MUSCULOSKELETAL DISORDERS AND WHOLE-BODY VIBRATION EXPOSURE
among professional drivers of all-terrain vehicles

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En vibration är en rörelse som inte vet åt vilket håll den ska gå.

Rune 8 år
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ABSTRACT

Musculoskeletal disorders are common among professional driver groups. Ergonomic risk factors at work are often suggested as causative, aggravating or preserving. The general aim with this thesis is to investigate the association between musculoskeletal disorders and physical exposure with special focus on whole-body vibration (WBV), among professional drivers of all-terrain vehicles (ATVs). Drivers of ATVs are exposed to high WBV magnitude and shock. The thesis included drivers of forest machines, snow groomers and snowmobiles. A cross-sectional study revealed that ATV drivers had an increased risk for musculoskeletal symptoms in the neck-shoulder and thoracic regions, even after adjusting for age, smoking habits and psychosocial stress. Prevalence rates were within the range of 1.5-2.9 (CI: 1.2-5.2) compared to an age-matched group from the general population. No group of ATV drivers had a significantly increased risk of low back pain. Trend analysis showed no association between symptoms and exposure time. A clinical investigation of a subgroup found that it was common for ATV drivers with neck pain to have asymmetrical and focal neuropathies, pure or in a mix with a nociceptive disorder, in the neck and upper extremities (47-79%), which was in contrast to referents with neck pain who had more nociceptive disorders (27% prevalence of neuropathy). Two studies investigated characteristics of seated WBV exposure in forest machines (forwarders), snow groomers and snowmobiles. The magnitudes of WBV in ATVs, measured and analyzed according to ISO 2631-1, were between 0.5-3.5 m/s² (frequency weighted vector sum), which was considered high compared to limits suggested by the international standard ISO 2631-1 and the physical agents directive from the European Union (action value - 0.5 m/s² rms). Drivers of the ATVs were exposed to horizontally directed WBV and considerable shocks. Non-neutral neck positions are ergonomic risk factors that occurred infrequently and with short duration. The magnitude of seated WBV in forwarder vehicles varied substantially depending on the model, terrain condition and driver. This may result in different conclusions regarding health risk assessments. The main conclusion from this thesis is that musculoskeletal symptoms and disorders in the neck and upper extremities, among drivers of ATVs, may be a result of long-term exposure to shock-type and horizontally oriented seated WBV.

Keywords: Whole-body vibration, Shock, Ergonomics, Epidemiology, Musculoskeletal, Driver
Besvär i rörelseorganen är vanligt förekommande bland yrkesförare. Speciellt drabbade kroppsrutor är ländrygg, nacke och skuldror. Ofta föreslås ergonomiska orsaker i arbetet som utlösende, förvärrande eller bidragande faktorer till besvär. Huvudsyftet med den här avhandlingen är att undersöka förhållandet mellan besvär i rörelseorganen och exponering för fysiska faktorer i arbetet, med fokus på helkroppsvibrationer (HKV) hos yrkesförare av terrängväsende fordon såsom skogsmaskiner, pistmaskiner och snöskotrar. Förrasatt för terrängväsende fordon utsätts för höga nivåer av vibrationer som innebär stötar och slag. Detta beror delvis på det ojämna underlag vilket fordonet framför på. En tvärsnittsstudie visade att yrkesförare av terrängväsende fordon har ökat risk för besvär i nacken, skuldrorna och bröstryggraden, vilket inte kunde förklaras av ålder, rökvanor eller psykosocial arbetsbelastning. Oberoende av förarkategori varierade relativ risker för besvär mellan 1.5-2.9 (KI: 1.2-5.2) i jämförelse med en kontrollgrupp utan exponering. Ingen av förargrupperna hade någon signifikant ökad risk för symptom i ländryggraden. Sambandet mellan symptom och exponeringstid var generellt svagt. En klinisk studie av en subgrupp fann att det var vanligt att yrkesförare med besvär i nacken hade besvär av neurogen typ (47-79 %) i nacken och övre extremiteter. Detta skilde sig i jämförelse med en kontrollgrupp med besvär i nacken, vilka oftare hade besvär i rörelseorganen av nociceptiv typ (27 % neuropati). Två studier fokuserade på fältmätningar av exponeringssituationen gällande ergonomiska förhållanden för att framförallt karaktärisera HKV i skogsmaskiner (skotare), pistmaskiner och snöskotrar. Resultatet från fältmätningarna visade att den frekvensvägda vektorsumman, mätt och analyserad enligt ISO 2631-1, varierade mellan 0.5-3.5 ms², vilket för de flesta fordon innebar att de översteg det föreslagna gränsvärdet för länder inom den Europeiska Unionen (0.5 ms² r.m.s). Även föreslagna gränsvärden från ISO 2631-1 överskred för flertalet av fordonen. Den dominanta vibrationsriktningen varierade för olika typer av fordon vilket ansågs bero på fordonets konstruktion och på den arbetsuppgift som fordonet skall utföra. Alla fordon hade dock betydande nivåer av horisontellt riktade HKV med betydande inslag av stötar. En icke-neutral position av nacken är en ergonomisk riskfaktor i förarmiljöer.
som var av låg förekomst hos dessa förargrupper. Nivån av helkroppsvibrationer i skotare kan variera anmärkningsvärt mycket, beroende på maskintyp, terrängförhållanden och förare vilket påverkar hälsoriskbedömningar. Den generella slutsatsen av undersökningarna i denna avhandling är att symptombildan gällande musculoskeletala besvär i nacke och övre extremiteter för förare av dessa terränggående fordon kan vara ett resultat av lång tids exponering för höga nivåer av horisontellt riktade HKV med inslag av stötar och slag.

Nyckelord:  Helkroppsvibrationer, Stötar, Slag, Ergonomi, Epidemiologi, Muskuloskeletal, Förare
# ABBREVIATIONS AND SYMBOLS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ATV</td>
<td>All-terrain vehicle</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>CI</td>
<td>Confidence interval</td>
</tr>
<tr>
<td>d.o.f.</td>
<td>Degree(s)-of-freedom</td>
</tr>
<tr>
<td>eq.</td>
<td>Equation</td>
</tr>
<tr>
<td>HAV</td>
<td>Hand-arm vibration</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>ISO</td>
<td>International standard for organization</td>
</tr>
<tr>
<td>MTVV</td>
<td>Maximal transient vibration value</td>
</tr>
<tr>
<td>n.s.</td>
<td>Not significant</td>
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<tr>
<td>PEO</td>
<td>Portable ergonomic observational method</td>
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<tr>
<td>PRR</td>
<td>Prevalence rate ratio</td>
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<tr>
<td>r.m.s.</td>
<td>Root mean square</td>
</tr>
<tr>
<td>UEMSD</td>
<td>Upper extremity musculoskeletal disorders</td>
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<td>WBV</td>
<td>Whole-body vibration</td>
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<tr>
<td>WMSDs</td>
<td>Work-related musculoskeletal disorders</td>
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<tr>
<td>VDV</td>
<td>Vibration dose value</td>
</tr>
<tr>
<td>x</td>
<td>Vibration direction, back to front, back-and-forth</td>
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<tr>
<td>y</td>
<td>Vibration direction, right to left, lateral</td>
</tr>
<tr>
<td>z</td>
<td>Vibration direction, seat to head, vertical</td>
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DEFINITIONS

Bias Any trend in the collection, analysis, interpretation, publication, or review of data that can lead to conclusions that is systematically different from the truth.

Confounder A variable that is associated with both the outcome of the variable interest and a primary independent variable or risk factor. (Without being a consequence of the exposure factor).

Cross-sectional study A study of the association between disease and other variables among a population at a certain point in time. Often the prevalence is specified, not the incidence.

Degrees of freedom The minimum number of independent generalized coordinates required defining completely the configuration of the system.

Disorder Derangement or abnormality of function; a morbid physical or mental state. Disorder is a more vague condition compared to disease.

Disease Any deviation from the normal structure or function of any part, organ, or system of the body that is manifested by a characteristic set of symptoms and signs.

Dose A measure of exposure built on the intensity of exposure and its distribution over time. For vibration in vehicles; acceleration magnitudes and exposure duration.

Exposure-effect The biological change in an individual caused by an exposure. When the numerical values for both exposure and outcome are known, the relationship can be calculated.

Exposure-response The proportion of an exposed population having values showing an abnormal effect (fulfilling predefined case criteria).
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<tr>
<th>Term</th>
<th>Description</th>
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<tr>
<td>Mechanical impedance</td>
<td>The force transmitted from the seat to the body divided by the vibration velocity. The impedance reaches a peak at resonance.</td>
</tr>
<tr>
<td>Nociceptive pain</td>
<td>Sensation of pain caused by noxious stimulation of nociceptors.</td>
</tr>
<tr>
<td>Neurogenic pain</td>
<td>Sensation of pain caused by damage to, or dysfunction in, the peripheral or the central nervous system.</td>
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<tr>
<td>Non-neutral position</td>
<td>Refers to positions of the joints. A neutral position is within the normal physiologic range of movement for the respective joint.</td>
</tr>
<tr>
<td>Posture</td>
<td>The position of the body, body segment(s), or joint(s).</td>
</tr>
<tr>
<td>Resonance</td>
<td>Resonance occurs when the oscillation of the body is much greater than the input. Also referred to as natural frequency.</td>
</tr>
<tr>
<td>Shock</td>
<td>A sudden change of force, position, velocity, or acceleration that excites transient disturbances in a system.</td>
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<tr>
<td>Signs</td>
<td>Objective pathological findings from a clinical investigation of specific tissues (In this case the musculoskeletal system).</td>
</tr>
<tr>
<td>Symptoms</td>
<td>Subjective feeling of a functional disturbance in the musculoskeletal system. Usually musculoskeletal symptoms are felt like ache, pain, fatigue or discomfort.</td>
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<tr>
<td>Syndrome</td>
<td>A symptom complex, where special symptoms and clinical findings occur together, to a larger extent than what could be expected by random.</td>
</tr>
<tr>
<td>Transmissibility</td>
<td>The ratio of output acceleration to input acceleration. At resonant frequency, the acceleration transmissibility (hence the motion) will be greatest.</td>
</tr>
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ORIGINAL PAPERS

The present thesis is based on the following papers, which will be referred to by their Roman numerals:


IV Rehn B, Lundström R, Nilsson L, Liljelind I, Järvholm B. Variation in exposure to WBV for operators of forwarder vehicles - aspects on measurement strategies and prevention (manuscript).

Reprints were made with the kind permission of the publishers.
THESIS AT A GLANCE

Paper I

**Question:** Does professional drivers of ATVs have an increased risk of musculoskeletal symptoms in the neck, shoulders, upper- and lower back?

**Method:** Cross-sectional study. A questionnaire was sent to professional drivers of snowmobiles, snowgroomers and forest machines and also to a control group from the general population.

**Evaluation methods:** Standardized Nordic Questionnaire (SNQ), prevalence ratios adjusted for age, smoking habits and job strain (Karasek’s demands/control model). Totally 431 drivers and 167 controls were included in the analysis.

**Results:** Among drivers, significantly increased prevalence ratios within the range of 1.5-2.9 were revealed for symptoms from the neck, shoulder and thoracic regions during the previous 12 months. There was however not an increased risk of symptoms from the lower back.

**Conclusion:** Drivers have an increased risk for musculoskeletal symptoms in the neck, shoulder and thoracic region. The drivers didn’t have an increased risk of low back pain, it appears that other factors than WBV exposure could explain the occurrence of symptoms among ATV drivers, however not age, smoking or job strain.

Paper II

**Question:** What are the characteristic features of WBV exposure among professional drivers of various ATV types and how frequent are the drivers' cervical spine is positioned in a non-neutral rotational position during operation?

**Method:** Field measurements to access exposure during ordinary occupational use of snowmobiles, snowgroomers and forwarders, totally 19 vehicles.

**Evaluation methods:** Seated WBV was measured according to the international standard ISO 2631-1. Simultaneous recordings of frequency and duration of rotational neck movements exceeding 15 degrees were achieved through an observational method, PEOflex®.

**Results:** The vibration total values of weighted r.m.s.-acceleration varied between 0.5-3.5 ms⁻², which for most vehicles meant that they exceeded the action value stated by the European Union (0.5 ms⁻²r.m.s.). Frequency and duration of non-neutral rotational neck postures were considered low for all driver categories.

**Conclusion:** Vibration magnitudes in ATVs are considerably high when compared to the European Unions action value and to the health guidance caution zones in ISO 2631-1. The dominant vibration direction varies, but all vehicle types have a high influence of vibration, containing shocks, in horizontal directions. Non-neutral rotational positions of the neck are ergonomic risk factors that occur infrequently and with short duration for professional drivers of ATVs such as snowmobiles, snowgroomers and forwarders.
Page III

**Question:** Does cases with neck pain among professional drivers of ATVs have a different array of neuromusculoskeletal disorders compared to cases with neck pain in a referent group without exposure to WBV generated from driving ATVs?

**Method:** Cross-sectional case-case study of 45 ATV drivers and 15 referents.

**Evaluation methods:** Based on anamnesis, symptoms and signs, and in some cases chemical, electroneurographical and radiological findings, subjects were classified as having a nociceptive or neuropathic disorder or a mix of these types.

**Results:** The occurrence of asymmetrical and focal neuropathies, pure or in combination with a nociceptive disorder was common among cases in the ATV driver groups, which contrasted to the referent group who had more nociceptive disorders.

**Conclusion:** It is proposed that pain in the neck and upper extremities, clinically diagnosed as asymmetrical and focal neuropathies, among drivers of ATVs, may be a result from the typical exposure to shock-type seated WBV and unfavorable driving postures.

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Page IV

**Question:** What is the variation of seated WBV exposure among operators of forwarder vehicles and what are the sources for this variation? How will variation affect health risk assessments?

**Method:** Repeated field measurements of seated WBV in forwarders during occupational work.

**Evaluation methods:** WBV exposure was measured according to the international standard ISO 2631-1 for 7 forwarders operated by 11 drivers in 10 various terrain types.

**Results:** Exposure to seated WBV varies substantially which can result in different conclusions regarding health risk assessments. The highest magnitudes were achieved for travel activities. Forwarder model, terrain condition and driver were all influencing factors for the variation.

**Conclusion:** Measurement strategies should involve several conditions for the respective vehicle and driver. WBV exposure should be analyzed by both r.m.s.-magnitude and VDV. Reducing WBV magnitude can be achieved by selecting another model, modify the way the machine is driven and operate on easier terrain type.

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The committee of ethics, Umeå University has reviewed the studies included in this thesis (dnr. 98-442 & dnr. 00-241).
INTRODUCTION

Musculoskeletal disorders are frequent among populations in many industrialized countries (Hagberg et al 1995, Buckle & Devereux 1999, Lagerlöf 2000). In Sweden, the majority of all work-related illness constitute of musculoskeletal disorders (AFS 1998:1), which is also the most common reason for sick leave and disability pension (Statistics Sweden 2003, Folkhälsofarppot 2001, RFV 2003). Pain, fatigue and discomfort in the locomotor system are the first and most common symptoms associated with musculoskeletal disorders (Hagberg et al 1995). Musculoskeletal disorders associated with work applies particularly to neck, shoulder and lower back regions of the body (Buckle & Devereux 1999) and involve human suffering and extensive economical consequences for the individual, employer and society in the form of medical care, sick-leave and early retirement pension (SBU 2000, Buckle & Devereux 1999). Research can rarely explain why or how musculoskeletal pain in the lower back or neck arise, or how long musculoskeletal pain will persist, i.e. if pain is acute, passing or will remain as a chronic problem (SBU 2000). Although musculoskeletal disorders are recognized as being a result of multifactorial origin, ergonomic factors at work are usually suggested as causing, preserving or aggravating musculoskeletal disorders (Ariëns et al 2000, van der Windt et al 2000) and the term work-related musculoskeletal disorders (WMSDs) is therefore often used (WHO 1985, Hagberg et al 1995). It has been proposed that the problems related to WMSDs will increase since workers are becoming more exposed to work place risk factors that affect the disorders (Buckle & Devereux 1999). Hence, WMSDs constitutes a major health problem in the modern society and research is essential towards a better understanding of the relationship between risk factors at work and WMSDs, i.e. exposure and response, so that preventive actions can be suggested based on a scientific knowledge base.

Several epidemiological studies show that professional drivers of various earth moving vehicles have increased risks for musculoskeletal symptoms and disorders in the lower back, neck and shoulders, see review by Griffin (1990). Thus, drivers have musculoskeletal problems in the same anatomical body regions as other professions at
risk for WMSDs though the exposure situation is different, i.e. drivers are exposed to whole-body vibration (WBV) and other occupational groups are generally not. It seems as if these body regions are more susceptible for WMSDs than other body regions. It is however close to suspect exposure to WBV as a risk factor among drivers since several studies have indicated an association between exposure to WBV and musculoskeletal symptoms and disorders, preferably in the lower back (Bovenzi & Hulshof 1998). The driver seats in many earth moving vehicles vibrate at a frequency close to the natural frequency of the spine, which may serve as a reason for spinal damage (Wilder 1993). Further, it is evident that WBV can have the function as a mechanical load, although oscillating, resulting in biomechanical forces acting on and in various regions of the body, depending on the location of input and body posture.

Compared to other earth moving vehicles, terrain vehicles can qualitatively be regarded as bumpy because they operate in irregular off-road surfaces. This should result in exposing the driver to WBV that contains shocks, which may apply to horizontal vibration directions as well. It is hypothesized that terrain vehicles have higher magnitudes of vibration compared to vehicles operating on roads. Research has shown that when evaluating the effects of WBV on the human being the following five variables are of major importance; magnitude, frequency, direction, duration and variation with time (Wikström 1994). These characteristics are also used in the international standard for measuring and judging exposure to WBV, ISO 2631-1 (ISO 2631-1 1997). The WBV exposure situation, potentially harmful for drivers of terrain vehicles, should therefore be considered as typical and possibly distinct from that of drivers of other vehicle types.

The quantitative characteristics of vibration generated by terrain vehicles and its consequences for the human being is vaguely described, although some older studies indicate high levels of vibration in several directions and high prevalence of musculoskeletal symptoms (see chapter ‘Epidemiological studies on drivers of ATVs’). Therefore further research is necessary about details of musculoskeletal disorders and WBV and the conceivable association between them.

This thesis is an epidemiological approach that focuses on musculoskeletal symptoms and disorders as response and primarily WBV as exposure, among professional drivers of various terrain vehicles.
Work-related musculoskeletal disorders in epidemiological studies

Scope and occurrence of symptoms and disorders

Musculoskeletal disorders affect over 40 million European workers, which is more than 30% of the workforce. Estimates in various member states such as in the Nordic countries suggest that the total cost of WMSDs may vary between 0.5 %-2 % of the Gross National Product (Ringelberg & Koukoulake 2002, Toomingas 1998). In the United States conservative estimates of the economic burden due to musculoskeletal disorders are between $ 45 and $ 54 billion annually (NRC 1999).

The prevalence of self-reported neck and upper limb disorders varies between 14-46% within the European countries (Buckle & Devereux 1999). International reports about low back pain report point prevalence to 15-30 %, the one-month period prevalence to 19-43 % and the life time prevalence to 60-85 % (SBU 2000, Andersson 1999).

From ongoing statistical surveillance it is shown that the number of professional drivers in Sweden that report work-related health problems during the past 12 months from the neck, shoulders and lower back are 6.0 %, 9.3 % and 15.0 % respectively (Statistics Sweden 2003). The prevalence has increased slightly since earlier registrations (Statistics Sweden 2002) and is relatively high compared to other working groups dominated by men but not solely employed as drivers.

The exact extent of the problem with musculoskeletal symptoms and disorders is however difficult to establish because definitions, diagnostic criteria, and official statistics are rarely comparable from country to country (Armstrong et al 1993).

Some aspects on terminology and causes

Musculoskeletal refers to muscles, tendons, ligaments, joints, peripheral nerves and supporting blood vessels (Punett & Gold 2003). As a suggestion, the right appellation should however be neuromusculoskeletal since a large number of the defined disorders involve symptoms and signs, which applies especially to functional disturbances in the peripheral or central nervous system.
Sometimes musculoskeletal symptoms and musculoskeletal disorders are used synonymously in the literature. Musculoskeletal symptoms defined in this thesis refers to the subjective feeling of a functional disturbance usually felt as ache, pain, fatigue and discomfort in the musculoskeletal system (Hagberg et al 1995). A musculoskeletal disorder is defined more strictly and besides from subjective symptoms also tested by more objective methods to verify any derangement or abnormality (structural changes) of a tissue (pathology) or any functional disturbance for the musculoskeletal system that may cause the symptoms usually designated as signs (summarized by Toomingas 1998). Kilbom and coworkers defined work-related musculoskeletal disorders as a wide range of inflammatory and degenerative diseases and disorders that result in pain and functional impairment (Kilbom et al 1996). Diagnostics in epidemiological studies are usually proxies compared to diagnostics in clinical settings, where more invasive methods are used for confirmation of specific disorders (Toomingas 1998). Such proxies are “symptom diagnoses” based on symptoms alone or “syndromes” based on information on both symptoms and signs. For the neck and lower back, unspecified symptoms reported in questionnaires have been used as indicators for disorders and differentiated between radiating or non-radiating pain (Riihimäki 1991, Viikari-Juntura & Riihimäki 1999). For WMSDs in the neck and upper extremities there are a number of synonymous terms referring to how the disorder was achieved such as repetitive strain injuries (RSI), cumulative trauma disorders (CTD) and occupational cervico-brachial disorders (OCD) (Hagberg et al 1995). Use of these terms for disorders in the neck and upper extremities has been criticized because they suggest pathological mechanisms that are usually not proved (Hagberg 1996).

Work-related indicates that the disorder have some relation to work. The World Health Organization (WHO) stated that musculoskeletal disorders should be characterized as “work-related diseases” rather than as “occupational diseases” (WHO 1985). According to the definition by WHO work-related illnesses or diseases might by caused by, aggravated, accelerated or exacerbated by workplace exposures (Panel on musculoskeletal disorders and workplace 2001). An occupational disease is defined as a disease for which there is a direct cause-effect relationship between hazard and
disease, i.e. one causal risk factor (e.g. asbestos – asbestosis) (Armstrong et al 1993).

It is also practical to distinguish musculoskeletal disorders from musculoskeletal accidents with the former being a result from long-term exposure and the latter can be a result from an unexpected incident. A work-related disorder may however also be caused by a single strain or trauma, not necessarily a repetitive or cumulative one (Hagberg 1996).

Musculoskeletal disorders have a multifactorial origin due to several potential causative and contributing factors (WHO 1985, Hagberg et al 1995) and can therefore not directly be regarded as an occupational disease. The risk factors can be classified as either physical, psychosocial or individual and not all factors are related to work (Fredriksson et al 1998). Interaction is likely between various factors and the knowledge about interaction must be considered most limited.

**Physical work factors**

Exposure to seated WBV in a vehicle is inherently associated with other ergonomic risk factors for musculoskeletal disorders. For that reason, it is difficult to identify one single causal factor for drivers (Bovenzi & Hulshof 1998, Magnusson & Pope 1996, Magnusson & Pope 1998). For low back pain ergonomic risk factors such as lifting, carrying loads, twisting, bending and stooped positions of the trunk have been suggested as contributing or modifying (Burdorf & Sorock 1997, Hoogendoorn et al 1999, Wilder 1993). In a review, Magnusson and coworkers summarized awkward working postures common for several groups of drivers (Magnusson et al 1996). They proposed the following risk factors for neck and shoulder pain; i) extreme forward flexion of the cervical spine ii) static contraction of the neck and shoulder muscles to counteract for the weight of the head (due to forward flexion of the cervical spine), iii) elevated arms. and iv) twisted or bent working postures (Magnusson et al 1996). Other studies have shown that prolonged seating may cause neck and shoulder symptoms (Ariëns et al 2000, Fredriksson et al 2002, van der Windt et al 2000). Thus, the total mechanical exposure situation for professional drivers should be looked upon as a combination of both vibration and posture.

Postures and movements can be hazardous and present a risk if they are awkward and strenuous and performed over a long period.
To prevent musculoskeletal disorders, it is important that working postures are such that joints move in a small range of their possible mobility, close to what is called “neutral position of specific joint” (EN 2001). This thesis focused particularly in postural load of the neck since this risk factor had been highlighted in an earlier study (Eklund et al 1994) and since a lot of the work for ATV drivers was believed to involve awkward postures of the neck.

Besides exposure to ergonomic risk factors, also other physical environmental factors, relevant for various driver groups, can influence physiological responses such as noise, climate and light (Winkel J et al 1998, Virokannas & Anttonen 1994, Hildebrandt et al 2002).

**Psychosocial work factors (Non-physical)**

There has been an increasing awareness of the impact of psychosocial work factors as such has proved to have a significant effect for developing musculoskeletal disorders (Lundberg et al 1999, Sjögaard et al 2000, Ariëns et al 2001). Some studies have shown that a poor psychosocial work environment includes high demands and little influence on the work situation and creates risk factors of equal importance as physical factors (Bongers 1993, Malchaire 2001, van der Windt et al 2000). Physical and psychological risk factors at work may also interact and increase the risk for musculoskeletal disorders (Devereux et al 1999, 2002).

It has generally been assumed that psychosocial work factors may induce muscle tension and thus form a link to musculoskeletal disorders. This tentative psychobiological association is supported by several authors according to Lundberg & Johansson (1999).

Most studies on the psychosocial work factors among professional driver groups have concerned cardiovascular diseases (e.g. Belkic et al 1994). There are though a few studies that have indicated the importance of psychosocial work factors on the incidence and perception for low back pain among professional drivers (Krause et al 1997, Magnusson et al 1996). In a large study of 1449 urban transit drivers, Krause et al (1997) reported that high psychological demands and job dissatisfaction were most strongly correlated with reported spinal injuries. Magnusson et al (1996) reported that high stress and job dissatisfaction were significantly correlated with the amount of sick leave. Less is known about the relationship between psychosocial
work factors and musculoskeletal disorders other than that of the lower back for professional driver groups.

**Individual factors**

Overall, individual factors have received most scientific attention compared to physical and psychosocial work factors. In the textbook *Work related musculoskeletal disorders (WMSDs): a reference book for prevention* (Hagberg et al 1995), the authors summarizes individual factors important for musculoskeletal disorders. The authors concluded that evidence exists only for a few factors such as age, smoking, inflammatory disorders and diabetes although other factors were discussed as anthropometry, gender, anatomical differences, tissue type, alcohol, personality, psychiatric disorders, neuromuscular and metabolic diseases. A review on personal risk factors for low back pain also concluded that age and smoking are important variables together with injury history, relative strength and gender (Dempsey et al 1997). Overwhelmingly, most occupational drivers are men. Thus, this thesis focuses on the male population of drivers and doesn’t cover a gender perspective. Anthropometry has not been distinguished as an important risk factor but is probably important in a vehicle since space can be restricted.

**Age**

The risk for most musculoskeletal disorders increases with increasing age up to 55-59 years of age (AMV 1998, Kilbom et al 1996). The decline in the oldest age group is probably a result of early retirement among those with heavy physical jobs (AMV 1998).

**Smoking**

The association between smoking and back pain is consistent throughout many epidemiological studies. Yet it is by far too weak to be the only risk factor (Ernst 1993). Various hypotheses on the pathomechanisms have been discussed such as accelerated degeneration at all levels of the lumbar spine due to nicotine reduced blood flow and smoke-induced coughing causing mechanical strain (Ernst 1993, Kilbom et al 1996).
Whole-body vibration (WBV)

Vibration is an oscillatory motion. The motion is by definition not constant but alternately greater and less than the average value (Griffin 1990). Vibration in a vehicle enters the driver’s body via the seat and makes the whole-body shake - whole-body vibration (WBV). Sometimes the term ‘seated WBV’ is used to notify that vibration is entering the human body while the driver is in a seated position. WBV can also occur during standing on a vibrating floor like that in a plant or during lying, exemplified by traveling with a ship, lying in the cabin bed. The major location of input can in this manner vary. The most occurring position in terrain vehicles is seated although the seated postures can vary between and within vehicle types. The major location of input during seating is the ischial tuberositas. For some vehicles, like the snowmobile, it is also common to stand on the knees or on the feet while operating the vehicle.

Human response to WBV is a very complex phenomenon. Several extensive surveys have been conducted to summarize the effects on the human being and it can be concluded that responses are diverse (Damkot et al 1984, Frymoyer et al 1993, Hulshof & Zanten 1987, Kjellberg et al 1994, Sándover 1991, Seidel & Heide 1986). Human response to WBV can be divided into comfort, perception and health. This thesis will focus on health impairments and only aspects concerning the musculoskeletal system. WBV is believed to affect the musculoskeletal health by biomechanical constraints or by the physiological responses from exposure (Wikström 1994).

Several reviews have shown an association between exposure to seated WBV and low back pain (Bernard 1997, Bovenzi & Hulshof 1998, Lings & Leboeuf-Yde 2000). However, no dose-response relationship has been established. Therefore, the general opinion is now that occupations with exposure to WBV (job title) are at risk for development of low back pain, rather than pointing out WBV as the single causal factor. Today, the knowledge base is considered insufficient to suggest an association between exposure to WBV and neck and shoulder symptoms (Wikström et al 1994, Bernard 1997, Bovenzi & Hulshof 1998). Most epidemiological studies on health effects have focused on magnitudes in the vertical direction and knowledge about health effects due to exposure to WBV in horizontal directions is sparse. It should also be noted that most knowledge on the relation between WBV exposure and health outcome are based on
studies that are of cross-sectional or case-control type. These types of studies have a lower validity compared to prospective cohort studies.

Although beneficial effects of vibration has been known for a long time and utilized by various groups of therapists (e.g. Keller et al 2000), there has lately been an increasing awareness for the health effects that vibration can bring about. The main interest has concerned physical training in combination with vibration exposure with the aim to increase the muscular strength in the back or lower limbs (e.g. Bosco et al 1998, 1999, Issurin et al 1994, Issurin & Tenenbaum 1999). From that aspect, not all types of vibration can be considered detrimental. It is though important to identify the characteristics of harmful vibration and this can be done by establishing protocols on accurate description and comparison of the outcome parameters and variables of vibration characteristics, i.e. magnitude, frequency, direction, duration and variation with time.

**Magnitude**

The extent of the oscillation determines the magnitude of vibration. Magnitude can be quantified by displacement, velocity and acceleration. For practical reasons, the magnitude of vibration is usually described by its acceleration. The units for acceleration is meters per seconds squared (ms$^{-2}$) but a logarithmic scale can also be use to describe the acceleration magnitude in decibels (dB). The magnitude of vibration can be expressed in various specific ways such as r.m.s. or VDV.

**Frequency**

The repetition rate of the cycles of oscillation determines the frequency of vibration. The unit for frequency is hertz (Hz). One hertz means one cycle per second. A simple harmonic (i.e. sinusoidal) vibration is formed from a single frequency. In reality, vibration exposure is non-sinusoidal but can be represented by a combination of sinusoidal components having appropriate amplitudes, frequencies and phases. The human body seems to be most sensitive for WBV within the frequency range of 0.1 to 100 Hz and usually the lower frequency components are attributed to the adverse health effects (Griffin 1990, ISO 2631-1 1997), with some differences for the vertical and horizontal directions (Wikström 1994). According to the standard, ISO 2631-1 (1997), analysis of the influence on health should be performed within the frequency range 0.5 to 80 Hz.
Separate frequency weightings for each direction and different frequencies is usually applied to account for the sensitivity of the human body.

**Direction**

ISO 2631-1 (1997) defines three mutual perpendicular axes of the human body in seated, standing and recumbent positions. The basicentric coordinate system is described by the axes originates at a point from which vibration is considered to enter the body (for a seated person beneath the ischial tuberosities). Translational motions are described along these axes. For a seated person, motions in the x-axis are back to front or fore-and-aft. Motions in the y-axis are right to left or lateral. Motions in the z-axis are from foot to head or vertical (Griffin 1990). There are also three rotational axes described by the standard, whereby rotational motions are described. Rotation about the x-, y- and z-axis are named roll, pitch and yaw, respectively. Griffin (1990) states that rotational motion always produces some translation at all points other than the centre of rotation.

**Duration**

Health risk assessments are primarily based on the magnitude of vibration and duration of exposure (EU 2002, ISO 2631-1 1997). Assuming that responses are related to energy, two different daily exposures are considered equivalent when \( a_{w1}T_{1}^{1/2} = a_{w2}T_{2}^{1/2} \). Other studies indicate a time dependence according to \( a_{w1}T_{1}^{1/4} = a_{w2}T_{2}^{1/4} \). Exposure to vibration is proposed to be assessed over an 8 h period by measuring or calculating the daily vibration exposure (ISO 2631-1 1997, EU 2002). Most studies have measurement periods shorter than 8 h due to technical difficulties to store large amounts of data. Usually a selected representative period of the work is assessed and then extrapolated. Vibration exposure in epidemiological studies should thus be considered as estimates of the true daily occupational vibration exposure.
**Variation with time**

Variation with time can be divided into two subtypes depending on the variation with time, deterministic or stochastic (Burström et al. 2000). Deterministic vibration is further divided into periodic or non-periodic. The simplest type of periodic vibration is sinusoidal. The stochastic vibration is not predictable and is also named noise. Continuous vibration with small variation in amplitude is named stationary. A shock-type vibration (transient) is non-stationary and may appear during a short period with high amplitude (Burström et al. 2000).

Most experimental and laboratory studies on the acute effects of WBV exposure have been done using a simulator with one d.o.f. The type of applied vibration has been short-term, sinusoidal in the vertical direction although with varying magnitudes and frequencies. Thus, most conclusions based on laboratory studies refer to relatively simple vibration conditions and short-term effects. For observational studies, aiming at describing the WBV exposure during work and long-term health effects, the methodological problem has been to exactly state vibration doses. Various estimates of the true vibration dose are normally utilized. A review of WBV characteristics associated with low back disorders/problems is summarized in Table 1. From the review it seems as if the most critical direction for low back pain is the z-direction, i.e. vibration in the vertical plane. Less is known about other vibration measurements than the root mean square of the acceleration (r.m.s.) in relation to musculoskeletal symptoms.

Drivers of terrain vehicles will most likely be exposed to WBV of shock-type (non-stationary), which advocates the use of other vibration measurements that more accurately describes shock occurrence. A recent review of epidemiological studies by Stayner (2001) showed no information at present that could be used for the health evaluation of exposure to occasional shocks in comparison with exposure more continuous vibration. Thus the knowledge about adverse health effects from exposure to shock-type vibration is limited.
Table 1. Vibration characteristics for earth moving vehicles, associated with lower back disorders/problems

<table>
<thead>
<tr>
<th>Author / Year</th>
<th>Type</th>
<th>R.m.s.-magnitude (ms⁻²)</th>
<th>Range (ms⁻²)</th>
<th>Direction</th>
<th>Dominant direction</th>
<th>Dominant frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Johannning 1991</td>
<td>Subway cars</td>
<td>0.55</td>
<td>0.32-0.99</td>
<td>Vector sum</td>
<td>z-axis</td>
<td>2.5, 12.5</td>
</tr>
<tr>
<td>Boshuizen et. al /</td>
<td>Freight-container</td>
<td>1.04</td>
<td>-</td>
<td>Vector sum</td>
<td>z-axis</td>
<td>2.5, 3.15</td>
</tr>
<tr>
<td>1992</td>
<td>tractors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boshuizen et. al /</td>
<td>Fork-lift trucks</td>
<td>0.80</td>
<td>-</td>
<td>Vector sum</td>
<td>x- and z-axis</td>
<td>1.6, 2.5</td>
</tr>
<tr>
<td>1992</td>
<td>Busses</td>
<td>0.40</td>
<td>0.18-0.65</td>
<td>z-axis</td>
<td>z-axis</td>
<td>-</td>
</tr>
<tr>
<td>Bovenzi &amp; Betta 1994</td>
<td>Tractors</td>
<td>1.22</td>
<td>0.89-1.47</td>
<td>Vector sum</td>
<td>z-axis</td>
<td>-</td>
</tr>
<tr>
<td>Malchaire et. al /</td>
<td>Fork-lift trucks</td>
<td>1.59</td>
<td>0.39-3.80</td>
<td>z-axis</td>
<td>z-axis</td>
<td>4, 5</td>
</tr>
<tr>
<td>1996</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

-Data missing

Further detailed information on human vibration is found in “Handbook of human vibration” (Griffin, 1990) and in ISO 2631-1 (1997).

Exposure - Response

A group of experts on musculoskeletal disorders (Armstrong et al 1993) presented a conceptual model for the pathogenesis of WMSDs, which demonstrates the relation between common exposure factors and different responses. The model contains sets of cascading exposure, dose, capacity and response variables, such that response at one level can act as dose at the next. Response to one or more doses can diminish (impairment) or increase (adaptation) the capacity for responding to successive doses. Armstrong and coworkers (1993) also suggested that it is possible that different dose definitions should be applied depending on the tissue at risk, e.g. vertebral disc, tendons or muscles.

Winkel & Mathiassen (1994) describe another model of the association between external exposure and musculoskeletal health. The model is similar to that proposed by Armstrong et al (1993), but emphasizes modifying factors such as individual factors and surrounding environment that can modify each step in the model. External exposure refers to physical workload that can be described
in three dimensions; level, repetitiveness and duration (Winkel & Mathiassen 1994).

The latest contribution for understanding of the relation between ergonomic exposure factors and musculoskeletal disorders is the framework of the National Research Council (NRC) of USA (NRC 1999). This model show considerable agreement with the other mentioned models although the relation between various factors is more detailed and covers many levels of the problem for the workplace as for the person such as organizational factors, social context, impairment and disability.

**Suggested model for exposure to WBV and musculoskeletal health**

This thesis uses a revised model, from that suggested by Winkel & Mathiassen (1994). The revised model describes the effects of WBV on musculoskeletal health (Figure 1). Vibration can be seen as an oscillating mechanical exposure factor. The exception compared to other mechanical factors is that its characteristics must be described also by the frequency and type, due to the nature of vibration. Vibration at the seat will in turn via transmission cause biodynamic responses that act on and in the musculoskeletal system of the individual operator and can be called internal exposure (Westgaard & Winkel 1997). The biodynamic response is primarily affected by the interaction between the body and the points of contact with the motion, body posture, body dimensions, driving style and the characteristics of vibration (Griffin 1990). The dose of WBV can also be described, in similarity to other mechanical loads, as a product of magnitude and duration. Techniques exist to measure the transmission, impedance and magnitude of absorbed vibration during laboratory conditions, which is referred to as energy absorption (Holmlund 1998). These measures are usually achieved during laboratory conditions and not regularly used in field studies. The internal exposure generates acute responses, which are defined as reversible physiological and psychological alterations. Over time these responses creates more long-lasting effects on the musculoskeletal system that may be of either positive or negative character for the musculoskeletal health. From studies on other ergonomic risk factors it is believed that occasional high loads, repeatedly moderate loads or sustained low physical load serve as potential harmful combinations of occurrence and magnitude responsible for musculoskeletal
disorders. This may also apply to WBV although it is not known what combination of magnitude and occurrence that is most detrimental for the musculoskeletal system. The nature of vibration also makes the frequency component important for this question, partly since the number of load cycles increases with the frequency of vibration.

Pathomechanisms for back disorders during exposure to WBV

The most common anatomical entities with pathology in the lower back for people exposed to WBV are vertebral plate end fracture, disc degeneration or degeneration of other tissues in affected segment (Griffin 1990, Wikström et al 1994, ISO 2631-1 1997). Several suggestions for pathomechanisms for the lower back have been described in the literature (see below). The effects of repeated loads are summarized by Brinckmann & Pope (1990) and it was concluded that bone, like all other materials, is subject to mechanical fatigue. The disk exhibits viscoelastic properties, which during exposure to vibration induces ‘vibrocreep’ that makes the disc less compliant and probably more susceptible for mechanical stress (Troup 1978, Keller et al 1987). Fatigue of the back muscles has been shown during exposure to vibration (Hansson et al 1991) and it is believed that the muscular exertion of the muscles adds to spinal stress (Troup 1978). Vertebral compression fractures in snowmobile riders might be caused from high peak vertical acceleration events, creating forces, which are suggested to be occasionally greater than the human tolerance (Roberts et al 1971). There are no studies specifically directed towards pathomechanisms in the neck or the shoulders among any professional driving group and translation of pathomechanisms suggested for the lower back should be done with caution.
Figure 1. Model for the pathogenesis of WMSDs during exposure to WBV. Revised from Winkel & Mathiassen (1994) and with WBV as example of exposure.
**Terrain vehicles**

Noted by the Swedish National Institute for Working Life (1998), is that in the North of Sweden or Sweden alone, there are up to 20,000 professionals who operate terrain vehicles. A large proportion of terrain vehicles in professional use are snowmobiles where approximately 15,000 are used by reindeer herders, military, police, forestry workers and the energy industry. Additionally, many individuals in the northern part of Sweden use terrain vehicles during leisure time, especially snowmobiles and three- and four-wheelers. This thesis focus particularly on three types of terrain vehicles during occupational use namely; forest machines (forwarders and harvesters), snowgroomers and snowmobiles. Other types of terrain vehicles and its consequences for the musculoskeletal health are not within the scope of this thesis. From an international perspective, the terminology for naming terrain vehicles is a bit confusing and contradictory, but this thesis uses the term all-terrain vehicles (ATVs) for the vehicle types included in the studies.

**Epidemiological studies on drivers of all-terrain vehicles**

The following sections summarize epidemiological studies on all-terrain vehicles. The referred studies are divided into three categories involving: 1) solely exposure measurements, 2) solely response outcomes, and 3) both exposure measurements and response outcomes. Studies that not explicitly report magnitude of exposure or response outcome are not referred to, nor are studies focusing on exposure to hand-arm vibration and associated responses.

**Exposure**

During the 1970s, Hansson & Wikström (1976) measured WBV in various forest machines and related their results to ISO 2631 (1974). Four out of 66 machines had vibration levels that could constitute a health hazard, when supposing an eight-hour working day. They also reported high acceleration levels within the frequency range of 1.5-6 Hz for the vertical direction and 1-3.15 Hz for the horizontal directions. The authors stated large influences of vibration in horizontal directions. In the 80s, Wikström & Eskilsson (1983) conducted a survey of forest-machine drivers’ exposure to seated
INTRODUCTION

WBV. During normal work conditions, the obtained acceleration levels were in the range of 0.23-0.68 ms$^{-2}$ r.m.s.. Harvesters had lower vibration levels than other machine types. A study by Wikström (1993) showed that while driving a forest machine, rotation of the neck (30-50 degrees) had large effects of both discomfort and EMG-level. Eklund & coworkers (1994) measured head postures in forestry machine workers, by use of a direct measurement technique (electric goniometer) and found less head rotations compared to drivers of fork-lift trucks and crane operators.

Response

In 1980s, Jonsson & coworkers (1983) showed a high prevalence of musculoskeletal symptoms among forest machine drivers. The highest prevalence was found in the neck and shoulder region (65%). Every second driver (49%) had complaints in the back during the previous 12 months. Näyhä et al (1994) examined reindeer herders using a postal questionnaire. Among the respondents, 38% reported troubles in the upper limbs and shoulders, which according to their own judgment were caused by snowmobile driving. Further, 34% reported such symptoms in the knees and 42% in the back. Individuals reporting the most exposure also reported joint symptoms more frequently. Axelsson & Pontén (1990) reported that 50% of the 1,174 logging-machine operators they studied had “overload syndrome”, defined as complaints and injuries to the neck, arms and cervical spine. The authors did not relate symptoms to exposure from WBV, but suggested one-sided, repetitive, short-cycle working movements with arms and hands as a risk factor.

Exposure and response

Anttonen (1994) measured WBV in snowmobiles and found frequency-weighted acceleration levels on the seat from 1.0 to 6.1 ms$^{-2}$ during a ten years period. Using the ISO standard (Part1-1985), risk evaluation was performed, which predicted health problems. Information of health status was assessed through a questionnaire, which showed that more than half of the included subjects (reindeer herders) had suffered from back symptoms during the previous year, but few of them considered exposure to WBV as a health hazard.
Rationale for this thesis

To summarize the introduction chapter, there are several professionals in Sweden and other industrialized countries that operate vehicles during their work. Some of them are exposed to seated shock-type WBV such as drivers of terrain vehicles who operate their vehicles off-road. The WBV exposure situation for drivers of terrain vehicles is not fully clarified and interaction with other risk factors is likely. The exposure situation may contribute to a number of symptoms and disorders in the musculoskeletal system. There seems to be no contemporary studies on the association between long-term exposure to shock-type WBV and musculoskeletal disorders. Musculoskeletal disorders are a major concern in the modern society that has negative consequences on many levels. A thorough extensive clinical investigation of musculoskeletal disorders has not been conducted among a group of people exposed to shock-type WBV.
AIMS

The general purpose of this thesis is to increase the knowledge regarding three main questions

- Can the working environment for professional drivers of ATVs be considered harmful for the musculoskeletal system?
- What are the risk factors for symptoms and disorders in the musculoskeletal system for drivers during operation of ATVs, with special reference to WBV exposure?
- Can something be done to prevent the occurrence of musculoskeletal symptoms and disorders among drivers of ATVs?

The specific aims are

♦ to assess the risk for musculoskeletal symptoms in the neck, shoulder, upper- and lower back for professional drivers of various ATVs (Paper I).
♦ to investigate the existence of neurogen musculoskeletal disorders in the neck and upper extremities among cases with neck pain operating various ATV and compare the array of disorders with referents from the general population (Paper III).
♦ to explore exposure to seated WBV and postural load during occupational use of various ATVs (Paper II).
♦ to describe how exposure to WBV varies and how sources for variation contributes in forwarders (Paper IV).
SUBJECTS AND METHODS

Subjects

In Paper I, 875 registered male drivers of ATVs in the four most northern counties in Sweden were the original target population for an inquiry. All 394 workers registered as drivers of forest machines in the region were included together with 304 workers randomly selected from jobs known to comprise work with snowmobile driving and all 177 workers listed as drivers of snowgroomers in the area. A random sample from the general population in the same region, with an age restriction of 20-60 years served as control group. The control group consisted of 800 male persons.

A subgroup of the target population and control group in Paper I constituted subjects in Paper III, in which cases with neck pain that had agreed to participate in deeper examinations were semi-randomly assigned and clinically investigated, in total 60 subjects. The subjects in Paper III were divided into four groups, each consisting of 15 persons; i) drivers of forest machines, ii) drivers of snowmobiles, iii) drivers of snowgroomers and iv) control subjects.

All drivers included in the analyses in Paper I and Paper III had at least 3 years exposure from driving an ATV at work (exposed group), whereas control subjects had at maximum 1 year experience from driving an ATV (unexposed group).

All-terrain vehicles

In Paper II, the ergonomic working environment was investigated for forest machines, (forwarders) (n=6), snowmobiles (n=6) and snowgroomers (n=7) with focus on WBV exposure. In addition, postural load for the neck region was investigated in Paper II.

Paper IV focused on variation in WBV exposure in forwarders (n=7). Repeated measurements during occupational use were conducted and variation was analyzed using vibration magnitudes as dependent variables and driver, model and terrain conditions as explaining variables.

All operation of vehicles was investigated during professional use in one of the four most northern counties in Sweden between the

Data collection methods

Musculoskeletal symptoms from questionnaire (Paper I)

In 1999 a self-administered questionnaire was sent to the target population and the control group. Two reminders of the questionnaire were sent to those who didn’t answer at fixed times. In total the response rates were; 75.4 %, 73.0 %, 78.5 %, 65.5 % for drivers of forest machines, snowmobiles, snow groomers and control group, respectively. No information was collected about the non-responders. There were 215 drivers of forest machines, 137 drivers of snowmobiles, 79 drivers of snow groomers and 167 controls included in the final data analysis. A Swedish version of the Nordic questionnaire (Kourinka et al 1987) was used for subjective symptoms. The Nordic questionnaire includes items with dichotomized response alternatives (yes or no) regarding symptoms (ache, pain or discomfort) originating from various regions of the musculoskeletal system at some point during the previous 12 months. Those who reported symptoms also answered additional items on the consequences of each symptom for their working capacity, meaning not being able to manage daily work at some point during the past 12 months (severe symptoms).

Job strain

The job strain was measured according to a Swedish version of Karasek’s demands/control model (Karasek 1979), which was included in the questionnaire. The version held five items about psychological job demands and six items about control over work. All items have response categories that are scored on a categorical scale of 1 to 4, ranging from “never” to “almost always”. For analysis in the questionnaire, job strain was computed as the ratio between the weighted sum scores of psychological demands and control for each subject.
Exposure time

Each individual estimated his exposure time in total number of hours of driving a terrain vehicle; forwarder, harvester, machine for soil scarification, snowmobile, snowgroomer, snowweasel, terrain motorcycle and four-wheeler. Exposure time concerned the previous 12 months and life-time.

Smoking

In addition, each individual also gave information about his smoking habits. For the questionnaire in Paper I smoking habits was classified as either current smoker, non-smoker or smoked earlier.

Table 2. Subjects in Paper I. Number of subjects (n), age, cumulative exposure duration during all years (lifetime) and during the previous year in hours (h) for drivers of terrain vehicles and controls, mean, range. Smoking habits and the percentage of subjects with jobs exposed to WBV or ergonomic risk factors (job exposure)

<table>
<thead>
<tr>
<th></th>
<th>Forest machine</th>
<th>Snowmobile</th>
<th>Snowgroomer</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>n</strong></td>
<td>215</td>
<td>137</td>
<td>79</td>
<td>167</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td>49 (26-69)</td>
<td>44 (22-62)</td>
<td>42 (23-60)</td>
<td>44 (22-62)</td>
</tr>
<tr>
<td><strong>Cumulative exp. duration (h)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifetme (range)</td>
<td>41,865 (4,330-135,860)</td>
<td>4,898 (80-39,080)</td>
<td>8,980 (684-36,120)</td>
<td>0.6 (0-64)</td>
</tr>
<tr>
<td>Previous year (range)</td>
<td>1711 (0-3,996)</td>
<td>298 (0-1,600)</td>
<td>635 (32-1,540)</td>
<td>1.3 (0-96)</td>
</tr>
<tr>
<td><strong>Smoking (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current user</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Never used</td>
<td>53</td>
<td>68</td>
<td>62</td>
<td>64</td>
</tr>
<tr>
<td>Used earlier</td>
<td>30</td>
<td>18</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>Unknown</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td><strong>Job exposure (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current job</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>29</td>
</tr>
<tr>
<td>Previous job</td>
<td>82</td>
<td>53</td>
<td>57</td>
<td>30</td>
</tr>
</tbody>
</table>

Musculoskeletal disorders from clinical investigation (Paper III)

The clinical assessment of musculoskeletal disorders in the neck and upper extremities entailed both taking a history and a physical examination that was carried out according to a checklist. The
examining physician was a specialist in occupational medicine and blinded as to the subjects’ exposure characteristics. In order to facilitate for symptom history, subjects began by completing a form containing pain drawings concerning the quality of their physical symptoms (dull, tingling, pricking, radiating, burning, throbbing, numbness or other) and a form concerning the nature of the symptoms in their left and right hand respectively (numbness, reduced hand strength, prone to drop objects, pain in wrist, pain in finger, coldness in hand or finger, white fingers, reduced dexterity, tremor, feeling of cramp, hand perspiration). Customary medical anamnesis (symptom history) was then directed towards the medical history and other diseases (current complaints, general condition, previous sickness, medication and heredity). Subsequently, the physical examination was conducted following a predetermined study protocol. Tests for the presence of neurological symptoms were conducted in line with methods presented in a review article by Nilsson (Nilsson 2002), who also presented sensitivity and specificity for these tests. The nerve provocative tests were; 1) Neck compression test (Spurling’s test); 2) Nerve stretch test (Arm-laségue); 3) Plexus brachialis compression (gentle pressure in fossa supraclavicularis elicits a tingling sign over the plexus area, radiating and following the nerve distribution in arm and hand); 4) Tingling sign (Tinel); 5) Wrist flexion test (Phalen); 6) Pronator compression test at the elbow; 7) Test for thoracic outlet syndrome (Abduction External Rotation test - AER). Motor function (deltoideus, wrist extensors, finger extensors, finger spread) and tendon reflexes (biceps, triceps, brachioradialis) were also examined using four alternatives (0-3), where 0 means no reflex, 1 reduced, 2 normal and 3 increased. Superficial sensibility was measured on dig II and dig V, both hands, by van Frey hairs (Semmes-Weinstein monofilaments, described in Bell-Krotoski et al (1995)).

Grip strength was tested using of a dynamometer that measures air pressure in a bulb (Martin vigorimeter, large bulb for men). The best of three strength tests was noted. Quantitative sensory testing (QST) of thermal perception was carried out (Termotest®, Somedic Sales AB) according to the “thermal sensory limen” (TSL). Neutral zone was defined as the range in which the sense of temperature had adapted, i.e. there was no sensation of warmth and cold - indifferent. Lundström presented in a review article (Lundström 2002) the fundamental neurophysiological bases for QST as well as associated methodological and practical aspects of importance in the diagnostic
process regarding vibration-induced neuropathy and applied in this study. In addition, ordinary clinical tests for muscles, tendinitis and joints for the neck, shoulders, elbows and wrists/hands were used and included: 1) Inspection – posture, movement patterns, asymmetries, muscle, bone and skin abnormalities; 2) Range of motion (ROM) – subjects wore eyeglasses with straight pegs attached and sticking out. Active and passive ROM as well as pain arches were then determined by analysis of video registration executed simultaneously from the side and from above; 3) Testing for muscle contraction pain and muscle strength; 4) Palpation of muscle tendons and insertions. All provocative tests were executed for both left and right side where appropriate and classified as negative or positive. A memorandum was written and a complete case record was assembled.

Finally, each subject was classified as having a nociceptive or neuropathic disorder based on symptom history, symptoms and signs. In uncertain cases, subjects were further investigated using chemical, radiological or electroneurographical methods. The examiner also had access to results from earlier radiological tests. The origin of any nociceptive disorder (muscle, tendon, joint or unknown) was also classified. Neuropathic pain was further distinguished using the classification system presented by Koltzenburg (2002). Koltzenburg divides neuropathic pain into 1) asymmetrical and focal neuropathy; 2) symmetrical painful neuropathy; 3) central neuropathic pain. A subject could have a disorder classified as a combination of both nociceptive and neuropathic disorders (mixed disorder). If the investigation did not show conclusive symptoms and signs of a neuromusculoskeletal disorder, the subject was not classified.

Table 3. Subjects with neck pain in Paper III. Number of subjects, age and total exposure time (hours) for respective group

<table>
<thead>
<tr>
<th>DRIVER CATEGORIES AND REFERENTS</th>
<th>Forest machine</th>
<th>Snowmobile</th>
<th>Snowgroomer</th>
<th>Referents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Age (mean ±sd)</td>
<td>51 ±9</td>
<td>49 ±8</td>
<td>42 ±7</td>
<td>46 ±8</td>
</tr>
<tr>
<td>*Exposure time (mean ±sd)</td>
<td>44 ±26</td>
<td>4 ±5</td>
<td>9 ±4</td>
<td>0.7 ±2</td>
</tr>
</tbody>
</table>

*Driving ATVs (cumulative duration / *10^3 hours)
**Whole-body vibration (Paper II and Paper IV)**

Measurement of whole-body vibration was performed on the interface between the seat and the pelvis of the respective driver and analyzed according to the international standard ISO 2631-1 (1997). The measurement plate held three orthogonal accelerometers (B&K 4322) for the x-, y- and z-axes respectively. The signals were preamplified and band-pass filtered (0.1-1000 Hz) by a charge amplifier (B&K 5974) and recorded on an eight-channel DAT-recorder (Sony PC 208 Ax). Calibration signals were recorded before each field measurement (B&K 4294).

**Magnitude**

Root mean square vibration magnitude

R.m.s.- magnitudes are based on the second power of the acceleration time history in either x, y or z-directions (eq.1).

\[
a_w = \left[ \frac{1}{T} \int_0^T a_w^2(t) dt \right]^{1/2} \quad (\text{ms}^{-2}) \quad \text{(Equation 1)}
\]

Sum of vectors

The vibration total value \( a_v \), is the sum of vectors of the frequency weighted acceleration magnitudes for all three directions, i.e. x, y and z (eq. 2). This measure is, according to ISO 2631-1 (1997), primarily recommended for the assessment of discomfort. When using the formula for health risk evaluation in seated persons, it is assumed that no dominant axis of vibration exists. In such contexts the x- and y-axes are adjusted with a factor of 1.4.

\[
a_v = \sqrt{\left[1.4a_{wx}\right]^2 + \left[1.4a_{wy}\right]^2 + a_{wz}} \quad (\text{ms}^{-2}) \quad \text{(Equation 2)}
\]

Crest factor

In accordance with the ISO-standard (ISO 2631-1 1997), crest factors were formed by peak magnitudes and r.m.s.– magnitudes determined over the complete duration of measurement, using the running r.m.s. evaluation method with an integration constant of one second.
When the crest factor is over 9 it is recommended that additional methods are used like MTVV (Maximum Transient Vibration Value) and VDV (Vibration Dose Value).

**MTVV**

MTVV (eq. 3), is the highest magnitude of \( a_w(t_0) \) read during the measurement period. The running r.m.s. evaluation method was used to assess MTVV and the time integration constant (\( \tau \)) was set to 1 second.

\[
MTVV = \max \left[ a_w(t_0) \right] \quad (\text{ms}^2) \quad \text{(Equation 3)}
\]

When

\[
a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left[ a_w(t) \right]^2 dt \right\}^{\frac{1}{2}}
\]

**Vibration dose value (VDV)**

VDV (eq. 4), is based on the fourth power of acceleration and in this way more sensitive to shocks compared to the r.m.s.-magnitude.

\[
VDV = \left\{ \int_{0}^{\tau} \left[ a_w(t) \right]^4 dt \right\}^{\frac{1}{4}} \quad (\text{ms}^{1.75}) \quad \text{(Equation 4)}
\]

It is possible to determine the total VDV of the vibration to which the person is exposed by summing VDV for x, y and z-directions (eq. 5) and this summation apply equally to all axes.

\[
VDV_i = \left\{ VDV_x^4 + VDV_y^4 + VDV_z^4 \right\}^{\frac{1}{4}} \quad (\text{ms}^{1.75}) \quad \text{(Equation 5)}
\]

To characterize daily occupational vibration exposure consisting of two or more periods, i, the equivalent 8 h frequency-weighted
acceleration $a_{w,e}$ was calculated (eq. 6) with the following formula (ISO 2631-1 1997);

$$a_{w,e} = \left[ \frac{\sum a_{m}^2 T_i}{\sum T_i} \right]^{\frac{1}{2}} \text{ (ms}^{-2} \text{)} \quad \text{(Equation 6)}$$

For the VDV value the following formula (eq. 6) was used for the same purpose (ISO 2631/1, 1997);

$$VDV_{total} = \left( \sum VDV_i^4 \right)^{\frac{1}{4}} \text{ (ms}^{-1.75} \text{)} \quad \text{(Equation 7)}$$

**Risk assessment**

ISO 2631-1

The magnitude of vibration was compared with health guidance caution zones in the international standard ISO 2631-1 (Equation B.1 and Equation B.2). For exposure below the zone health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely. The recommendations are mainly based on exposures in the range of 4 h to 8 h (ISO 2631-1 1997).

Physical agent’s directive

Estimating weighted r.m.s. acceleration for an eight-hour working day from exposure data sampled for less than eight hours is possible when assuming that human response is related to energy and that the exposure is kept constant during the working day. The formula below (eq. 8), was used when estimating recommended exposure time according to the directive on physical agents stated by the European Union, in regard to exposure action r.m.s.-value 0.5 ms$^{-2}$ (9.1 ms$^{-1.75}$ for VDV) and exposure limit r.m.s.-value 1.15 ms$^{-2}$ (21 ms$^{-1.75}$ for VDV) for daily exposure.
$T_i = \left( \frac{a_{w2}}{a_{w1}} \right)^{e} T_2$ (hours) \hspace{1cm} (Equation 8)

Where $a_{w2} = $ stated value, $a_{w1} = $ measured magnitude, $e = 2$ when using r.m.s. vibration magnitudes and $e = 4$ when using VDV.

**Postural load (Paper II)**

A direct observational method, PEOflex - portable ergonomic observational method flexible, was used to assess non-neutral neck positions. A more detailed description of PEOflex is given by Fransson-Hall et.al (1996). Assessment was done using video registrations simultaneously performed with vibration measurements. A non-neutral neck position was set at rotation in the transverse plane exceeding 15 degrees. When performing the analysis, the observer continuously registered neck rotations, neck relative to torso (sternum as reference line, chine and nose as measurement line). Before conducting the analysis, this position was memorized by the observer after having people held this position and measured by more exact methods. The limit of 15 degrees is a proposal from a Swedish expert group, who developed a model for help in the process of evaluating occupational diseases for the Swedish national occupational injury insurance (Tegner et al. 1983). The group suggested a detrimental effect if the neck sustained a rotational posture between 15-45 degrees for more than 75% of the working time.

**Data handling and statistical analyses**

**Paper I**

A generalized log-linear model was utilized to determine the prevalence rate ratio (PRR) of musculoskeletal symptoms adjusted for age, smoking and job strain. Age and job strain were treated as continuous parameters whereas smoking was treated as a discrete variable. Significance refers to the 95% confidence interval, not including 1.0. P-values for trends were formed by cumulative exposure duration all years.
**Paper II**

Vibration magnitudes, r.m.s. and VDV, were compared between axes and groups using one-way analysis of variance (ANOVA). This was followed by post-hoc multiple comparisons using Tukey’s honestly significant difference test for cases with equal variances and Tamhane’s T2 test for cases with unequal variances. Homogeneity of variance was analyzed using the Levene test. P-values less than 0.05 were considered statistically significant.

**Paper III**

Fischer’s exact test was utilized to compare differences between occurrence of asymmetrical and focal neuropathy between drivers and referents (2x2 table). P-values less than 0.05 were considered statistically significant.

**Paper IV**

Univariate variance analysis was performed using a generalized linear model. The major response variables in the variance analysis were $a_v$ and time-weighted VDV. Operators, models and terrain types, served as explaining variables and were all regarded as fixed. P-values less than 0.05 were considered statistically significant.
RESULTS

Musculoskeletal symptoms and disorders

Musculoskeletal symptoms among drivers of ATVs (Paper I)

The prevalence of symptoms was larger in the neck, shoulder and thoracic regions in all groups of ATV drivers compared to the control group. Compared to controls, the driver groups also showed increased prevalence of severe symptoms in the neck, shoulder and lower back (Table 4).

Table 4. Prevalence, given as percentages of musculoskeletal symptoms [severe symptoms in brackets] for neck, shoulders, upper- and lower back during the previous 12 months among the drivers of terrain vehicles and control group. Prevalence rate ratios (PRR) and 95% confidence intervals (CI) for symptoms the previous 12 months compared to the control group.

<table>
<thead>
<tr>
<th></th>
<th>Drivers of all-terrain vehicles and control group</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forest machine (n=215)</td>
<td>Snowmobile (n=137)</td>
<td>Snowgroomer (n=79)</td>
<td>Control group (n=167)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^1)</td>
<td>2.3 (1.7-2.9)</td>
<td>1.8 (1.3-2.4)</td>
<td>2.2 (1.6-2.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^2)</td>
<td>1.9 (1.4-2.5)</td>
<td>1.9 (1.4-2.5)</td>
<td>2.2 (1.6-2.0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^1)</td>
<td>1.9 (1.5-2.5)</td>
<td>1.6 (1.1-2.1)</td>
<td>1.8 (1.3-2.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^2)</td>
<td>1.6 (1.2-2.1)</td>
<td>1.5 (1.2-2.1)</td>
<td>1.8 (1.3-2.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^1)</td>
<td>2.4 (1.4-4.2)</td>
<td>2.8 (1.6-6.0)</td>
<td>2.7 (1.4-5.2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^2)</td>
<td>2.2 (1.2-3.9)</td>
<td>2.9 (1.6-5.2)</td>
<td>2.7 (1.4-1.9)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^1)</td>
<td>1.1 (0.9-1.4)</td>
<td>1.3 (0.9-1.6)</td>
<td>1.2 (0.9-1.6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PRR(CI)(^2)</td>
<td>0.9 (0.8-1.2)</td>
<td>1.3 (1.0-1.6)</td>
<td>1.2 (0.9-1.6)</td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Crude value
\(^2\) Adjusted for age, smoking and job strain
The prevalence ratios, crude and adjusted for age, smoking and job strain, were increased for the neck, shoulder and thoracic regions for all groups of ATV drivers. There were no significantly increased risks of low back pain for any of the driver categories. There were statistically significant associations with age and job strain for forest machine operators concerning shoulder and lower back and the associations for these body regions were included in the statistical model. No other associations were found (Table 4).

In general, the exposure-response relation between symptoms of musculoskeletal disorders and duration of operating a terrain vehicle was weak. The only significant trend was established in the group of snowmobile drivers for symptoms in the upper back ($p=0.038$).

**Musculoskeletal disorders in the neck and upper extremities among drivers of ATVs (Paper III)**

A mix of a nociceptive and neuropathic disorder was in general more common in the driver groups especially among drivers of snowmobiles and snow groomers (55 % (24/44) vs. 20 % (3/15)). All cases in the mixed group had an asymmetrical and focal neuropathy. The total prevalence of cases diagnosed as asymmetrical and focal neuropathy were 47 %, 67 %, 79 % and 27 % for drivers of forest machines, snowmobiles, snow groomers and referents respectively. In general, ATV drivers had a higher prevalence of asymmetrical and focal neuropathies compared to referents ($p=0.018$). Differences were most pronounced for drivers of snow groomers ($p=0.009$) but less clear for the other ATV driver categories ($p=0.450$ for drivers of forest machines and $p=0.066$ for drivers of snowmobiles). Drivers of forest machines and referents had the highest prevalence of a pure nociceptive disorder in comparison to the other disorder types (8 cases out of 15 for both groups). The most common origin for a nociceptive disorder was the muscle tissue (Table 5).
Table 5. Classification of neuromusculoskeletal disorder type in the neck and upper extremities, origin of nociceptive disorder and further classification of a neurogenic disorder for drivers of ATVs and for referents in this study. A subject diagnosed as having a nociceptive disorder could have several origins of pain (muscle, tendon, joint). Units in number of people if not stated. P-values for Fischer’s exact test between driver categories and referents concerning prevalence of asymmetrical and focal neuropathy

<table>
<thead>
<tr>
<th>DRIVER CATEGORIES AND REFERENTS</th>
<th>Forest machine (n=15)</th>
<th>Snowmobile (n=15)</th>
<th>Snowgroomer (n=15)</th>
<th>All drivers (n=45)</th>
<th>Referents (n=15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nociceptive</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>Muscle pain</td>
<td>8</td>
<td>4</td>
<td>2</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>Tendonal pain</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Joint pain</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Unknown</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Neuropathic</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Asymmetrical and focal neuropathy</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Symmetrical painful polyneuropathy</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Central neuropathic pain</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Mixed</td>
<td>5</td>
<td>9</td>
<td>10</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>No longer pain</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Prevalence of asymmetrical and focal neuropathy</td>
<td>47%</td>
<td>67%</td>
<td>79%</td>
<td>64%</td>
<td>27%</td>
</tr>
<tr>
<td>(7/15)</td>
<td>(10/15)</td>
<td>(11/14)</td>
<td>(28/44)</td>
<td>(4/15)</td>
<td></td>
</tr>
<tr>
<td>P-value</td>
<td>0.450</td>
<td>0.066</td>
<td>0.009</td>
<td>0.018</td>
<td>-</td>
</tr>
</tbody>
</table>

The most common specified types of asymmetrical and focal neuropathy were carpal tunnel syndrome (CTS) and thoracic outlet syndrome (TOS). Seven drivers compared to zero referents had at least one of these diagnoses (Table 6).
Table 6. Manifestations and specific diagnoses for cases with neuropathic disorders (pure and mixed). Units in number of people

<table>
<thead>
<tr>
<th>DRIVING CATEGORIES AND REFERENTS</th>
<th>Provocative tests</th>
<th>Forest machine (n=15)</th>
<th>Snowmobile (n=15)</th>
<th>Snowgroomer (n=15)</th>
<th>All drivers (n=45)</th>
<th>Referents (n=15)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive manifestation$^a$</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Negative manifestation$^b$</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>8</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Provocative manifestation$^c$</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>27</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CTS</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>TOS</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Radialis entrapment</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Medianus entrapment$^d$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Dysesthesia, pain, paresthesia
$^b$Numbness, reduced sensibility or proprioception
$^c$From nerve provocative tests
$^d$Pronator teres syndrome

Exposure

Whole-body vibration exposure among drivers of ATVs (Paper II)

Snowgroomers had their highest vibration r.m.s.-magnitudes in the z-direction compared to the other directions (Table 7). The mean magnitude of vibration was significantly higher in the z-direction compared to both the x- and y-axes (p<0.05). In contrast, the dominant direction for snowmobiles was found to be the x-axis, except for two vehicles. The z-axis for snowmobiles was in general lower compared to the other axes, however not significant. Forwarders had the most dominant direction in the y-axis with significantly higher mean magnitudes compared to the other vibration directions. Between vehicles, snowmobiles had higher vibration magnitudes in the x-axis, compared to snowgroomers (p<0.05). Forwarders had the highest vibration magnitudes in the y-axis and compared to snowgroomers, there was a significant difference (p<0.05). Snowgroomers had higher magnitudes in the z-direction.
compared to forwarders (n.s.), but not compared to snowmobiles. The highest vibration magnitudes, as defined by the vibration total value \(a_v\), were found in snowmobiles. Again however, the differences were not statistically significant (Table 7).

In general, snow groomers had the highest VDV in the z-direction, which was significantly higher compared to the other directions, but MTVV were dominant in the x-axis (Table 7). The dominant magnitudes for snowmobiles, VDV and MTVV, were found in the x- and z-axes. However there was not any significant difference in VDV between the axes. Forwarders had their highest VDV in the y-direction (n.s.) but the highest MTVV were found in the z-axis. Statistically significantly differences in VDV between vehicles were found between snowmobiles and snow groomers in the x-axis, and also between snowmobiles and snow groomers and between forwarders and snow groomers concerning the y-axis. There weren’t any statistically differences for the z-axis (Table 7).

Table 8 shows that, when evaluating the most dominant direction, by use of r.m.s.-magnitudes, there were two vehicles in this study, that held vibration magnitudes below the action value for an eight-hour working day which is stated in the physical agent’s directive from the European Union (2002). There were three snowmobiles and one forwarder that held vibration magnitudes exceeding the limit value. The other vehicles had vibration magnitudes below the limit value. When analyzing VDV, one snowmobile, one snow groomer and one forwarder showed magnitudes exceeding the action value. No vehicle had VDV exceeding the limit value. In general, shorter allowed exposure times were achieved using equation B.1 and B.2 from the international standard (ISO 2631-1) and most vehicles had vibration magnitudes that restricted recommended daily exposure times below eight hours. However, there were two snow groomers that had vibration magnitudes that did not restrict recommended exposure times below eight hours, independent of equation and upper or lower limit. There was one snowmobile that was not restricted below eight hours when using equation B.2 and upper limit. There were two forwarders that were not restricted below eight hours. However, one of these forwarders was only restricted by use of equation B.1 and lower limit.
Table 7. Mean values of whole-body vibration levels in three different directions (x, y, z), for a typical working cycle. Frequency weighted r.m.s. magnitudes adjusted by a factor of 1.4 for the x- and y-axes as suggested by ISO 2631-1. Vibration total value (a_v) for respective vehicle, Maximal transient vibration value (MTVV), Vibration dose value (VDV) and crest factor

<table>
<thead>
<tr>
<th>Vehicle nr</th>
<th>Time (s)</th>
<th>1.4a_wx</th>
<th>1.4a_wy</th>
<th>a_wz</th>
<th>a_v</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snowgroomer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1976</td>
<td>0.4</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>5.3</td>
<td>3.8</td>
<td>3.2</td>
<td>2.7</td>
<td>3.0</td>
<td>5.5</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>316</td>
<td>0.4</td>
<td>0.4</td>
<td>1.0</td>
<td>1.1</td>
<td>7.2</td>
<td>4.6</td>
<td>3.4</td>
<td>1.7</td>
<td>2.0</td>
<td>6.4</td>
<td>6</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>1616</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>0.6</td>
<td>5.5</td>
<td>4.3</td>
<td>3.4</td>
<td>2.7</td>
<td>1.8</td>
<td>3.4</td>
<td>&gt;9</td>
<td>&gt;9</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>1196</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9</td>
<td>1.0</td>
<td>8.6</td>
<td>5.4</td>
<td>2.4</td>
<td>1.8</td>
<td>1.7</td>
<td>6.6</td>
<td>5</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>1460</td>
<td>0.4</td>
<td>0.5</td>
<td>1.1</td>
<td>1.3</td>
<td>7.4</td>
<td>3.7</td>
<td>2.2</td>
<td>2.2</td>
<td>2.6</td>
<td>9.6</td>
<td>6</td>
<td>6</td>
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<tr>
<td>6</td>
<td>1220</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.5</td>
<td>6.0</td>
<td>4.2</td>
<td>1.9</td>
<td>3.3</td>
<td>2.5</td>
<td>8.0</td>
<td>8</td>
<td>8</td>
<td>&gt;9</td>
</tr>
<tr>
<td>7</td>
<td>1192</td>
<td>0.5</td>
<td>0.4</td>
<td>1.1</td>
<td>1.2</td>
<td>11.0</td>
<td>7.8</td>
<td>6.0</td>
<td>1.6</td>
<td>1.3</td>
<td>3.2</td>
<td>&gt;9</td>
<td>&gt;9</td>
<td>3</td>
</tr>
<tr>
<td>Mean:</td>
<td>1252</td>
<td>0.4</td>
<td>0.4</td>
<td>0.8</td>
<td>0.9</td>
<td>7.3</td>
<td>4.8</td>
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†Not a complete working cycle
Table 8. Allowed exposure times in hours (h) before the action value and the limit value are exceeded when supposing an eight-hour working day. Values from the directive 2002/44/EC of the European Union (2002). Equation B.1 and Equation B.2 from the health caution guidance zones in the international standard ISO 2631-1.

| Frequency analysis showed that snowmobiles, compared to the other types of vehicles, had their highest vibration magnitudes in the span from 0.2 to 2.5 Hz for the x-axis (Figure 2). Forwarders had their highest magnitudes in the x-axis, ranging between 0.8 to 5.0 Hz. Snowgroomers had a more widespread and smooth frequency span in the x-axis, from about 0.2 to 50 Hz with a small peak in the span between 0.2-10 Hz. When comparing vibration in the y-axis, it was found that forwarders had their highest magnitudes in the frequency span from 1.0 to 2.0 Hz with a distinct peak in the 1.25 Hz one-third-octave band. Snowmobiles had their highest vibration magnitudes in the y-direction ranging between 0.2-10 Hz. The frequency span for snowgroomers in the y-axis was more widely spread compared to the other vehicle types. For the z-direction it seemed that all vehicles have |

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<th>Action value (h)</th>
<th>Limit value (h)</th>
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<th>Upper limit (h)</th>
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Figure 2. Mean one-third octave bands in the $x$, $y$ and $z$ direction for respective vehicle type. Snowgroomers ($n=7$), snowmobiles ($n=6$) and forwarders ($n=6$)
their peaks between 2.0-8.0 Hz with the most distinct peak accrued to snowgroomers in the 4 Hz one-third-octave band. Snowmobiles had a more widespread frequency span in the z-direction compared to the other vehicle types (Figure 2).

**Postural load (Paper II)**

The ergonomic analysis showed that the frequency of rotational positions exceeding 15 degrees had a median of about 2 rotations per/minute for all driver categories. Duration spent in this position for drivers of snowgroomers and snowmobiles varies from 4-7% (mean) of the total registration period whereas for forwarder drivers the amount of time spent in a non-neutral neck position varies between 10-19%. Most events were short, often no longer than two seconds. The longest time with the neck rotated more than 15 degrees was 22 seconds, which was achieved by one forwarder driver (Table 9).

**Table 9.** Quantification of number of events per minute (Nr/min) and duration in percent (%) of the total registration period spent with the neck rotated more than 15 degrees, median and range. The mode, median, shortest (Short) and longest (Long) time with the neck rotated more than 15 degrees in seconds (s). All parameters in whole numbers

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<th>Mode (s)</th>
<th>Median (s)</th>
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<th>Long (s)</th>
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Sources for variation of WBV exposure among operators of forwarders (Paper IV)

From Table 10 it can be seen that the mean vibration acceleration was largest during travel activities, especially during travel empty. Loading cargo gave slightly higher WBV than unloading cargo. Figure 3 and Figure 4 shows the variation between measurements in vibration magnitudes, $a_v$ and VDV$_t$, for the four activities defined for forwarders. Variation was largest for activities involving travel. Table 11 shows the equivalent acceleration magnitudes. Most measurements for respective vehicle reached different conclusions regarding health risk assessment due to the variation in exposure. The variance analysis showed that forwarder models and terrain types had a statistically significant impact as a source for variation in $a_v$ magnitudes during traveling empty ($p_{forwarder}=0.019$, $p_{terrain}=0.036$; Adjusted R-squared 0.41). For traveling loaded, forwarder models and operators had a significant impact on the variation of $a_v$ ($p_{forwarder}<0.000$, $p_{operator}<0.000$; Adjusted R-squared 0.84). Variation in the time-weighted VDV$_t$ was not significantly influenced by any of the explaining variables during traveling empty. (Adjusted R-squared – 0.051 for the model). For traveling with cargo, variation in time-weighted VDV$_t$ was significantly explained only by forwarder models ($p=0.001$; Adjusted R-squared 0.39).

Table 10. Means, standard deviations, minima, maxima, coefficient of variation (CV) of the acceleration magnitudes $a_v$ (ms$^{-2}$) and VDV$_t$ (ms$^{-1.75}$). CV was calculated using all measurements from all vehicles and operators for respective activity

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Performing a health risk assessment using the guidelines in the EU-directive (EU 2002) showed that the smallest and highest vibration r.m.s.–magnitudes reached can affect recommended exposure times substantially (Table 11) when applying the action value. For most drivers the risk assessment resulted in two different conclusions (restricted or allowed exposure times) depending on when or under what circumstances the measurement was undertaken.
Figure 4. Overview of vibration magnitudes, vibration dose value (VDVs) on y-axes, for each model (1-7) during the four activities in the working cycle. Separate marker style for respective operator.
Table 11. Equivalent acceleration magnitudes (Acc) and range in exposure times, rounded off to full hours for individual operators before the action value and the limit value, as stated in the EU’s physical agents directive, are exceeded when supposing an eight-hour working day. Magnitudes (usually y-axis dominant), calculated with respect to the proportion of activities found in this study. A value >8 h mean that the exposure time isn’t restricted by the directive.

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<th>$v_{VDV_{total}}$ (ms$^{-1}$)</th>
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DISCUSSION

This thesis found an increased risk of musculoskeletal symptoms in the neck, shoulder and thoracic region, but not in the lower back, among professional drivers of various ATVs. Musculoskeletal disorders in the neck and upper extremities are often of neurogenic type among these driver categories. WBV magnitudes are high in ATVs and drivers of these vehicles are exposed to shocks in several directions. WBV magnitudes can vary substantially due to various factors and this can result in different conclusions regarding health risk assessments.

Methodological considerations

Internal validity

This thesis was based on studies of cross-sectional type, two papers covering health perspectives and two papers covering the physical working environment with focus on WBV exposure. Neuromusculoskeletal symptoms and disorders are generally episodic in nature and of relatively short duration, which is why a cross-sectional study has less power to reveal the natural course of symptoms and disorders. It is also difficult to draw firm conclusions about any single causative factor compared to longitudinal studies. However aspects on point differences between a group highly exposed to shock-type WBV from driving ATVs and a control group not exposed can be achieved. Exposure assessments done at a point in time can’t reveal dose magnitudes, only estimates of doses, which is a disadvantage that makes conclusions on relationships weaker. This thesis used self-reported exposure time as an estimate to study the relation between vibration exposure and symptoms (Paper I). The WBV magnitudes and doses reached by the individual driver are not possible although the exposure assessments (Papers II, IV) give an indication of the existing WBV magnitudes in ATVs on a group basis. The awareness of a risk may have influenced the way the worker answered to the questionnaire in Paper I. However, there were no economical gains from reporting a symptom in Paper I. Furthermore, it seems unlikely that they should have reported a high prevalence of symptoms from the neck/shoulder and not from the low back if
awareness of risk has influenced the answers. We also asked about symptoms from the knees (data not reported here) and there was no difference between any of the groups (the prevalence varied between 27 and 32 percent). Thus, it was considered that a biased reporting of symptoms due to awareness of risk was unlikely.

**Measurements**

The Nordic questionnaire is recommended for screening musculoskeletal symptoms and evaluations of ergonomic workplace programs. Reliability and validity for the questionnaire are considered acceptable (Kourinka et al 1987, Dickinson et al 1992, Baron et al 1996). The major limitation with the Nordic questionnaire is that it doesn’t grade incidence or severity of symptoms. From a recent study using a modified version focusing on temporal impact it has been suggested that one-year prevalence may mean sensation of pain once or twice or all the time during a year (Ektor-Andersen 2002). The same study showed that the severity of pain (measured by VAS score) could range from about 20 till 70 on a 100 scale. These findings underline the need for additative measurements in questionnaires if a deeper comprehension of pain is aimed. Paper I presented prevalence of severe symptoms, meaning not being able to work during the preceding 12 months period, which gives some indication of severity among drivers of ATVs. The prevalence for severe symptoms were in general higher among ATV drivers in comparison with control subjects but not as clearly indicated risk as when using the 12 months prevalence for moderate symptoms.

Studies have shown that high quantitative job demands and low coworker support can be independent risk factors for neck and shoulder pain (Ariëns et al 2001, Bongers et al 2002). There are also indications that low decision authority is another risk factor for neck pain (Ariëns et al 2001). A study by Peter & coworkers (1998) found that stressful working conditions as defined by effort-reward imbalance are associated with high rates of reported symptoms in public transport workers, especially in professional drivers. It would be of value to apply effort-reward imbalance models in relation to musculoskeletal disorders also for forest machine drivers since it has been implied that these drivers have high working demands but still tend to stay within their present work.

At present there is no standardized system for the assessment of WMSDs across or within the member states of the European Union
DISCUSSION

Musculoskeletal disorders in earlier studies have mostly been categorized according to screening methods and criteria for diagnosis suggested by Waris & co-workers (1979) and to additional tests and questions suggested by Viikari-Juntura (1983). A criteria document for case definitions when evaluating the work-relatedness of upper-extremity musculoskeletal disorders was recently introduced by Sluiter & co-workers (2001). In similarity to the clinical study (Paper III) the screening methods and criteria were based on symptoms and signs and some also involved specific nerve provocation tests. The focus of the clinical study in this thesis was to investigate the existence particularly of neuropathic associated disorders in the neck and upper extremities as accurately as possible why chemical, electroneurographical and radiological findings were used for the diagnostic process. Reproducibility of this type of investigation on a larger population may be questioned, since the classification was made by an experienced physician who based his judgment on time consuming evaluation methods. Internal validity should on the other hand be high, using this procedure.

PEOflex was used to assess neck rotations of ATV drivers during operation. The video-registration procedure created a two-dimensional picture in the approximate frontal plane for evaluation of movements around a frontal axis, which can be argued. Important aspects on three-dimensional movements of the neck are unfeasible. The intra-observer reliability in this study was quite low compared to intrarater agreement in the study by Fransson-Hall (Fransson-Hall et al 1996), which reflects the difficulties in estimating the rotational neck position using the described procedure. Since there were only few subjects in the present study and only one measurement event, which did not hold numerous working cycles, the generalization can be questioned. Longer registration periods up till full working days are desirable.

**External validity**

This thesis focused on men with jobs known to involve operating ATVs. This eliminates a gender perspective. The cross-sectional study (Paper I) involved a large amount of the target population in the four most northern counties in Sweden and the participation rate was about 70%. Both crude and adjusted prevalence ratios showed a marked increased risk compared to an age-matched control group. The findings are interpreted as strongly evident for an increased risk
of musculoskeletal neck and shoulder symptoms among drivers of ATVs in the northern part of Sweden. Inferential conclusions on differences between ATV drivers and other workers regarding musculoskeletal disorders in general (Paper III) can be drawn, since the subjects were randomly assigned. In view of the fact that the examination concerned cases with neck pain that had pain for at least 6 months, i.e. disorder of a chronic character it excludes pain patterns concerning the acute phase of disorder.

Exposure to WBV in the ATVs included in this study showed that the magnitudes are high during occupational use (Paper II). Magnitudes during occupational use may differ from those generated during operation of ATVs during leisure time why conclusions in this thesis only applies to professional use of ATVs. Measurements of ATVs was done in some of the four most northern counties in Sweden and terrain types may differ somewhat compared to those from the southern part of Sweden as well as from those in other countries. Working conditions may also differ between geographical regions due to seasonal variations. Other terrain vehicles than those included in the thesis (i.e. snowmobiles, snowgroomers and forwarders) may have other characteristics of WBV since they have different construction and work tasks. It is believed though, that other terrain vehicles, in similarity to the ATVs in this thesis, have high WBV magnitudes in horizontal directions containing shocks. Variation and sources of variation applies only to the described forwarders included in Paper IV. More vehicles and various vehicle types must be investigated before variation in WBV among ATVs in general can be fully described. The method of analyzing separate activities can however serve as a model of investigating other WBV doses in other vehicle types.

**Human response in relation to vibration characteristics**

Most aspects of human responses to vibration characteristics have concentrated on comfort not on health. The following section will discuss the WBV exposure characteristics and health outcome from this thesis compared to what has been reported from other studies on WBV in various earth moving vehicles. Figure 5 illustrates the time-history of the acceleration for various vibration measurements applied on the seat of a fork-lift truck running over an obstacle. The time-
history in this illustration is relatively short compared to measurements used in this thesis. Figure 5 illustrates the variation of different magnitudes during real-time. From this illustration it is obvious that point and average values transformed from vibration data will result in different magnitudes and in turn different conclusions regarding its’ effects on the musculoskeletal health.

![Figure 5. Example of a vibration (acceleration) signal and various vibration measurements in real-time. From a fork-lift truck running over an obstacle. (Printed with permission from Peter Jönsson, Luleå University of Technology, Department of Human Work Science, Division of Sound and Vibration, Sweden)](image)

**Magnitude**

**Root mean square vibration values (r.m.s.)**

The most evaluated WBV magnitude in relation to health effects is the r.m.s.-acceleration (Griffin 1990). R.m.s.—magnitudes for ATVs in this thesis varied between 0.9-1.7 ms$^{-2}$ (vibration total value). As mentioned in the introduction chapter, WBV characteristics associated with low back disorders/problems seems to have the z-direction as a dominant, i.e. most vibration occurs in the vertical plane (Table 1). Mean magnitudes for those vehicles were 0.55 ms$^{-2}$ for
subway cars, $1.04 \, \text{ms}^{-2}$ for freight-container tractors, $0.80-1.59 \, \text{ms}^{-2}$ for fork-lift trucks, $0.4 \, \text{ms}^{-2}$ for buses and $1.22 \, \text{ms}^{-2}$ for tractors. Also WBV exposures in various other heavy equipments have been associated with low back pain. In mobile heavy equipment the mean-weighted r.m.s.-acceleration was recently reported to $1.20 \, \text{ms}^{-2}$ (Cann et al 2003). There was however no information available on the dominant directions. During normal work conditions, the obtained acceleration levels for forest machines during the 1980s were in the range of $0.23-0.68 \, \text{ms}^{-2}$ (Wikström & Eskilsson 1983). Anttonen & Niskanen (1994) measured WBV in snowmobiles and found frequency-weighted acceleration levels on the seat from $1.0$ to $6.1 \, \text{ms}^{-2}$ during a ten years period. Compared to ATVs of older type and other categories of vehicles, there seem to be no major reduction or alteration in vibration total values on a group basis.

**Vibration dose value (VDV)**

VDV for ATVs in this thesis were between $2.1-7.6 \, \text{ms}^{1.75}$ (Paper II). The highest achieved VDV was $14.1 \, \text{ms}^{1.75}$ which was in the z-direction for a snowmobile. VDV is more sensitive to shocks compared to the r.m.s.-value. However, there seems to be no studies of VDV in relation to musculoskeletal health, so comparisons are not possible at present. Griffin presented estimated and true VDV for some vehicle types (Griffin 1990). True VDV magnitudes in a small car during a $60 \, \text{s}$ testing period (city road, $55 \, \text{kmh}^{-1}$) were $0.3$, $0.5$ and $0.7 \, \text{ms}^{1.75}$ for the x, y and z-directions respectively. The VDV during $60 \, \text{s}$ for a van was $0.9$, $1.4$ and $1.8 \, \text{ms}^{1.75}$ for x, y, and z-directions respectively. For tractors the VDV varied between $2.1-3.2 \, \text{ms}^{1.75}$ for x-direction, $2.7-4.9 \, \text{ms}^{1.75}$ for y-direction and $2.9-6.4 \, \text{ms}^{1.75}$ during various work. Sample duration varied between $25-120 \, \text{s}$ and time to reach $15 \, \text{ms}^{-1.75}$ varied substantially between axes and type of work. VDV in a tank at various speeds on a test course varied between $3.3-14.5 \, \text{ms}^{1.75}$ for the z-direction (sample duration $30 \, \text{s}$) and VDV increased with increasing speed (Griffin 1990). VDV was recently presented for some heavy equipment in the construction industry (Cann et al 2003). Magnitudes in these vehicles were between $3.35-31.7 \, \text{ms}^{1.75}$ for $20 \, \text{minutes}$ testing periods for mobile groups such as wheel and crawler loader, off-road dump trucks, variable reach forklift, backhoes, graders, scrapers, bulldozers, forklifts, ride-on power trowels, skid steer vehicles and compactors (Cann et al 2003). There was no information regarding dominant vibration directions. It
is noteworthy that VDV can be high in other types of vehicles. VDV will be used more in view of the fact that the EU-directive considers the VDV as important as the r.m.s-magnitude. Thus, more comparisons and health outcome in relation to VDV will be possible in the near future.

**Maximal Transient Vibration Value (MTVV)**

MTVV was measured in Paper II and showed mean magnitudes for ATVs between 3.2-10.4 ms$^{-2}$ for all directions. MTVV is the highest r.m.s.-magnitude (during 1s) over the whole period of registration. Since there are no exploratory studies that have reported MTVV, no comparisons can be made. The MTVV gives some idea of the alterations in magnitude compared to the r.m.s.-magnitude during the measurement period for the vehicles in this thesis (Paper II). Use of MTVV might however obscure the occurrence of repetitive shocks since only a point value is reported.

**Crest factor**

Paper II indicated that crest factors are often higher than 9 in several translational directions, especially for forwarders. Studies of responses of the body to mechanical shock of high magnitudes have been largely concerning with discrete events, such as automobile accidents and the ejection of pilots from aircraft (Griffin 1990), not consequences from long term exposure to shock-type vibration with high crest factors. Boshuizen et al (1992), have reported crest factors exceeding 6, indicating that vibration in forklift trucks and freight-container tractors contain significant jerks. Griffin (1990) presented crest factors for some vehicles. In a car the crest factors varied between 4.7-5.5 whereas for a van the crest factors varied between 4.1-20.0. For tractors the crest factors varied between 3.6-12.8 and for tanks between 3.6-21.2. The highest crest factors were found in the z-direction for all vehicles. Thus, high crest factors are existent also in other types of vehicles.

**Frequency**

Resonance in seated positions has been revealed for the neck within frequencies of 1-4 Hz vertical and for the shoulders within 0.4-2.2 Hz vertical. At resonance frequencies, body parts have their largest motions and should be relatively more susceptible to detrimental
effects compared to other vibration frequencies (Dupuis 1989). WBV, transmitted from the seat to the neck and shoulder area has been investigated in laboratory studies and the transmission is affected, for example, by different body postures such as extended or rotated attitude of the spine (Holmlund 1998, Mansfield & Griffin 2002, Griffin 1975, Wilder et al 1982). The dominant frequency bands for ATVs are similar to the other vehicle types and peaks in the frequency span for the vertical direction includes resonance frequencies for the cervical spine (1-4 Hz).

**Direction**

This thesis showed a high influence of vibration in horizontal directions for various ATVs. The biodynamic behavior of the body during transmission of horizontal vibration to the head is not as extensively studied as during vibration exposure in the vertical direction. However, Fairley & Griffin (1989) measured the apparent mass during horizontal vibration and found one resonance frequency in the region of 3.5 Hz for the fore-aft direction and one about 1.5 Hz for the lateral direction. The effect of a backrest was most pronounced for the fore-and-aft direction. Seated subjects to study motions of the head in six axes at site, during exposure to horizontal WBV, used a bite-bar for the purpose (Paddan & Griffin 1988). Results from the bite-bar data revealed that, fore-and-aft seat motion mainly resulted in head motion within the mid-sagittal plane (x-z plane). Transmissibility for several axes was greatest at about 2 Hz. A backrest greatly increased head motions at frequencies above 4 Hz. Lateral seat motion caused lateral head motion with a maximum transmissibility at about 2 Hz and the backrest had minor influence during lateral vibration. An example of the complex interaction between the back and neck during exposure to WBV is ‘head nodding’, that has been observed in individuals during exposure to vertical vibration in the buttocks. Sandover (1991) argues that this might arise from the fact that the center of gravity of the head is slightly offset from its pivot point. An in vivo study showed that horizontal and rotational motions appeared in lumbar vertebrae when subjects were exposed to sinusoidal vertical vibration in the resonance frequency span (Panjabi et al 1986). Apparently, motion of the head with different characteristics is possible, though pure vertical axis vibration is induced.
As interesting are the negative results, that despite exposure to relatively high vibration doses, there was no increased risk of low back pain. Speculatively, but logically, the influence of horizontal vibration could be the cause also for this phenomena. The data collected here suggests that, the type of physical stress that is created on the spine, when driving these types of vehicles is due to repeated loads of bending or shearing character. In vivo measurements of the spine behavior in relation to health effects have not focused on repeated loads in horizontal directions (Griffin 1990, Brinckmann & Pope 1990). Most in vitro measurements that have been conducted on specimens of the vertebral column have focused on the number of repetitions, load magnitude and application point, but not on horizontal force directions and the effects of such load (Griffin 1990, Brinckmann & Pope 1990). Hence, the knowledge base on effects due to repeated loads in horizontal directions is scarce. Cross talk of force components in all degrees of freedom alters the resulting force vector, possibly reducing the vertical component, which seems to be the critical direction for low back symptoms and disorders. Using this reasoning, influence of horizontal vibration may be protective for the lower back but detrimental for the neck. Some ‘evidence’ of this association was reported by Bonney & Corlett (2003). Results their laboratory study showed that the spinal length increased during exposure to a combination of vertical and horizontal directions at 4 Hz suggesting unloading of the spine during these exposure conditions. Torsional load combined with vertical load of the lumbar spine has caught some attention in the literature (Adams & Hutton 1981), but is of secondary interest in this context.

**Inverted seated human cone model**

With support from the observations retrieved in the field studies, a dynamic model is proposed - inverted seated human cone model. The trunk and head individually, or together, describe a pendulum action with the buttocks and thoracic spine as origos. Imposed movements of the trunk and head should have their boundaries describing the shape of a cone with the apex pointing at the seat. If the acceleration-deceleration phases between the head and trunk do not coincidence, stress of a bending or shearing character would hypothetically be created between these body segments. Horizontally directed vibration should constrain the back- and neck muscles of the driver to counteract for imposed movements of the trunk and head, which
otherwise would be flung from side-to-side and backward-and-forward and produce stress on various regions and tissues of the spine. From a biomechanical point of view the trunk and head are considered relatively heavy, which makes produced forces such as inertia important. This proposed biodynamic reaction could also subject the shoulder muscles on the operator to static overload, since the operators have to stabilize their body not solely with neck- and back muscles, but also with muscles belonging to the upper extremities. Even though the vibration is directed horizontally, one can view the model as a spring-mass system with characteristics such as stiffness and dampening. Some of these movements could be unpredictable for the driver, which may make the detrimental effects even more serious. Especially if the applied vibration is of shock-type, which was shown to be existent in the working environment for ATV drivers. These movements could explain the obtained symptoms in the neck, shoulder as well as for those in thoracic region that were reported as sites for pain or discomfort by the all-terrain driver groups (Paper I). Exposure to shock-type vibration during operation of ATVs may involve pressure to and stretching of peripheral nerves in the neck and upper extremities. The seated driving posture in itself may also have negative consequences for the peripheral nerves. Abnormal postures, positions or movements may directly affect nerve tension or pressure, producing chronic compression. These positions may also affect the muscles producing secondary nerve compression or muscle imbalance contributing to symptoms (Novak & Mackinnon 1997, Novack & Mackinnon 2002).

The inverted seated human cone model suggests that the longer distance from the seat, the greater lever. Or in other words, imposed movements of neck should be more excessive for tall persons. The proposed model must however be studied further by laboratory as well as epidemiological studies. This model has been proposed earlier by researchers trying to establish a model describing the biodynamic behavior during various vibration conditions and has concentrated on trunk and head movement in a single plane (e.g. Fard et al 2003).
Figure 6. “The inverted seated human cone model”. Biodynamic reaction of the head, trunk and upper extremities due to the nature of vibration characteristics in ATVs. Imposed movements of the trunk and head should have their boundaries describing the shape of a cone with the apex pointing at the seat.

**Duration**

The understanding of the various possible effects of the duration of vibration is far from complete (Griffin 1990). The respondents in Paper I reported exposure times from driving ATV drivers during the previous 12 months. The estimated effective exposure time using those figures and assuming a winter season of 4 months (80 working days) approximately averaged usage to 3.7 h/day for snowmobile drivers and 7.9 h/day for snowgroomer driver, which exceed the daily exposure time limits obtained in this study. Drivers of forwarders are bound to the seat about 90% of their working time, which is not restricted to a specific season. Thus, exposure time varied between the ATV groups, implying that other work tasks exist for drivers of snowgroomers and snowmobiles. However, as could be seen in Paper I, the exposure-response relation between symptoms of
musculoskeletal disorders and duration of operating a terrain vehicle was weak. The only significant trend was established in the group of snowmobile drivers for symptoms in the upper back.

**Variation with time**

The special exposure situation for ATVs is the high magnitudes of shock-type vibration, as was indicated in Paper II. Knowledge of long-term effects of shock-type vibration is brief. Effects of short-term exposure to high levels of vibration and shock were studied among stage rally drivers and co-drivers by Mansfield & Marshall (2001). Although the vibration characteristics were not quantified most subjects reported symptoms of musculoskeletal injury foremost in the lumbar, thoracic and cervical spine but also in the shoulders. This study was uncontrolled. A clinical study on rally drivers showed no significant differences in lumbar degenerative findings as assessed from MR images compared to a reference group (Videman et al 2000). Acute effects of shock-type (transient) vibration have been studied in comparison with shockless vibration for vertical directions during laboratory conditions (Dupuis et al 1991). Results showed that increasing shock amplitude and also increasing numbers of shocks lead to increasingly acute effects that varied, depending on the kind of shock used. Parameters were biodynamic behavior of the trunk and head, EMG positioned in the cervical and lumbar region, infrared thermography (IRT) for thermal behavior of the skin in the lumbar area (Dupuis et al 1991).

**Influence of other factors**

Only short periods with rotational neck postures exceeding 15 degrees were found in Paper II. It could be discussed whether these short periods could have negative effects itself, or in combination with vibration exposure for professional ATV drivers. A non-neutral neck position, occurring simultaneously with exposure to excessive shock would on the other hand be undesirable. For the lumbar region, it has been addressed that an awkward posture, putting the spinal joints in extreme positions, preferably in a rotational attitude, would be especially hazardous during simultaneous exposure to WBV and shock (Wikström et al 1994).
Exposure to HAV

A potential risk factor for musculoskeletal disorders in the neck and upper extremities is exposure to hand-arm vibration (HAV). Anttonen measured HAV in snowmobiles, terrain motorcycles and four wheelers and found vibration values between 1.6-12.7 ms\(^{-2}\) (Anttonen & Niskanen 1994, Anttonen et al 1995). A Swedish investigation revealed high values (1-5 ms\(^{-2}\)) of HAV in snowmobile and snowgroomer vehicles (Olofsson & Burström 2000). For some of the drivers of these types of terrain vehicles it was found that exposure to HAV could be a risk factor, particularly for white-fingers. However, transient shock-type vibration from the steering devices with high amplitude should have the capacity to reach both the shoulder and the neck region and thereby also affect the musculoskeletal system (Sakakibara et al 1986, Palmer et al 2001). Transmission of vibration from a hand-held power tool to various parts of the hand and arm varies depending on several factors such as arm position and grip force (Burström et al 2000). In general, vibration below 10 Hz has the capacity to transmit proximally to the wrist and elbow. At higher frequencies, vibration affects mainly distal parts (Burström et al 2000). Low frequency components of HAV are prevalent in ATVs. Some studies have shown degenerative diseases in the wrist and elbow joints caused by exposure to HAV of shock-type indicating a serious detrimental effect (Gemne & Saraste 1987). Hence, HAV might be considered as a possible contributory or confounding risk factor for neck and shoulder pain although epidemiological studies show inconclusive evidence for this association. The weak association is mainly due to low quality of study designs, as suggested by Ariëns & coworkers (2000).

Implications

This thesis demonstrates that the risk for symptoms of musculoskeletal disorders in the neck region is high among drivers of various ATVs such as snowmobiles, snowgroomers and forest machines. Compared to earlier studies, there seems to be no reduction of symptoms over years despite technical improvements of the vehicles. Disorders among these driver groups involve to a large extent pathological engagement of nervous structures in the neck and upper extremities, which may be more difficult to rehabilitate compared to nociceptive disorders. It was expected that the ATV
driver groups would have a high prevalence of low back pain, but the thesis showed that the neck region (neck, shoulder, thorax) was most at risk for symptoms. Symptoms and disorders in this region may be caused by the typical working environment for ATV drivers, i.e. exposure to high magnitudes of horizontally oriented shock-type WBV. This type of vibration results in continuous passive jolts of the operator’s head. The resulting biodynamic behavior of the body is argued to be a possible pathomechanism for these disorders in the neck.

Modern technical improvements of these vehicles may have improved the overall comfort and slightly reduced the magnitudes of vibration but, as shown in the thesis, the WBV magnitudes are still high compared to the EU’s directive and the health guidance cautions zones in ISO 2631-1. The terrain conditions, driving style and machine type forms the characteristics of vibration in ATVs and ATVs should therefore be considered typical and distinct compared to other vehicle types. However other vehicles may also produce shock-type WBV such as other vehicles operating off-road, e.g. military vehicles. Certain aircrafts and ships could have similar WBV characteristics and operators of these vehicles may share the same problems with musculoskeletal disorders. Various trains have shown high magnitudes of horizontal WBV including shocks and operators of these vehicles reported foremost high prevalence of various back symptoms (Johanning 1991, Johanning et al 2002).

Operating ATVs during work must be considered as a highly potential risk for developing musculoskeletal symptoms and disorders. Thus, health surveillance of these groups is of particular concern. It is important that symptoms and disorders are detected and prevented at an early stage. They may otherwise turn manifest and more difficult to treat. The simplest ways to reduce the harmful dose of WBV is done by identifying critical activities and reduce the exposure times for these activities, although this procedure will request organizational changes. This thesis shows that it is possible to reduce magnitudes for forwarders in several ways, i.e. selecting another model, change the way the machine is driven and alter the terrain conditions. There is though a problem with non-stationary shock-type vibration. This type of vibration has the potential to cause more serious injuries even during relatively short exposure times. The possible detrimental effects from horizontally oriented shocks in the neck region and their prevention must be studied further since there are several questions to be resolved.
CONCLUSIONS

General

The general conclusions based on information retrieved from the studies included in this thesis is that the working environment for drivers of ATVs can be considered to be harmful for the musculoskeletal system, especially for the neck and upper extremities. Further, musculoskeletal disorders of neurogenic type are common in the neck and upper extremities among cases of ATV drivers with neck pain. Musculoskeletal symptoms and disorders are proposed as being a result of the typical exposure situation. The magnitudes of WBV exposure in ATVs are high with major influence of vibration in horizontal directions that also contains shocks of considerable magnitude. Risk assessment reveals that vibration exposure in many ATVs used during work exceed recommended occupational exposure limits. Vibration exposure in ATVs varies substantially, depending on characteristics of the vehicle type, driving technique and alterations in the terrain. Prevention can be accomplished by identifying critical activities during a working day and reduce the exposure durations for these activities.

Specific

♦ Most drivers that use ATVs during work in the four most northern counties in Sweden are men.

♦ The risks for symptoms of musculoskeletal disorders in the neck, shoulders and upper back are about 2 till 3 times higher among professional drivers of ATVs compared to a control group from the general population without exposure to WBV caused by driving terrain vehicles. The risks don’t differ substantially between driver categories (forest machine, snowmobile, snowgroomer).
Adjusting prevalence ratios (PRR) for age, smoking and psychosocial job strain (Karasek’s control demands/model), reveal that other risk factors are necessary for an explanation of the occurrence of musculoskeletal symptoms among professional ATV-drivers. Frequency and duration of non-neutral rotational positions of the neck do however not seem to be a risk factor.

Despite exposure to relatively high vibration magnitudes, there is no increased risk of musculoskeletal symptoms in the lower back among the professional ATV-drivers. The result is contradictory compared to what could have been predicted based on results from epidemiological studies on other types of vehicles.

The dominant vibration direction varies depending on the ATV type, which probably is a reflection of the particular design of the vehicle and also its function. The altered dominant vibration direction does however not influence the pattern of musculoskeletal symptoms among the ATV-drivers.

Vibration magnitudes in ATVs are considerable high when compared to the action value from the physical agents directive (0.5 ms \(^{-2}\), r.m.s.) proposed by the Council of the European Union. Most ATVs in this study exceed the action value for an eight-hour working day.

There may be an association between symptoms of musculoskeletal disorders in the neck region and exposure to horizontal WBV among drivers of forwarders, snowmobiles and snowgroomers.

Cases of professional ATV drivers with neck pain, in contrast to a control group, have a high prevalence of asymmetrical and focal neuropathies in the neck and upper extremities. The finding is most obvious for drivers of snowgroomers. It is proposed that this type of disorder results from the typical exposure to shock-type seated WBV and unfavorable working postures.
♦ Although drivers of forest machines have longer exposure times to seated WBV, there are fewer cases with asymmetrical and focal neuropathies compared to drivers of snowmobiles and snow groomers, indicating static muscle work during operation of forest machines.

♦ WBV magnitude can vary substantially in forwarder vehicles, which strongly affects the health risk assessments. The hazardous dose can be prevented by minimizing exposure times for critical activities (travel activities for forwarders).

♦ Reducing WBV magnitudes and preventing musculoskeletal symptoms may be done by selecting another forwarder model (or modification), by information on the dependency of the driver style and changing terrain conditions by building roads in the worst terrain types.

♦ The great variation in WBV magnitude for forwarders underlines the urge for long measurement periods and repeated measurements during various conditions and for all activities for a full description of the vibration characteristics in ATVs.

♦ During transport empty with forwarder, the most important factors for variation are the machine type and terrain conditions expressed in ground carrying capacity and surface structure. During transport with cargo the machine type and operator are the most important sources.

♦ Both r.m.s. and VDV should be used for health risk assessment, since they are influenced by various factors.
NEW ASPECTS IN THIS THESIS

As far as could be found in the published literature, mainly the following research issues, methods and results have not been reported earlier.

♦ A controlled study comparing prevalence ratios of musculoskeletal symptoms among drivers of various ATVs and a referent group from the general population. In addition, prevalence ratios were adjusted for potential confounders such as age, smoking habits and psychosocial factors (job strain according to Karasek’s demands/control model). The ATV drivers don’t have an increased risk of low back pain, which was expected (Paper I).

♦ This thesis gives a more detailed description of the vibration conditions in ATVs compared to earlier studies. Comparison of r.m.s. and VDV between various types of ATVs and risk assessment, both according to the physical agent’s directive (vibration) of the European Union and to the health guidance zones from ISO 2631-1. The most pronounced difference, besides from high magnitudes and shocks, is the variation of dominant vibration direction between ATV types, although all studied ATVs have a high influence of horizontal vibration (Paper II).

♦ Clinical investigation directed towards neuromusculoskeletal disorders in the neck and upper extremities a group of professional ATV-drivers and referents. Besides from anamnesis, symptoms and signs the study used chemical, radiological and electroneurographical methods for uncertain cases in the diagnostic process. All groups of ATV drivers have a high prevalence of asymmetrical and focal neuropathy (Paper III).

♦ Analysis of variation in exposure to WBV magnitudes and sources for variation in an ATV (forwarder). WBV data was collected through repeated measurements during ordinary occupational use of forwarders (Paper IV). Variation of WBV exposure can affect health risk assessments considerable due to several factors.
FUTURE PERSPECTIVE

It is essential that future epidemiological studies on associations between WBV and musculoskeletal symptoms and disorders among ATV drivers are longitudinal, i.e. retrospective or prospective. By doing that it is possible to investigate in what way a long-term health effect (response) is related to the dose of WBV exposure. Most aspects that can be revealed through cross-sectional studies are covered. However, to study musculoskeletal health among other driving groups exposed to horizontal shock-type vibration for comparisons would add further understanding of the association. A gender perspective on this research area would add valuable information since women seem to be more affected in the neck due to ergonomic risk factors.

Different characteristics of WBV exposure (r.m.s., VDV, MTVV, crest factor) and their relation to health effects should be addressed for other vehicles and vibration in rotational directions should be assessed in the field. Technical improvements can probably result in opportunities for longer exposure assessments and give the experimenter the “true” vibration dose meaning exposure data for the full working day and not estimation based on short measurements. The main question that has to be resolved is what is most harmful? Exposure to a high magnitude during a short period of time or exposure to a lower magnitude for a longer period of time? It would also be desirable to estimate the frequency of shocks seeing as the MTVV and crest factor only report the single highest magnitudes.

This thesis studied non-neutral positions of the neck. There are however several other ergonomic risk factors that need to be evaluated for the groups of ATV drivers such as forward flexion of the head.

Most laboratory studies on the acute effects of WBV have been executed using a movement simulator with capacity to vibrate in only one direction, i.e. 1 degree of freedom (d.o.f.), often the z-axis. Lately, powerful simulators with capacity of generating imposed movements in 6 d.o.f. have been achievable for research purposes. It is thus possible to study acute effects also when exposed to vibration in lateral and rotational directions (roll, pitch, yaw) and hereby imitate WBV generated from terrain vehicles and other vehicles. The proposed inverted seated human cone model can thereby be
investigated and more details on the biodynamic behavior and mechanisms can be explored by using advanced techniques for movement registration. Acute effects of the human being during exposure to horizontal WBV should be studied in order to evaluate any link between vibration exposure, motor control and musculoskeletal pain. One question that should be answered is if there are relatively more movements in the neck region during horizontal vibration compared to vertical, and what magnitude the movements and forces have. Relatively small movements would suggest that the driver uses static muscle contraction of the neck muscles rather than dynamic contraction to withstand the vibration.

HAV exposure among operators of ATVs, have high r.m.s.-magnitudes. Since shock-type HAV may have the power to reach the neck area, further studies should be concentrated on the consequences of exposure to HAV generated by terrain vehicles.

Weestgard & Winkel (1997) discuss three areas of prevention, namely technical, personal and organizational. An obvious suggestion for technical improvements, based on the results from this thesis, would be to develop horizontally oriented dampening systems for the driving chair. Such dampers have been discussed earlier and studies are under the development stage (Vibseat). An intervention suggested in this thesis would be to let the drivers wear specially designed neck collars that would help them to withstand repetitive and powerful shock movements of the head. The simplest way to reduce the harmful dose of WBV is however still to reduce exposure times for critical activities.
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