5 (2.8)*

Table 3. Average pain magnitudes, and standard deviations, are shown for all pain locations that were identified on the pain diagram and rated on the pain scale. The results are presented for the low and high discomfort individuals for both the student and assembly worker group. The magnitude of pain located in the low back is significantly higher compared to ratings at all other pain sites for the high discomfort individuals (p<0.0003). Furthermore, the low back pain location is the only pain site that could distinguish between high and low discomfort individuals within the student group (p<0.001) and the assembly worker group (p<0.0003) (*significant data are presented in italic*). No significant differences between low and high discomfort individuals were found for any of the other locations.

	Students		**Assembly workers**	
Pain Location	Low discomfort	High discomfort	Low discomfort	High discomfort
Shoulder	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	1.3 (2.5)
Neck	0.0 (0.0)	2.3 (4.0)	0.0 (0.0)	0.0 (0.0)
Upper Back	1.3 (1.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Lower Back	*0.3 (0.4)*	*6.3 (0.6)*	*0.2 (0.4)*	*3.5 (1.3)*
Thigh, Posterior	0.0 (0.0)	0.0 (0.0)	0.2 (0.4)	0.0 (0.0)
Knee, Posterior	1.0 (1.4)	1.7 (2.9)	0.2 (0.4)	1.5 (3.0)
Feet	0.0 (0.0)	1.3 (2.3)	0.5 (0.8)	2.0 (2.3)

Appendix D

The effects of physical demands of a "light" assembly task on women who have had low back pain

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Abstract

Objective. To determine whether individuals who had recently had low back pain responded differently to the same "light" assembly task compared to those who had not had low back pain.

Methods. Nine women who had had low back pain (LBP individuals) performed a simulated industrial "light" assembly task for one hour. The task consisted of one minute cycles with 55 seconds of work in mild trunk flexion and 5 seconds of recovery in upright standing. Proven and proposed risk factors for low back pain reporting such as spinal loading, local muscular fatigue and perceived discomfort were measured. Trunk angle and lumbar spinal curvature were measured to evaluate alterations in posture.

Results. Peak compression force was low and cumulative compression force was high and similar between the LBP individuals and two comparison groups, students and assembly workers, 27.1, 29.9 and 28.2 MN s, respectively. Local muscular fatigue, measured by a decrease in mean power frequency, was similar between the groups, ranging from 4.3 to 9.2 Hz. LBP individuals did not change trunk angle or lumbar curvature more than individuals who had not had low back pain. LBP individuals tended to rate higher discomfort, 3.2 out of 10, compared to assembly workers (1.4).

Conclusion. Individuals who had had low back pain responded similarly to those who had not had low back pain during a "light" assembly task. However, the tendency of LBP individuals to perceive higher discomfort might affect injury reporting, possibly followed by time off work.

Relevance

A large number of individuals in the workplace have, or have had, an episode of low back pain. It is useful for health care practitioners and the designers of work to know how a history of low back pain affects work performance and perceived discomfort during "light" tasks.

Key words: Low back pain; Risk factors; Prolonged loading; Women; Industrial task simulation

1. Introduction

A large percentage of the population, 80 to 85 per cent, suffers from disabling low back pain at some point in their life [1,2]. Injuries to the back, compared to all other injuries in U.S. industries, have been estimated by the National Safety Council to represent the highest percentage in reported injuries, total compensation and medical payment cases. About 13% of the cases reporting injury to the back returned to work after one workday, about 24% returned after three to five workdays and about 18% returned after 31 workdays or more [3]. These numbers indicate that, beside the fact that low back pain is costly, many workers have had an episode of low back pain and a large number of these individuals return to work. It was questioned whether individuals who had recently had low back pain responded differently to the same "light" assembly task compared to those who had not had low back pain

Variables that have been proven or proposed to be risk factors for the reporting of low back pain are peak spinal loading [4,5,6], cumulative spinal loading [6,7], perceptions of high exertion [8] and muscular fatigue [9]. Previous work from our laboratory showed that a "light" assembly task involved low peak spinal loading, since the trunk was in a mild forward inclination angle only, but the task was demanding in terms of cumulative spinal loading, due to this prolonged mild trunk flexion. Ratings of perceived discomfort, a modified version of ratings of perceived exertion, were high after one hour of "light" assembly in a student population (3.8 out of 10) and low for experienced assembly workers (1.4). Furthermore, local muscular fatigue, measured by a reduction in mean power frequency, developed over the one hour assembly task duration [10].

Cycles of 55 seconds of constant mild trunk flexion followed by 5 seconds of upright standing, have been shown to increase discomfort, probably due to the static nature of the posture [10]. Strategies that might avoid development of discomfort or alleviate discomfort during constant mild trunk flexion are movement of the trunk and changes in spinal curvature. Movement allows for sharing of the load between muscles or other tissues and this could allow for partial or full recovery from fatigue. Although introduction of short recovery breaks could benefit discomfort, it might not be beneficial in terms of recovery time at the end of the workday since intermittent contractions have been shown to increase recovery time compared to sustained contractions [11,12]. Furthermore, load sharing between various tissues might put weaker tissues at a greater risk of injury.

The purpose of this study was to determine whether individuals who had recently had low back pain responded differently to the same "light" assembly task compared to those who had not had low back pain. It was hypothesized that 1) individuals who had had low back pain will alter trunk posture and lumbar curvature over time to alleviate discomfort and pain and that 2) perceived discomfort of individuals who had had low back pain will exceed that of those who had not had low back pain.

2. Methods

2.1. *Participants*

Nine women who had had low back pain (LBP individuals) participated in this study (height 1.66 m, SD = 0.07; body mass 60.3 kg, SD = 12.7; age 25 years, SD = 7.2). Individuals were excluded if the pain in their low back, defined as the area between the lower part of the rib cage and the pelvis, was severe (exceeding a score of 40 in the Revised Oswestry Pain Questionnaire) [13] and when they reported moderate pain in other areas such as neck, upper back and upper or lower extremities. All participants read and signed the informed consent form approved by the Office of Human Research at the university.

2.2. *Industrial assembly task*

The task consisted of 55 seconds of assembly work in a 30° inclined forward trunk posture and 5 seconds of recovery in upright standing (55/5 second work/recovery ratio). The task was performed for a one hour duration. During recovery, the participants were allowed to move their torso freely and shuffle their feet but they were not allowed to step away from the work station. Participants stood on a hard surface and no anti-fatigue mats were used. The task consisted of assembly of small building blocks which were located on a table in front of the participant. Participants were instructed not to lean onto the table with their hands since this would help support their upper body weight and use of this strategy during the assembly duration was discouraged by the experimenter. To perform the task, participants used their preferred working posture and they were allowed to alter their posture over time. The task involved essentially zero external forces on the hands and in most plants would be considered to be a low loading job since the trunk was at a mild forward inclination only.

2.3. *Spinal maximum range of motion test*

Participants moved their torso through the maximum range of motion in flexion for spinal movement normalization purposes. The participants started in upright standing, they flexed forward as far as possible aiming to touch the floor and then they returned to upright standing.

2.4. *EMG fatigue test*

EMG fatigue tests were performed while standing with the trunk flexed forward 30° from vertical. The low back was positioned in a lordosis (hollow back). A handle with a length adjustable chain and a 5 kg weight was held in the hands. The end of the chain had to be kept just above the floor to allow for the 30° trunk angle, thereby improving replication of this trunk angle. This static posture, involving sub-maximal loading, was maintained for 5 seconds at the beginning of testing and at set intervals during the task (total of 8).

2.5. *Data acquisition and reduction*

2.5.1. *Biomechanical model*

A biomechanical model (4DWATBAK, University of Waterloo) was used to estimate peak and cumulative spinal loading. A detailed description of the two dimensional version of this model can be found in work by Andrews *et al.* [14] and Norman *et al.* [6]. The model has been "risk validated" meaning that its outputs have been shown to be able to produce an epidemiological estimate of risk of reporting of low back pain [6,8]. Video was used to estimate the trunk flexion angle and guided the positioning of the model's moveable manikin to the body posture obtained during the task. The manikin provided joint coordinate data which, in combination with gender, height and weight of the participants, were used to produce estimates of peak spinal compression force, reaction shear force, joint shear force and extensor moment. Cumulative loading was obtained by extrapolating single estimates, taken at eight set intervals during the one hour task performance, to a 7 ½ hour workday for literature comparison purposes.

2.5.2 *Spinal Kinematics*

The 3SPACE isotrak (Polhemus Inc.) was used to measure spinal kinematics in three dimensions. The 3SPACE is an electromagnetic device and consists of a source which was placed over the sacrum and a sensor which was placed over the spinous process of the 12th thoracic vertebra. The accuracy and viability of the 3SPACE isotrak has been evaluated by McGill *et al.* [15]. The 3SPACE was calibrated to zero in upright standing. Data collection was done for a duration of one minute during the maximum range of motion test and during the one hour task performance at set time intervals (total of eight data collections). A sampling frequency of 20.5 Hz was used.

The angle of spinal curvature in flexion during the maximum range of motion test and during the assembly task were obtained. The angle of spinal curvature in flexion during the assembly task was expressed as a percentage of the maximum range of motion in flexion. The variation in spinal curvature, in flexion, lateral bending and twisting was quantified during the middle 45 seconds of each 55 second period of assembly using the standard deviation.

2.5.3. *Electromyography*

EMG electrodes were placed bilaterally, 3 cm lateral to the 3rd lumbar vertebra representing the lumbar portion of the Iliocostalis Lumborum and 1-2 cm lateral to the 5th lumbar vertebra representing the Multifidus. These muscles support trunk extensor moments about L4/L5. Signals were prefiltered to obtain a bandwidth of 5 to 500 Hz, amplified with a differential amplifier (CMRR 80dB @ 60 Hz) to produce signals between 2 and 8 V and A/D-converted at 1024 Hz.

EMG fatigue test data were used to calculate Mean Power Frequencies (MPF). Each 5 second record was clipped into 10, half second pieces. The MPF of each clipping was calculated and the MPFs of the middle 8 clippings were averaged to obtain 1 MPF per EMG fatigue test. The change in MPF over the task duration was quantified by taking the difference between the MPF obtained before the assembly task was started and the MPF obtained at the end of the task.

2.5.4. *Perceptions of physical demands*

Perceptions of physical demands of the tasks were recorded using two 10 point rating scales; ratings of perceived discomfort and ratings of pain. For the discomfort scale, the zero point was defined as "no perceived discomfort" and 10 was defined as "extreme perceived discomfort". Ratings of perceived discomfort were taken at the beginning and during the assembly task (total of 9). A pain diagram, front and back view of the entire body, was completed before, during and after the assembly task (total of 3). Participants were asked to circle body areas in which pain was felt. Pain experienced in each body part was quantified using a 10 point scale with the zero point defined as "no pain" and 10 defined as "extreme pain".

2.5.5. *Questionnaires*

The Revised Oswestry Pain Questionnaire was completed at the beginning of the testing session. Scores between 0 and 20 are considered minimal disability and between 20 and 40 reflect moderate disability [13]. Individuals with a score exceeding 40 were excluded from the study to reduce the risk of re-injury during the testing session.

A task performance questionnaire was completed at the end of the testing session. The questions addressed the individuals' perceptions of their work posture in terms of whether they altered their work posture over time and why they altered their work posture.

2.5.6. *Measure of productivity*

Participants were instructed to place as many assembly blocks onto a base as could be done comfortably and to maintain this assembly pace for the full one hour task duration. The number of assembly blocks was counted at set time intervals (total of 20) during the one hour task duration to quantify productivity and monitor changes in productivity over time.

2.6. *Statistical analysis*

To determine whether risk factors for low back pain reporting, trunk angle and lumbar curvature were significantly different between students, assembly workers and LBP individuals, a one-way ANOVA was performed and the LSD post hoc test was used. A one-way ANOVA with repeated measures on time was performed to evaluate changes in trunk angle and lumbar curvature over time. Significance of repeated measures was determined using the Greenhouse-Geiser p-values and the degrees of freedom were adjusted using the Greenhouse-Geiser epsilon to account for non-random allocation violation [16]. Paired comparisons were done using the protected least significant difference (protected LSD) [17]. The level of statistical significance was set at 5%.

3. Results

3.1. Reported low back pain

The responses of LBP individuals in this study were compared to those of five students and ten assembly workers who participated in a previous study. The LBP group differed from the comparison group in that most LBP individuals had a recent low back pain episode whereas only few comparison individuals had a recent back pain episode.

Of the comparison group, ten out of 15 women did not report a history of low back pain (Table 1). Two individuals, ID 8 and 11, had had a previous low back complaint but did not experience back pain in the past six months. Three individuals, one student (id 2) and two assembly workers (id 14 and 15), had mild or moderate low back pain in the past six months. Only one individual, ID 17 who did not report a low back pain history, experienced a pain level of 1 in the low back before testing started. None of the students, but all assembly workers had experience with tasks similar to the experimental task.

All except two LBP individuals, ID 43 and 45, experienced low back pain in the past six months (Table 2). None of the LBP individuals reported pain before testing (a 0 on a pain scale from 0 to 10) except participant 42 who rated a pain magnitude of 1 for the low back. Most women were recruited through the Chiropractic Research Clinic at the university and some were recruited through notices posted on the university campus. Diagnosis was available for seven out of nine LBP individuals and a variety of problems from discogenic, facet or myofacial origin were identified (Table 3).

3.2. Quantification of risk factors

The proven and proposed risk factors for low back pain reporting to which the students, assembly workers and LBP individuals were exposed are compared in table 4. Peak spinal loading was low, as was expected, since upper body weight was the only load that had to be supported in this assembly task. Cumulative spinal loading was, however, high due to the constant mild trunk flexion and estimates exceeded control data, individuals who did not report low back pain, and case data, individuals who did report low back pain, obtained during a study in a large automobile assembly plant [6]. Spinal loading was not significantly different between the three groups of participants ($p<0.18$ to $p<0.72$, depending on the mode of loading).

Local muscular fatigue developed as shown by the significant decrease in MPF over the one hour work duration ($p<0.005$ to $p<0.034$, depending on muscle site and participant group). The magnitude of the MPF decrease was not significantly different between the three groups of participants ($p<0.59$ for L3 and $p<0.95$ for L5).

3.3. Trunk angle and lumbar curvature

The trunk angle obtained during the assembly duration was not significantly different between the three groups of participants ($p<0.14$; Table 5). The lumbar curvature, expressed as a percentage of maximum range of motion in flexion, did not differ significantly between the three groups of participants ($p<0.64$). Furthermore, no significant difference between the three participant groups was found for the average change in lumbar curvature during assembly within a work cycle, as measured by the standard deviation in flexion ($p<0.13$), lateral bending ($p<0.12$) and axial twisting ($p<0.31$).

No significant changes over the one hour work duration for the LBP individuals were found in trunk angle ($p<0.30$), angle of lumbar curvature in flexion ($p<0.11$) and the change in lumbar curvature (SD in flexion $p<0.17$, SD in lateral bending $p<0.53$ and SD in axial twisting $p<0.31$).

3.4. Discomfort and pain ratings

The average rating of perceived discomfort of the students was significantly higher than that of the assembly workers ($p<0.039$; Table 6). The average rating of LBP individuals was similar to the high rating of the students but the rating was not significantly higher compared to the assembly workers ($p<0.13$; Table 7). Discomfort ratings differed between individuals ranging from a low 0 to a high 10.

The pain reported for the low back was significantly higher compared to other pain sites for the assembly workers ($p<0.016$; Table 6) and LBP individuals ($p<0.0016$; Table 7). The same trend can be seen for the students. The pain magnitude per location did not differ significantly between the three groups of participants ($p<0.25$ to $p<0.97$, depending on pain location).

3.5. Measurement of productivity

Production rate, measured by the number of assembly blocks that were put onto a base, did not differ significantly between the three groups ($p<0.51$). LBP individuals increased productivity over time from 17.4 to 21.9 blocks per 55 seconds ($p<0.038$), assembly workers increased from 18.2 to 21.1 blocks ($p<0.046$) and students maintained the same assembly pace.

3.6. Task performance questionnaire

Participants were asked to describe if and how they changed their task performance over the work duration and why they changed (Table 8 and 9). The majority of the students, assembly workers and LBP individuals reported a shifting of body weight laterally, from one foot to the other or they leaned to one side. Individuals attributed this change in task performance to discomfort, pain and/or fatigue.

4. Discussion

Participants in this study were selected based on their low back pain history. Students and assembly workers in the two comparison groups would ideally not had had a history of low back pain and the LBP individuals in the current study would ideally had experienced low back pain in the past six months. Finding comparison individuals who had not experienced low back pain and selecting LBP individuals who were in mild or moderate pain only at the time of testing was challenging. Selective recruitment through an employment office, of assembly workers with recent low back pain, was not possible because information regarding the low back pain histories of employees was not available to the employment office. LPB individuals were therefore recruited through a chiropractic clinic with a patient base that consisted mainly of students and university employees who did not have experience with light assembly. Some compromises in participant selection were made and their implications are addressed below.

As a group, the individuals in the current study differed from the students and assembly workers in that all nine individuals had had low back pain and seven out of nine experienced pain in the past six months. For the students, only one out of five individuals, and for the assembly workers, four out of ten individuals, had had low back pain with two of these individuals not experiencing back pain in past six months.

When the two LBP individuals who did not experience low back pain in the past six months were excluded from the analysis, only small changes in the means occurred and the same conclusions could be drawn. Their elimination resulted in a small increase of 0.2 out of 10 in the discomfort rating and average pain rating for the low back. This change was too small to alter differences between the three participant groups.

Conclusions also remained the same when excluding four assembly workers who had had low back pain in the past six months. Elimination of these individuals resulted in an increase in average pain in the low back and an increase in discomfort instead of a decrease as was expected. Exclusion of these four assembly workers made the assembly worker group more comparable to the group of LBP individuals. However, elimination of the one student who has had low back pain in the past six months affected the significant difference in discomfort between the students and assembly workers and the average discomfort of the students was no longer significantly higher compared to the assembly workers ($p<0.12$).

Since exclusion of the individuals discussed above did not alter the findings, except one, these individuals were kept in the main analysis to benefit the sample size. It is important to note that if low back pain was present on the day of testing, this pain would most likely affect the behavior of the participants. Only two individuals, one LBP individual and one assembly worker, experienced mild pain in the low back before testing. None of the other participants reported any pain before testing.

The risk factors for low back pain reporting to which the students, assembly workers and LBP individuals were exposed were similar. Peak and cumulative spinal loading was expected to be similar between the three groups since the same task was performed. Some small differences in spinal loading estimates between the groups can be noted which can be explained by differences in upper body weight.

The magnitude of back extensor muscle fatigue that developed over the one hour task duration was also similar between the three groups. This does not contradict the repeatedly reported differences in spectral measures of the lumbar extensor musculature between back pain patients and individuals without a history of low back pain [18,19,20]. The difference in our findings compared to the literature can be explained by the selection of the patients and muscular activation levels obtained during testing. Discriminant analysis has been done with chronic low back pain patients who had had back pain for a duration exceeding six months, whereas the participants in our study were not chronic. They were recurrent or first time back pain patients recovering or recovered from their recent back pain episode. Furthermore, for discriminant analysis moderate to high muscular activation levels, between 40 to 80 % of MVC, were used, whereas our measures were taken during activity levels below 20 % of MVC, as was determined from EMG in previous work.

The LBP individuals did not alter their trunk posture or lumbar curvature over time more than those who had not had low back pain. Therefore, the first hypothesis was rejected. However, the majority of participants reported a shifting of their body weight side ways, from one leg to the other, to reduce discomfort, pain and/or fatigue. The nature of the task seemed to allow for more room for changes in lateral movement than trunk flexion, possibly due to the set table height. It is thought that changes in posture in flexion-extension should be build into the task because this might allow for more effective postural relief.

Perceived discomfort of LBP individuals did not exceed that of those who had not had low back pain, during the "light" assembly task evaluated in this study. The second hypothesis was rejected. Since perceived discomfort was not significantly different between the three groups this might explain why there was no difference in the amount of trunk and spinal movement between the groups. Movement is thought to be a strategy to reduce discomfort and because LBP individuals did not significantly exceed the discomfort of others, they did not introduce more movement.

However, ratings of perceived discomfort of the LBP individuals were fairly high, 3.2 out of 10, and similar in magnitude to the ratings of the students (3.8). Although the ratings of perceived discomfort of the LBP individuals were not significantly higher than those of the assembly workers (1.4), the tendency of the LBP individuals and the students to perceive the assembly task as more demanding is important. Individuals with high discomfort and pain are more likely to report low back pain, possibly followed by time off work.

In general, production rate and perceived discomfort increased slightly over time indicating that higher discomfort did not result in a decrease in production rate, as was expected. The increase in production rate was most likely due to a learning effect.

The inability to measure any difference between the three participant groups, even when excluding LBP individuals who did not have low back pain in the past six months and comparison individuals who did have LBP in the past six months, might explain why the elimination of these individuals did not alter the findings of our analysis. The responses of individuals within each of the three groups varied widely and, therefore, elimination of a few individuals did not change the response of the entire group.

The responses of LBP individuals to a particular task, in terms of discomfort and pain, might be affected by the location from which the pain originates. Pain from discogenic origin will be aggravated in spinal flexion whereas pain from facet irritation might be alleviated by spinal flexion. The two individuals, ID 41 and 46, with the highest ratings of pain for the low back area were individuals who were diagnosed with low back pain from discogenic origin. Therefore, the assembly task, which involved mild trunk flexion, might have aggravated their complaints and this task is not recommended for these two individuals. However, one individual, ID 47, who was also diagnosed with low back pain from discogenic origin rated a moderate discomfort of 2 which was similar to ratings from individuals with low back pain originating from facet of myofacial origin. These differences in pain between individuals with the same diagnosis might be due to differences in the individuals' perceptions or due to the difficulty involved in determining the underlying problem resulting in an inaccurate diagnosis.

All assembly workers had experience with tasks similar to the "light" assembly task performed in this study. None of the students and LBP individuals, except one, had experience with this type of task. It was noted that assembly workers enjoyed the task more than students and this might have affected their ratings of discomfort and pain. LBP individuals were more similar to the students in that these two groups were both inexperienced with the task and they were almost all recruited from the same population, university students. The average discomfort of the LBP individuals and students was similar and tended to be higher than that of the assembly workers. It is not clear whether the high discomfort ratings of the LBP individuals were due to their back pain history or unfamiliarity with the task as the students were.

5. Conclusions

Individuals who had had low back pain responded similarly to those who had not had low back pain during a 1 hour simulation of a "light" assembly task in terms of changes in trunk posture and lumbar curvature, ratings of perceived discomfort, spinal loading and local muscular fatigue.

The first hypothesis, that individuals who had had low back pain would alter trunk posture and lumbar curvature over time to alleviate discomfort, was not supported by the data. The LBP individuals did not change trunk angle or lumbar curvature more than those who had not had low back pain. This might be explained by the statistical similarity between groups in perceived discomfort.

The second hypothesis, that perceived discomfort of individuals who had had low back pain would exceed that of those who had not had low back pain, was not supported by the data. Perceived discomfort of LBP individuals did not exceed that of those who had not had low back pain, during the "light" assembly task evaluated in this study. However, the tendency of the LBP individuals to perceive the assembly task as more demanding than assembly workers is important. Individuals with high discomfort and pain are more likely to report low back pain, possibly followed by time off work.

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Table 1. Information regarding the low back complaints of the five students and ten assembly workers are presented. No data entry for various participants means that they had not experienced low back pain. One student (id 2) and two assembly workers (id 14 and 15), reported low back pain that occurred in the past six months. Two additional assembly workers reported having experienced back pain previously but they were pain free in the past six months. None of the students but all assembly workers had experience with this type of task.

	Participant ID	2	3	4	5	6	7	8	10	11	12	13	14	15	17	18
How often have you have separate episodes in the last year?	Pain is constant															
	Daily															
	One or more times a week							✓								
	One or more times a month	✓												✓		
	Every 2-3 months															
	Every 6 months or more									✓			✓			
How long was each episode?	Less than 1 hour															
	1 hour to 1 day	✓						✓					✓	✓		
	More than 1 day to 1 week									✓						
	More than 1 week to 1 month															
	More than 1 month to 5 months															
	More than 6 months															
How would you rate your pain or discomfort over the past 7 days?	None							✓		✓			✓			
	Mild	✓												✓		
	Moderate															
	Severe															
	Unbearable															
In the past 6 months, on average, how intense was your pain or discomfort?	None							✓		✓						
	Mild	✓											✓			
	Moderate													✓		
	Severe															
	Unbearable															
Diagnosed	Yes															
	No or not available	✓						✓		✓			✓	✓		
Experience with this task	Yes						✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	No	✓	✓	✓	✓	✓										

Table 2. Details regarding the low back complaints of LBP individuals are presented. The frequency, duration, pain magnitude, availability of diagnosis, Revised Oswestry Pain Questionnaire score and experience with the task are shown. All, except two individuals (id 43 and 45), reported low back pain that occurred in the past 6 months. Only one individual had experience with this type of task.

	Participant ID	40	41	42	43	44	45	46	47	48
How often have you have separate episodes in the last year?	Pain is constant									
	Daily									
	One or more times a week			✓						
	One or more times a month									✓
	Every 2-3 months		✓				✓	✓	✓	
	Every 6 months or more	✓			✓	✓				
How long was each episode?	Less than 1 hour									
	1 hour to 1 day					✓				
	More than 1 day to 1 week		✓	✓	✓			✓	✓	✓
	More than 1 week to 1 month	✓					✓			
	More than 1 month to 5 months									
	More than 6 months									
How would you rate your pain or discomfort over the past 7 days?	None	✓			✓	✓	✓	✓		
	Mild		✓	✓					✓	✓
	Moderate									
	Severe									
	Unbearable									
In the past 6 months, on average, how intense was your pain or discomfort?	None				✓		✓			
	Mild	✓	✓			✓				✓
	Moderate							✓	✓	
	Severe			✓						
	Unbearable									
Diagnosed	Yes		✓	✓	✓		✓	✓	✓	✓
	No or Not available	✓				✓				
Revised Oswestry Pain Questionnaire (out of 100)		16	8	40	8	4	0	14	20	12
Experience with this task	Yes		✓							
	No	✓		✓	✓	✓	✓	✓	✓	✓

Table 3. Diagnosis was available for seven out of nine LBP individuals. All were diagnosed with mechanical low back pain and their specific information is presented below.

Participant id	Diagnosis provided by health care professional
41	Mechanical low back pain: discogenic, lumbar
42	Mechanical low back pain: acute L5 facet irritation and sacroiliac syndrome on the right
43	Mechanical low back pain: myofacial origin; quadratus lumborum and erector spinae
45	Mechanical low back pain: sacroiliac syndrome; quadratus lumborum hypertonicity
46	Mechanical low back pain: discogenic, lumbar
47	Mechanical low back pain: discogenic, lumbar
48	Mechanical low back pain: quadratus lumborum strain

Table 4. The risk factors to which LBP individuals were exposed were compared to those of students and assembly workers (mean and standard deviation). Estimates of peak and cumulative spinal loading and muscular fatigue (MPF) did not differ significantly between the three groups of participants. Fc = spinal compression force; Fsj = joint shear force; Fsr = reaction shear force; M = extensor moment.

Measure		Students; (n=5)	Assembly workers; (n=10)	Individuals who had had low back pain; (n=9)
Peak Fc (N)		1178 (158)	1111 (164)	1069 (219)
Peak Fsj (N)		165 (177)	163 (134)	120 (89)
Peak Fsr (N)		180 (36)	161 (24)	149 (29)
Peak M (N m)		56 (10)	51 (8)	49 (11)
Cum Fc (MN s)		29.9 (4.0)	28.2 (4.2)	27.1 (5.6)
Cum Fsr (MN s)		4.5 (0.9)	4.0 (0.6)	3.7 (0.8)
Cum M (MN m s)		1.4 (0.2)	1.3 (0.2)	1.2 (0.3)
MPF (Hz)	L3	- 4.3 (5.0)	- 6.3 (4.2)	- 5.4 (4.9)
	L5	- 8.1 (8.6)	- 6.7 (4.9)	- 9.2 (8.3)

Table 5. No significant differences between the three groups of participants in trunk angle and lumbar curvature measures (lumbar curvature as a percentage of maximum range of motion and standard deviation in flexion, lateral bending and twisting) were found during the assembly duration. The mean and standard deviation are shown.

Measure	Students; (n=5)	Assembly workers; (n=10)	Individuals who had had low back pain; (n=9)
Trunk angle (°)	36.5 (8.2)	32.9 (4.3)	30.4 (4.3)
Lumbar curvature (% of ROM)	48.0 (20.9)	56.0 (18.2)	50.5 (12.6)
Change in flexion, SD (°)	1.0 (0.3)	0.9 (0.3)	1.4 (0.8)
Change in lateral bending, SD (°)	0.8 (0.4)	0.7 (0.4)	1.1 (0.5)
Change in twisting, SD (°)	0.7 (0.3)	0.6 (0.3)	0.9 (0.4)

Table 6. The magnitude of perceived discomfort ratings are presented for each student (id 2 through 6) and assembly worker (id 7 through 18) as well as the mean value per group is shown. Discomfort, developed over the one hour work duration, ranged from 0 to 6 between individuals. The pain magnitude reported for the low back was significantly higher compared to other pain sites for the assembly workers (p<0.016). For the students the pain ratings for the low back tended to be higher compared to pain rated for other sites (p<0.088).

Participant id	2	3	4	5	6	avg (sd)	7	8	10	11	12	13	14	15	17	18	avg (sd)
Discomfort	6	1	5	1	6	3.8(2.6)	2	2	1	1	0	5	1	0	2	0	1.4(1.5)
Pain Location																	
Shoulder	0	1	0	0	0	0.2(0.4)	5	0	0	0	0	0	0	0	0	0	0.5(1.6)
Neck	0	0	0	0	7	1.4(3.1)	0	0	0	0	0	0	0	0	0	0	0.0(0.0)
Upper Back	0	2	0	1/2	0	0.5(0.9)	0	0	0	0	0	0	0	0	0	0	0.0(0.0)
Lower Back	*6*	*0*	*7*	*1/2*	*6*	*3.9(3.4)*	*5*	*2*	*0*	*1*	*0*	*4*	*0*	*0*	*4*	*0*	*1.6(2.0)*
Thigh, Post.	0	0	0	0	0	0.0(0.0)	0	0	0	1	0	0	0	0	0	0	0.1(0.3)
Knee, Post.	0	2	5	0	0	2.6(2.8)	6	0	0	0	1	0	0	0	0	0	0.1(0.3)
Feet	0	0	4	0	0	0.8(1.8)	4	0	1	0	0	4	0	2	0	0	1.1(1.7)

Table 7. The change in discomfort over one hour task duration is shown and a large difference between individuals, ranging from 0.5 to 10, can be seen. The pain magnitude reported for the low back location was significantly higher compared to pain ratings at other sites (p<0.0016).

Participant ID	40	41	42	43	44	45	46	47	48	avg (sd)
Discomfort	2	5	0.5	3	2	1.5	10	2.5	2	3.2 (2.8)
Pain Location										
Shoulder	0	0	0	0	0	0	7	0	0	0.8 (2.3)
Neck	0	1	0	0	1.5	4	9	0	0	1.7 (3.0)
Upper Back	0	0	0	0	0	0	0	3	0	0.3 (1.0)
Lower Back	*2*	*5.5*	*2.5*	*3*	*2*	*1*	*7*	*2*	*2*	*3.0 (2.0)*
Knee, Posterior	2	0	0	0	0	0	1	0	0	0.3 (0.7)
Feet	0	0	0	3	0	0	0	0	0	0.3 (1.0)

Table 8. Task performance data for students and assembly workers is presented. Eight out of 15 individuals reported to shift weight between legs and three out of 15 leaned to one side. Nine out of 15 contributed this change in task performance to discomfort, pain and/or fatigue.

Participant ID	Did you notice any change in the way you performed the task over the 1 hour duration?	Why did you change the way you performed the task?
2	Shift weight from side to side, hunch forward	Fatigue, discomfort
3	Increased movement side to side, curved spine	Discomfort, fatigue
4	Changed weight from left to right foot	Muscle pain
5	Leaned to the left side	Uncomfortable
6	Leaned to the right and moved more	Pain, foot numb
7	No	N/A
8	Shifted weight between legs	Fatigue, habit
10	No	N/A
11	Shifted weight to right leg	dull ache in left hip
12	No	N/A
13	Switched weight back and forth between feet	discomfort
14	Shifted weight from foot to foot	Boredom
15	Moved side to side	No reason reported
17	Shifted weight to left side	Discomfort
18	Raised body (up-down movement)	Boring

Table 9. The task performance questionnaire was completed after the one hour task duration. Six out of nine LBP individuals described a shifting of body weight from one foot to the other and one individual leaned to one side. Six out of nine LBP individuals reported a change in their task performance due to muscular discomfort or fatigue.

Participant ID	Did you notice any change in the way you performed the task over the 1 hour duration?	Why did you change the way you performed the task?
40	Sometimes supported weight on 1 hand	Muscular discomfort
41	Bend one knee, alternated periodically	Muscular discomfort
42	Shifted weight to the left	Muscular discomfort and tiredness
43	Positioned weight on one foot, then the other	Feet were hurting
44	No	N/A
45	Put weight on one foot and then the other	Boredom
46	Avoided trunk flexion, moved from side to side	Muscular fatigue, boredom
47	Bent over more, moved feet and spinal posture	Muscular discomfort, tightness
48	Transferred weight between feet	Boredom, fatigue