



# Associations between Hand–Wrist Musculoskeletal and Sensorineural Complaints and Biomechanical and Vibration Work Constraints

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A 3-year prospective epidemiological study was conducted to investigate the relationship between musculoskeletal complaints (MS) and sensorineural complaints (SN) of the workers in the hand–wrist region. A group of 69 workers (G1) using vibrating tools in eight different working situations was compared to a group of 62 workers (G2) performing heavy work without vibration and 46 workers (G3) performing light work without vibration. Biomechanical constraints (force, postures, repetitiveness and movement velocities) were analysed for each working situation and the vibration exposure at the eight workplaces with the 69 workers. MS and SN data were collected using the nordic questionnaire, modified to collect information about the frequency intensity and duration of complaints. The prevalence of complaints at the start of the study was significantly greater for G1 (72.5%) than for G2 (56.5%), itself greater than for G3 (30.4%). The prevalence of SN was about 40% for G1 and 2.5 times smaller in the two other groups. During the two years follow-up, new cases of ‘serious’ MS and SN developed. The annual incidence was respectively 8.3 and 5.4% on average. The incidence of MS was slightly but not statistically significantly greater for G1, while the incidence of SN was statistically higher ( $P < 0.01$ ) for G1 (10.9%) than for the two other groups (4.1 and 2.1%). Forces and angular repetitiveness were the only biomechanical factors significantly greater for G1. The vibration exposure duration of the G1 workers varied, in average, from 10 to 70% of the work time and the weighted personal exposure amplitude ( $A_{EPW}$ ) varied from 0.5 to 25.4  $ms^{-2}$ . The probabilities of complaints at the beginning of the study (cross-sectional study) were estimated using multiple logistic regression models. The prevalence odds ratio (POR) for MS was equal to 4 for G1 compared to G2 and equal to 9 compared to G3. Force and vibration exposure were the main constraint parameters associated with this likelihood. As far as the SN are concerned, G2 and G3 were not statistically different, but the POR for the G1 workers was 4.5 compared to both groups. The most significant constraint factor was the weighted personal exposure acceleration. The same procedure was used to estimate the likelihood of development of ‘serious’ complaints (longitudinal study). The three groups did not appear significantly different concerning the ‘serious’ MS, while the incidence odds ratio (IOR) of ‘serious’ SN was very high (28.5) and significantly greater for G1 than for the two other groups. The likelihood of development of ‘serious’ SN increased with  $A_{EPW}$ . According to this prediction model, the risk of ‘serious’ SN would be about 6% at the proposed European ‘action’ value (2.5  $ms^{-2}$ ) and about 10% at the ‘limit’ value (5  $ms^{-2}$ ). © 2001 British Occupational Hygiene Society. Published by Elsevier Science Ltd. All rights reserved

*Keywords:* epidemiology; hand–arm vibration; risk assessment; vibration

## INTRODUCTION

Received 27 June 2000; in final form 9 November 2000.  
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Review of the scientific literature of the last 30 years shows that two different fields of research have co-existed: the first concerning the disorders developed by workers exposed to hand/arm vibration and the

other concerning the musculoskeletal upper limb disorders (ULDs) linked to repetitive work without vibration.

The researches in these two fields have separately developed sometimes divergent methods for the analysis of constraints, for the diagnosis of the disorders, and for clinical tests.

The first studies on hand/arm vibration were concerned with the osteoarticular problems associated with the use of percussive vibrating tools (Malchaire *et al.*, 1986; Gemne and Saraste, 1987). Later, the researches focused on vascular problems, mainly vibration induced white finger. These last studies revealed the existence of other disorders associated with vibration (Pyykkö, 1986): tingling (Juntunen *et al.*, 1983), decrease in grip force (Färkkilä *et al.*, 1980, 1986), decrease in tactile sensitivity (Lidström *et al.*, 1982).

Subsequently, during the last 10 years, many studies have focused on these sensorineural (SN) effects.

In the abundant literature concerning ULDs, vibration is considered as a risk factor, acting directly through mechanical stress of the tissue (Bovenzi *et al.*, 1991), and indirectly through an increase in the grip force of the objects (Tonic Vibration Reflex, Radwin *et al.*, 1987) or through the increase of the time (duration) for which static postures are maintained (Gemne, 1997).

The association between exposure to vibration and ULDs, and in particular carpal tunnel syndrome, was observed by Pelmeur *et al.* (1992), Bovenzi *et al.* (1991), and Kakosy (1994). The prevalence of ULDs would be two (Silverstein *et al.*, 1987) to five times (Bovenzi *et al.*, 1991) greater for workers exposed to vibration than for workers exposed to high force constraint during repetitive work.

Few studies actually dealt with both biomechanical and vibration constraints, and they were mainly cross sectional in nature. Further research comparing the developments of both types of complaints and disorders as a function of the biomechanical and vibration constraints is therefore essential in order to organize prevention adequately.

This was the objective of the prospective research reported in the present paper. The development and evolution of musculoskeletal complaints (MS) and sensorineural complaints (SN) were observed during 2 years and studied in relation to two types of hand and wrist constraints: biomechanical and hand/arm vibration.

In the study, SN were defined as episodes of tingling and numbness in the fingers during the last 12 months.

This study follows a first prospective research (Malchaire, 1995) conducted in Belgium on a population of 1500 workers, among whom 200 were followed during 2 years: that research concerned the hand and wrist complaints and biomechanical factors, excluding any exposure to vibration.

## STUDY POPULATION

Three groups of male workers were studied:

The first group (G1) included all the workers (69) exposed to vibration in eight industrial environments:

1. Car assembly plant: bolting (12 subjects)
2. Car assembly plant: grinding and polishing (13 subjects)
3. Quarries: rock drilling (8 subjects)
4. Quarries: stone cutting (10 subjects)
5. Wood industry: pallet repairing (9 subjects)
6. Metal industry: polishing of seat frameworks (5 subjects)
7. Metal industry: grinding of metal frameworks (4 subjects)
8. Metal industry: polishing gun barrels (8 subjects).

These sectors were selected in order to get a fairly large range of vibrating tools: drillers, grinders, polishers, pneumatic hammers, etc.

The second group (G2) included 62 subjects performing heavy and repetitive hand and arm work, without vibration in a steel industry. They were packing coils (about 1m in diameter and height, weight around 10 t) and metal sheets (length and width around 1 m, height around 0.3 m and weight around 1 t). Two types of packaging, in metal or in cardboard, were used. The parts handled were heavy, cumbersome and sharp edged and the work constraints were clearly important.

The third group (G3), taken as a control group, included 46 people performing light and non-repetitive tasks, without vibration, in the warehouse of the same steel industry.

Those workers were chosen at workplaces previously identified as fulfilling the criteria for the three groups. This was done on the basis of a short ergonomic analysis.

## MATERIAL AND METHODS

The protocol planned to interview each worker individually three times: at the beginning of the study and 12 and 24 months later. They were fully informed of the objectives and the protocol of the study and of the confidentiality of the results. They gave individually their free written consent to participate in the study and were free to withdraw at any time and for any reason.

All interviews were conducted by the same physio-therapist.

The checklist used to collect information was the same as in a previous study (Malchaire, 1995) with some questions added concerning vibration exposure and tingling episodes in the hand.

It included a total of 160 items concerning:

1. The personal characteristics: age, weight, height,

plant and workplace seniority, smoking habits, alcohol consumption, sports in general and involving the upper limbs, and hobbies.

2. The health status: chronic diseases other than upper limb disorders (diabetes, thyroid problems, hypertension, rheumatoid arthritis, gout...), accidents, drugs.
3. The actual and past working conditions: perception of the physical workload, lifting efforts performed with the hands and wrists, angular repetitiveness, exposure to some risk factors such as solvents, noise, and the use of vibrating tools. The G1 workers were invited to describe the types of machines they had used and they were using (grinders, drillers...) and to estimate the frequency and duration of use of each of them.
4. The occurrence of MS in answer to the following question from the Nordic questionnaire (Kuorinka *et al.*, 1987): 'Have you at any time, during the last 12 months, had trouble (ache, pain, discomfort) in the wrist/hand of the dominant hand', Yes or No. This question was repeated for the neck, the shoulders, the elbows and the low back, but the results will not be reported here.

Three additional questions were asked concerning:

- The characteristics of the symptoms: disturbance, diffuse pain or local and acute pain.
- The duration of the symptoms: less than 2 hours, less than one day, longer.
- Their frequency: seldom, sometimes, often or always.

Based on this information, the MS were classified in two categories:

- Moderate
  - 'Serious': local or acute pain, lasting more than one day, recurring often or always.
5. The episodes of tingling at the level of the fingers. The workers had to describe the frequency of occurrence of these episodes, the circumstances in which they appeared, the fingers involved, as well as problems of dexterity or muscular weakness. The SN were classified, first on the basis of the 'Stockholm' scale (Brammer *et al.*, 1987) in stage 1, 2 or 3, secondly, in 'moderate' and 'serious' (when tingling occurring often or always, that is at least once a week).

According to the nature of the item, the data were recorded in terms of intensity (light, medium, and heavy) or of frequency (never, sometimes, often, and always).

#### *Follow-up of the study population*

Not all the workers could be re-interviewed the second and third years for different reasons: change of job, refusal to further collaboration, departure from the company, absence due to disease or accident... The exact reasons for these absences were investi-

gated as far as possible. With one exception (one worker operated on for a carpal tunnel syndrome), the reasons did not appear to be directly related to MS or SN.

Among the 177 workers participating in the study the first year, (69, 62 and 46 respectively in the three groups), 152 were available the second year (57, 55 and 40) and 137 of the 152 the third year (47, 51 and 39). Therefore, 25 workers were only interviewed once, 15 twice and 137 three times as anticipated.

The prevalence reported hereunder is related to the data collected for the 177 subjects during the first interview and concerns therefore the occurrence of MS and SN during the 12 months preceding the study. The number of new cases per year (incidence) during the study had to be calculated for the persons without problems initially. As the initial prevalence of MS and SN was high, the number of subjects available for the incidence study was too limited. Therefore, it was decided to consider the evolution of the complaints instead of their occurrence. According to that choice, a hand-wrist was considered a new case, if the complaint changed from 'nil' or 'moderate' to 'serious' as defined here above, during the first or the second year of the prospective study. The incidence of 'serious' SN was calculated similarly.

In parallel with these interviews, measurements were performed for both hands to quantify the biomechanical constraints (awkward posture, forces, repetitiveness and the movement velocities) and, for G1, the exposure to hand-arm vibration.

#### *Measurement of biomechanical factors*

For practical reasons, the biomechanical constraints were evaluated only for 127 workers chosen at random from the 177 subjects (55 for G1, 39 for G2 and 33 for G3). The measuring procedure was described in detail in previous papers (Malchaire *et al.*, 1996, 1997).

The biomechanical constraints were summarised in the following variables for each work analysis and finally, across these work analyses, for each workplace:

- mDr: mean relative angle in radial or ulnar deviation (in % of the maximum deviation);
- mFr: mean relative angle in flexion or extension (in % of the maximum movement);
- $R_{ang}$ : angular repetitiveness, defined as the number of angular transitions (per minute) of the wrist from a 'neutral' position to an 'extreme' position (more than 50% of the maximum angle in deviation or more than 60% in flexion-extension);
- mVd and mVf: movement velocity in each plane. These velocities were computed as the mean absolute velocities in degrees per second in deviation and flexion-extension.
- mEMGr: mean relative RMS EMG value com-

puted in percentage of the maximum EMG value initially recorded;

- $R_{EMG}$ : force repetitiveness defined as the number of transitions (per minute) of the wrist force from low to high (relative EMG value greater than 15% of the maximum EMG).

#### *Measurement of hand-transmitted vibration*

The exposure to vibration could only be evaluated for 46 of the 69 workers of G1, chosen at random.

Recordings of the actual exposure were made on 3–7 workers, depending upon the number of workers per workplace. These recordings lasted from 10 to 50 min and included from 3 to 4 work cycles.

The workers were holding the machines with both hands at three workplaces only (workplaces 3 rock drillers, 8 metal grinders and 9 barrel polishers). In these three instances, vibration was recorded on both hands.

The vibration exposure was estimated in three steps.

1. Short duration recordings were made, using a tri-axial B & K 4321 accelerometer and a B & K 2231 sound level meter, to determine the dominant axes of vibration for each vibrating tool.
2. Vibration amplitudes were recorded for each vibrating machine during a representative work period, using a B & K 4384 accelerometer placed in the dominant axes of the vibration. This accelerometer was connected via a B & K 2231 sound level meter (with a vibration module B & K 2522) to a digital DAT recorder (TEAC RD111T). The frequency response of the recorder extended from 0 to 1500 Hz and the dynamic range was greater than 70 dB. The signals were played back in the laboratory and analysed using a frequency analyser (ONO SOKKI CF 350) in order to determine the weighted and unweighted equivalent acceleration. Measurements were performed on the handle or the body of the vibrating tool according to the way the user was holding the tool. Before any measurement in the field, the measuring equipment was calibrated using a calibration source B & K 4291.
3. The time during which the worker was exposed to vibration for each machine was determined. The hand adapter B & K UA0891 was located in the palm of the hand, in the axis X, in contact with the vibrating machine. The recordings lasted 10–50 min, depending upon the repetitiveness of the work. The adapter was connected to the sound level meter B & K 2513 carried by the worker. The DC output, proportional to the RMS acceleration amplitude, was recorded at a sampling frequency of 10 Hz on the Polylog digital data logger.

The vibration exposure at each workplace was characterised by the following parameters, combining the exposure duration for each machine recorded using the adapter and the vibration amplitudes recorded during the simulation phases:

- The weighted ( $A_{eqw}$ ) and unweighted ( $A_{eq}$ ) equivalent acceleration amplitudes for each worker during representative work phases;
- The total duration of vibration exposure;
- The weighted ( $A_{EPw}$ ) and unweighted ( $A_{EP}$ ) personal exposure amplitude, for an exposure of 8 h per day and 40 h per week.

The personal vibration exposure dose weighted ( $D_w$ ) and unweighted ( $D$ ) were evaluated for each subject from the personal exposure amplitude characterising his workplace and his seniority ( $T$ ) at that workplace by the following expressions:  $D = A_{EP}T^{0.5}$  and  $D_w = A_{EPw}T^{0.5}$ .

#### *Statistical methods*

The results for the three groups were compared by means of Chi-2 tests for the discrete variables (complaints and some personal data). For the continuous variables, a one-way analysis of variance was performed, followed by a Scheffe multiple range test.

The relationship between the likelihood of complaints and the work constraints was then studied with a multiple logistic regression, taking into account the personal confounding factors collected during the interviews.

For someone developing complaints for the first time during the  $i$ th year (first or second), the data used for the logistic regression were the data collected at the beginning of the  $i$ th year and the development or not of complaints during that year.

For those who participated in the study during one year only (and were seen twice only), the data used were again the development or not of complaints during that year and the personal data at the beginning.

For those who participated during the 2 years and who did not develop complaints, the data used were the absence of complaints and the personal data at the beginning of the second year.

The use of a logistic model or a linear general model (with a log link) to analyse cross-sectional data has been discussed in many papers (Lee and Chia, 1993; Lee, 1994, 1995; Stromberg, 1994, 1995; Zocchetti *et al.*, 1997; Thompson *et al.*, 1998). According to Lee (1995), Zocchetti *et al.* (1997) and Stromberg (1995), the logistic function should be used to force the prevalence and the incidence probability to range from 0 to 1. However, the choice of the logistic analysis leads to odds ratios (OR) rather than to risk ratios (RR); these are less easily interpreted, and the derivation of the RR from the OR is impossible in multivariate analyses without making assumptions about the other variables.

The prevalence odds ratios (POR) and the incidence odds ratios (IOR) directly derived from the coefficients of the logistic model will therefore be presented and discussed.

## RESULTS

### Population

Table 1 gives the mean and standard deviation of age, weight, height and seniority for the three groups of workers.

The three groups can be considered to be comparable, although the workers exposed to vibration have a slightly greater weight and the control group slightly lower workplace seniority.

Seventy-four percent of the subjects estimated their health to be 'good' or 'excellent'; 17% suffered from a 'chronic disease' (diabetes, thyroid problems, hypertension, rheumatoid arthritis, gout...); 56% had had an accident concerning the upper limbs. Compared to G1, the prevalence of chronic diseases was significantly greater in G2 and lower in G3.

As far as their personal habits are concerned, globally, 47% of the workers were smokers, 67% drank alcohol (from a little to a lot) and 45% practised one sport or another (4.5% a sport involving the upper limbs) more than once a week. 60% of the workers had heavy extra-occupational activities or hobbies and 20% used vibrating tools during these activities.

The workers exposed to vibration consumed alcohol and used vibrating tools during their hobbies more significantly than the others.

### Prevalence and incidence

Table 2 gives for the three groups, the prevalence during the 12 months prior to the study and the incidence of 'serious' MS and SN during the study.

The three groups differ regarding to initial prevalence of complaints significantly greater for G1 (72.5% on either or both sides) than for G2 (56.5%), itself more than G3 (30.4%).

The prevalence of SN (on either or both hands) is

about 40% for G1 and 2.5 times smaller in the two other groups. Most of these SN correspond to stage 1 (SN1) of the Stockholm scale, a few to stage 2 (SN2) and none to stage 3 (SN3). The frequency of these tingling sensations differs also very significantly between G1 and the two other groups: 25% complaining at least once per week in G1 and 2% only in G2 and G3. These SN were responsible for work interruptions in 19% of the workers in G1 and 5% only in the two other groups.

The complaints, the biomechanical constraints and the vibration exposure (G1) were evaluated separately for both hands/wrists. From the 354 hands/wrist at the start of the study, 222 did not present 'serious' MS or SN and were available for the follow-up study (64, 86 and 72 respectively for G1, G2 and G3). During the two years follow-up, new cases of 'serious' MS (37) and SN (24) appeared. The annual incidence was then respectively 8.3 and 5.4% on average.

The comparison of the incidence between the three groups led to the following conclusions:

- The number of new cases of 'serious' MS was greater for G1, but this increase was not statistically significant: incidence of 10.2, 8.7 and 6.3% respectively for the three groups.
- The increase was statistically significant ( $P < 0.01$ ) for SN: 10.9, 4.1 and 2.1% respectively.

### Biomechanical and vibration constraints

Figure 1 compares the mean values of the biomechanical parameters for the three groups of workers.

The most significant conclusions are:

- Velocities and amplitudes of movement of the wrist were of the same order of magnitude for the three groups.
- Forces (actually the electromyographic activity recorded on the forearm) were significantly more important for G1: +60% with respect to G2 and +190% by comparison to G3.

Table 1. Means and standard deviations of the characteristics of the 3 groups of workers and statistical significance of the differences between the group exposed to vibration and the two others (one-way analysis of variance)<sup>a</sup>

	G1 vibration	G2 heavy work		G3 control group	
N	69	62		46	
Age (yr)	35.6 (7.2)	35.1 (6.9)	–	35.6 (6.3)	–
Weight (kg)	81.3 (12.4)	75.4 (12.4)	***	74.9 (11.9)	***
Height (cm)	174.6 (6.7)	173.7 (7.8)	–	172.9 (5.9)	–
Workplace seniority (yr)	7.0 (6.1)	7.2 (6.2)	–	4.9 (4.7)	*
Plant seniority (yr)	12.9 (8.4)	13.4 (7.0)	–	14.4 (6.6)	–
Smoking (%)	47.8	53.2	–	37.0	–
Sport (%)	44.9	37.1	–	54.3	–
Alcohol (%)	82.6	53.2	***	63.1	*

<sup>a</sup>–NS; \* $P < 0.05$ ; \*\*\* $P < 0.001$ .

Table 2. Prevalence at the start of the study and incidence during the study of hand-wrist MS and SN<sup>a</sup>

Complaints	Prevalence (%)					Incidence (%)				
	Total	GR1	GR2	GR3	Chi <sup>2</sup>	Total	GR1	GR2	GR3	Chi <sup>2</sup>
<i>MS</i>										
Right hand	47.5	65.2	45.2	23.9	**	9.8	9.4	11.5	8.3	–
Left hand	36.2	53.6	27.4	21.7	*	7.0	10.9	6.4	4.2	–
<i>Sensorineural</i>										
Right hand	20.3	33.3	11.3	13.0	**	6.1	12.5	3.8	2.8	*
Left hand	18.6	29.0	14.5	8.7	*	4.8	9.4	4.3	1.4	–

<sup>a</sup>–NS; \* $P < 0.05$ ; \*\* $P < 0.01$

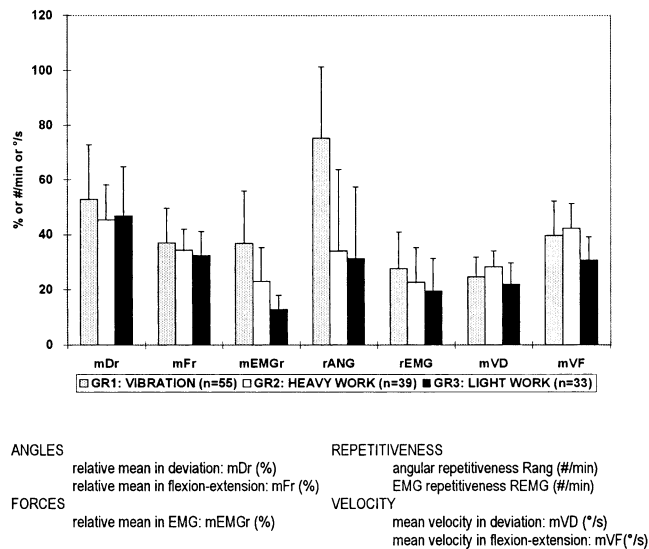


Fig. 1. Mean and standard deviation values of the biomechanical constraint parameters for the three groups.

- Angular repetitiveness was about twice as great for G1 as for the two other groups.

For the workers of G1 exposed to vibration, on average, the exposure duration varied from 10 to 70% of the work time and the  $A_{EPw}$  varied from 0.5 to 25.4

$ms^{-2}$  (Table 3). On average, the order of magnitude of the unweighted personal exposure acceleration was about seven times greater.

The frequency weighted vibration exposure dose varied from 1.2 to 70.6  $ms^{-2} yr^{0.5}$  and the unweighted dose between 6.4 and 500.7  $ms^{-2} yr^{0.5}$ .

Table 3. Characteristics of vibration exposure in the eight conditions of G1

Workplace	Hand	% Time exposed (%)	Weighted personal amplitude $A_{EPw}$ ( $ms^{-2}$ )	Unweighted personal amplitude $A_{EP}$ ( $ms^{-2}$ )
1. Bolters	Right	9.2	0.5	2.6
2. Grinders	Right	20.3	1.6	9.4
3. Rock drillers	Right	56.3	25.4	180.1
4. Rock cutters	Right	38.3	4.7	35.4
5. Pallet repairing	Right	32.9	7.4	30.1
6. Seat polishers	Right	67.2	5.5	41.3
7. Grinders	Right	43.5	9.0	150.0
8. Barrel polishers	Right	20.5	10.6	25.8
3. Rock drillers	Left	56.3	25.2	178.3
7. Grinders	Left	55.6	7.4	64.0
8. Barrel polishers	Left	14.0	6.3	17.3

*Logistic regression analysis of the likelihood of complaints in the first year cross sectional study*

Two multiple logistic regression models were computed using the downward stepwise procedure with, as dependent variable, the existence or not of MS or SN and, as independent variables, the personal and exposure data. A first multivariate model was computed, taking into account only the personal data. Then, all the factors describing the exposure conditions were added at once to the significant personal data resulting from this first model and the final model was derived using a downward stepwise procedure.

Table 4 shows the results for the MS. The results show that the likelihood of complaints was greater for the right wrist and for people suffering from chronic disease, bad health in general and problems with fine tasks. Two characteristics of previous working conditions were associated: the wrist efforts (positively) and the use of vibrating tools (negatively). Paradoxically, the likelihood of complaints was higher for the non-smokers.

The exposure conditions were taken into consideration in two different ways. The first method was to consider only the group to which belonged the worker: the likelihood of complaints was much greater for G1 than for G2, itself significantly greater than G3.

The second method was to take into consideration the mean biomechanical and vibration constraint parameters at each workplace. The significant parameters in the multiple logistic regression were mainly the parameters of force (mEMGr and  $R_{EMG}$ ) and the duration of use of the vibrating tools. Among the parameters describing the vibration exposure, only one remained in the multivariate regression model:

the duration of use of the vibrating tools. When this parameter was withdrawn, an association was found with the personal exposure acceleration or the dose. It is worth noting that neither the mean angles nor the velocities of movement were significant in the multiple regression.

Table 5 gives the same results concerning the SN. The same parameters of opinion of poor health and again of non-smoking were associated with the likelihood of these complaints. No difference existed between G2 and G3, while the fact of working with vibrating tools (G1) was associated with a large increase of the likelihood of complaints (POR = 4.5). When the constraints parameters were considered, instead of the fact of belonging to one group, two biomechanical parameters and the weighted personal exposure acceleration (POR = 3.55) were associated with SN. The association remained significant (POR = 1.24 and 1.30) when, instead of the  $A_{EPw}$ , the duration of exposure per day or the vibration dose was considered.

The same regression was run using the unweighted personal exposure accelerations and doses. The odds ratios became respectively 1.15 and 1.03 with significance levels slightly smaller than for the weighted values. When the mean difference in order of magnitude between unweighted and weighted values was taken into consideration, these odds ratios became respectively 2.67 and 1.23, slightly smaller than for the frequency weighted parameters.

*Analysis of the longitudinal data ('serious' complaints)*

Similarly, two multiple logistic regression models were computed with, as dependent variable, the incidence or not of 'serious' MS or SN, and, as inde-

Table 4. Multiple logistic regression for the MS as a function of the personal data (POR: prevalence odds ratios, 95% confidence interval and statistical significance)<sup>a</sup>

Factors	POR	CI 95%	Significance
<i>Personal data</i>			
Side (right vs left)	1.82	1.12–2.94	*
Health (bad)	2.38	1.35–4.35	**
Smoking	0.42	0.25–0.70	***
Chronic diseases	2.01	1.02–3.99	*
Wrist efforts at previous workplaces	2.51	1.49–4.23	***
Use of vibrating tools at previous workplaces	0.27	0.13–0.54	***
<i>Exposure groups</i>			
G1 vs G2	4.00	3.88–4.15	*
G2 vs G3	2.26	1.13–4.51	*
G1 vs G3	9.01	4.39–18.73	**
<i>Biomechanical constraint</i>			
Mean relative EMG: mEMGr (%)	1.46	1.16–1.83	**
Repetitiveness in force $R_{EMG}$ (#/min)	2.05	1.25–3.37	**
<i>Vibration constraint</i>			
Duration of use of vibrating tools per day (%)	1.31	1.07–1.61	**
Or weighted personal exposure acceleration $A_{EPw}$ ( $ms^{-2}$ )	3.36	1.28–8.84	*
Rr weighted vibration dose $D_w$ ( $ms^{-2} yr^{0.5}$ )	1.47	1.00–2.16	*

<sup>a</sup>\*\* $P < 0.05$ ; \*\*\* $P < 0.01$ ; \*\*\*\* $P < 0.001$ . All the odds ratios for the biomechanical and vibration parameters are computed for a variation of 10: 10%, 10  $ms^{-2}$ ,...

Table 5. Multiple logistic regressions between the SN, the personal data and the constraint parameters (POR: prevalence odds ratios, 95% confidence interval and statistical significance)<sup>a</sup>

	POR	CI 95%	Signification
<i>Personal data</i>			
Health (bad)	3.26	1.75–6.25	***
Smoking	0.54	0.30–0.97	*
Wrist efforts at previous workplace	3.42	1.77–6.63	***
Use of vibrating tools at previous workplace	0.23	0.10–0.52	***
<i>Exposure groups</i>			
G1 vs G2 and G3	4.50	2.39–8.48	***
<i>Biomechanical constraint</i>			
Relative mean angle in flexion extension mFr (%)	1.75	1.12–2.73	*
Repetitiveness in force $R_{EMG}$ (#/min)	2.20	1.29–3.77	**
<i>Vibration constraint</i>			
Weighted personal exposure acceleration $A_{EPw}$ ( $ms^{-2}$ )	3.55	1.68–7.51	***
Or weighted vibration dose $D_w$ ( $ms^{-2} yr^{0.5}$ )	1.30	1.01–1.69	*
Or duration of use of vibrating tools per day (%)	1.24	1.05–1.47	*

<sup>a</sup>\*\* $P < 0.05$ ; \*\*\* $P < 0.01$ ; \*\*\*\* $P < 0.001$ . All the odds ratios for the biomechanical and vibration parameters are computed for a variation of 10: 10%, 10  $ms^{-2}$ ,...

pendent variables, the personal and exposure data (Tables 6 and 7).

As in the analysis of the cross sectional data, the likelihood of 'serious' MS was more important for the subjects with chronic diseases and for those with difficulties performing fine manual tasks. It decreased slightly with height but more significantly with seniority at the workplace, mainly since actually seniority is smaller for G3 (Table 1). This likelihood was not significantly different for the three groups although the incidence was greater for G1. Again the most significant biomechanical parameter was the force (relative mean EMG). The IOR for repetitiveness and movement velocities were lower than 1, probably due to the correlation between these parameters and the forces. The logistic models did not show an association with any of the parameters characterising the vibration exposure.

The likelihood of 'serious' SN was more important

for the subjects with a poor health, sleeping problems, headaches and hobbies. It increased with weight, decreased with height and was smaller for smokers. The main result was the very large increase for the workers using vibrating tools (main association with the weighted personal exposure acceleration) and the lack of association with any biomechanical parameter.

Again the results were quantitatively about the same when the unweighted personal exposure acceleration and dose values were used in the last model. The IOR became 15.56 and 1.83 respectively with slightly greater confidence intervals (when compensated for the mean order of magnitude difference).

## DISCUSSION

### Prevalence

The prevalence of MS or SN was recorded using the Nordic questionnaire (Kuorinka *et al.*, 1987) as

Table 6. Multiple logistic regression for the incidence of 'serious' MS as a function of the personal data and the constraint parameters (IOR: incidence odds ratios, 95% confidence interval and statistical significance)<sup>a</sup>

	IOR	CI 95%	Signification
<i>Personal data</i>			
Chronic diseases (yes vs no)	3.35	1.11–10.16	*
Height (cm)	0.95	0.92–0.98	**
Workplace seniority (yr)	0.16	0.06–0.46	***
<i>Exposure groups</i>			
G1 vs G2 and G3	–	–	–
<i>Biomechanical constraint</i>			
Mean relative EMG mEMGr (%)	5.64	2.57–12.34	***
Angular repetitiveness Rang (#/min)	0.62	0.45–0.85	**
Mean velocity in flexion extension mVF ( $^{\circ}/s$ )	0.51	0.36–0.74	***
<i>Vibration constraint</i>			
	–	–	–

<sup>a</sup>–NS; \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$ . All the odds ratios for height, seniority and for the biomechanical and vibration parameters are computed for a variation of 10: 10 cm, 10%, 10  $ms^{-2}$ ,...



Table 7. Multiple logistic regression for the incidence of 'serious' SN as a function of the personal data and the constraint parameters (IOR: incidence odds ratios, 95% confidence interval and statistical significance)<sup>a</sup>

	IOR	CI 95%	Signification
<i>Personal data</i>			
Bad health	3.54	1.05–11.93	*
Sleeping troubles	4.84	1.54–15.19	**
Headaches	3.84	1.14–12.92	*
Weight (kg)	1.48	1.04–2.11	*
Height (cm)	0.76	0.62–0.92	**
Smoking	0.15	0.04–0.57	**
Hobbies	3.15	1.10–8.99	*
<i>Exposure groups</i>			
G1 vs G2 and G3	28.51	6.22–130.76	***
<i>Biomechanical constraint</i>			
<i>Vibration constraint</i>			
Weighted personal exposure acceleration $A_{EPw}$ ( $\text{ms}^{-2}$ )	18.45	3.84–88.67	***
Or weighted vibration dose ( $\text{ms}^{-2} \text{ year}^{0.5}$ )	2.04	1.30–3.21	**
Or % time using vibrating tools per day	2.50	1.65–3.80	***

<sup>a</sup>—NS; \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$ . All the odds ratios for height, weight and for the vibration parameters are computed for a variation of 10: 10 cm, 10  $\text{ms}^{-2}$ ,...

in most studies on MS disorders. However, interviews were used in order to limit the possibilities of misinterpretation by the workers and to collect the data from each participant. Therefore, the study is based on complaints and not on disorders. Workers suffering from disorders are less likely to still be at work. A question was added to the Nordic questionnaire to deal with SN disorders: 'Did you experience tingling or numbness in the fingers during the last 12 months?' Cases possibly due to personal physiological factors were excluded.

The Stockholm scale for SN disorders (Brammer *et al.*, 1987) defines stage SN2 as 'intermittent or persistent numbness, reduced sensory perception'. This publication mentions many possible sensory perception tests. However, it does not describe how the results of any of these tests can corroborate the subjective losses of perception. Subsequently, many researches attempted to determine what tests would be adequate and most failed. In a recent paper (Cock *et al.*, 2000), the authors showed again that the tests available do not make it possible to corroborate this classification. Therefore, it must be admitted that the Stockholm classification is based solely on symptoms of numbness or reduced perception. This was done in the present paper. The majority of the workers (22) were at stage SN1, six at stage SN2 and none at stage SN3. Based on this low prevalence, it was decided to refer in the rest of the study, not to the Stockholm scale, but simply to the presence or not of SN.

Studies about a possible association between MS and vibration exposure dealt mostly with carpal tunnel syndrome (Cannon *et al.*, 1981; Silverstein *et al.*, 1987; Wieslander *et al.*, 1989). Few were interested in MS in general.

The prevalence of MS in our study appears unusually high (70%) compared to that reported for forestry workers (58%, Bovenzi *et al.*, 1991), for riv-

eters (32%, Burdorf and Monster, 1991) and for people using unspecified vibrating tools (11%, Dimberg, 1985). A similar difference, but with lower orders of magnitude, was reported by Bovenzi *et al.* (1991) between a group exposed to vibration (58%) and a group with 'solely manual work' (10%).

As far as SN are concerned, our prevalence of 40% is of the order of magnitude of the values reported for forestry workers (53%, Färkkilä *et al.*, 1988), for dentists (29%, Stockstill *et al.*, 1993), for users of different vibrating tools (grinders, rock drill operators, motor sawyers, ... 23%, Kakosy, 1994), for riveters (17%, Burdorf and Monster, 1991) and for stone workers (40%, Bovenzi *et al.*, 1994). It is largely smaller than that reported on different groups (10 to 80%, Pyykkö, 1986; Pelmeur *et al.*, 1992).

The prevalence of SN reported for workers not exposed to vibration varies between 7% (Burdorf and Monster, 1991) and 16% (Letz *et al.*, 1992; Bovenzi *et al.*, 1994).

#### *Biomechanical constraints*

Biomechanical constraints were characterised in terms of posture, repetitiveness, forces and movement velocities. The overall methodology was presented and discussed earlier (Malchaire *et al.*, 1996, 1997). Although very sensitive to errors and artefacts (in particular the influence of temperature), the Penny and Giles goniometers were used for recording the angles of the wrists and, by differentiation, the angular velocities in the two planes. The temperature effect was controlled through calibration in the environment and on the worker, before and after the observation period. The surface EMG, often considered too inaccurate by neurophysiologists, was the only practical way to gain indication of the forces. Since the relation EMG to force is approximate, no attempt was made to derive the force, and the mean

EMG activity (in percentage of the activity during a maximum prehension handgrip) was used. Many different methods were reported to quantify repetitiveness: angular velocities (Marras and Schoenmarklin, 1993), number of work cycles per unit of time (Luopajarvi *et al.*, 1979), number of hand efforts (Stetson *et al.*, 1991) or movements (Moore *et al.*, 1991), number of parts manufactured per unit of time (Tanaka and McGlothlin, 1993). In the present study, it was decided to record the number of movements per minute from or towards an extreme position and the number of times the muscular activity became higher than 15% of the activity during the reference handgrip. These parameters were further discussed in Malchaire *et al.* (1996, 1997).

As observed in our previous studies (Malchaire *et al.*, 1996, 1997), the biomechanical parameters are highly intercorrelated, underlining the fact that the different components of biomechanical constraints tend to occur simultaneously. However, the parameters discriminating most between the three groups are forces (muscular activities) and repetitiveness. The use of vibrating tools at the workplaces encountered for this study required a significant increase in forces. This was also the case in the study by Silverstein *et al.* (1987). The variations in postures (repetitiveness) were also clearly increased, as observed also by the same authors and by Radwin and Armstrong (1985). This however cannot be generalised and is a function of the nature of the work and the number of different vibrating tools used.

#### *Vibration constraints*

ISO Standard 5349 (ISO, 1986) defines the method for measurement of hand transmitted vibration. It uses a monoaxial accelerometer successively placed in the three axes X, Y and Z or a tri-axial accelerometer and three recording or measuring devices in parallel. The accelerometer is fixed on the handle. This procedure is inapplicable in practice, as it clearly fails to recognise the real conditions where workers use intermittently one or several vibrating tools and, very often, in varying postures.

An alternative could be to use the hand adapter developed by Bruel & Kjaer (B & K UA0891) held in the hand of the worker against the handle of the vibrating tool. The frequency response of this adapter was however criticised (Rasmussen, 1982; Lemaire, 1991) and this procedure has never been validly compared to the ISO procedure. At this stage however, it can only be used to monitor, with accuracy, the time during which the different vibrating tools are used. This is undeniably the most reliable method for measuring the exposure duration, provided that the surveyed periods are representative of the long term exposure of the workers.

The exposure duration being adequately measured, it remains to estimate the exposure level for each vibrating tool.

In most cases, the hand position on the handle of the vibrating tool was changing constantly. Therefore, the tri-axial equivalent acceleration, square root of the sum of the square of the acceleration in the three axes, was estimated. Additionally, as the frequency weighting recommended by ISO 5349 was designed for vascular disorders (Bovenzi *et al.*, 1994) and is questioned for SN disorders (Griffin, 1997), both the weighted and unweighted equivalent acceleration amplitudes were estimated as recommended by Pelmeur *et al.* (1992). Ideally, this would require the recording of the AC acceleration signals in the 3 axes simultaneously and their analysis with and without frequency weighting. It appeared readily that such theoretically accurate evaluations were not possible without disturbing significantly the working conditions and therefore losing the representativeness of the data. A compromise was found in, first, determining the dominant axis for each vibrating tool using a tri-axial accelerometer and, secondly, recording the acceleration signal in the dominant axis during a representative work period of about 2 min. The weighted ( $A_{eqw}$ ) and unweighted ( $A_{eq}$ ) equivalent acceleration amplitudes were then derived to characterise each vibrating tool.

The personal exposure acceleration amplitude was finally estimated, combining the exposure data for a subject and the vibration data for the different tools he was using.

This procedure still suffers limitations:

- The vibration in the non-dominant axes is neglected. This is probably not a significant error in the case of rock drillers or bolters as the vibration is usually strongly unidirectional. It is less acceptable for grinders for which vibration is often of the same order of magnitude in two axes.
- The  $A_{eqw}$  and  $A_{eq}$  are assumed to be representative of the use of a given machine in any circumstances and by all workers. The observations showed that, at each workplace, the postures and working conditions varied little between the different workers. However, interindividual differences do exist very likely in terms of hand-handle coupling and therefore of vibration exposure.

These limitations cannot be quantitatively appreciated.

An additional source of error in the evaluation of the personal exposure acceleration is the lack of representativeness of the time periods during which the measurements were performed. Several strategies have been proposed for the evaluation of exposure to chemical agents (Hawkins *et al.*, 1991) or noise (Malchaire and Piette, 1997): these recommend taking several samples of a certain duration (in minutes or hours) over a period (in days or weeks) during which all variations of the work are occurring. The complexity of the measurement of vibration (as well as of the biomechanical constraints) made it impossible

to use such strategies in practice. However, the concept of homogeneous exposure group was used in making sure that all the subjects at each workplace had the same exposure and in conducting the measurement for at least 50% of these workers.

The biomechanical constraints and vibration exposure measured for a given worker at a given workplace cannot be considered as characteristics of that worker, as they are influenced by the conditions existing at the time of the measurement. We therefore chose to characterise each workplace by the mean values of the observations for all the workers surveyed at that workplace. These mean values incorporate therefore the within and the between subjects variations.

The data show significant differences between the subgroups exposed to vibration, regarding:

- The exposure duration: from 9 to 67% of the time.
- The frequency content: the ratio between the weighted and unweighted equivalent levels varying from 4 to 16.
- The range of personal exposure weighted amplitude ( $A_{EPw}$ ): ranging from 0.5 to 25.4  $ms^{-2}$  and of unweighted amplitude ( $A_{EP}$ ) ranging from 2.6 to 180.1  $ms^{-2}$ .

For six of the eight workplaces,  $A_{EPw}$  exceeded the action value of 2.5  $ms^{-2}$  and about the limit value of 5  $ms^{-2}$  proposed for a European Directive. The amplitudes and the range of personal exposure accelerations are such that the data could demonstrate an association with the complaints if such association exists.

### Incidence

As the prevalence of MS and SN was important, the number of participants in the prospective study would have been limited if the criterion of no history had been adopted. The statistical power of the study would have been reduced. A criterion of seriousness of the complaints was therefore adopted. This makes it difficult to compare the conclusions with those of the literature and those of our previous study.

The 'seriousness' of SN was defined solely on the basis of the frequency of the complaints. A criterion of intensity would have been little reliable in view of the subjectivity of the symptoms.

For the MS, the seriousness was defined not only as a function of their frequency but also of their intensity and duration.

Seven personal characteristics appear to be associated to the development of 'serious' SN: weight (positively), height (negatively), smoking habits (negatively), hobbies (positively) and health symptoms (positively). These will be discussed in a companion paper. Alcohol is a major confounding factor for the relation between neurological outcomes and

occupational risk factors. However, no association was shown between alcohol consumption and SN neither in univariate nor in multivariate statistical analyses. As most (75%) of the workers with and without development of 'serious' SN declared drinking alcohol, the data collected in this study do not allow discussion of the influence of this confounding factor.

Tables 4 and 6 show that, for the existence as well as the development of MS, the likelihood is influenced more by biomechanical constraints than by vibration exposure. The most significant parameter of vibration exposure is the duration of use of vibrating tools per day: this might be an artefact, the biomechanical constraints being greater when using vibrating tools.

In Table 6, three biomechanical factors are significantly associated, one positively (mean relative EMG) and the two other negatively (angular repetitiveness and mean velocity in flexion-extension). These negative associations are actually due to the multicollinearity existing between all the biomechanical factors. When both factors are included with the personal data in the multiple logistic regression without the other biomechanical factors, both are positively and significantly associated with the development of 'serious' MS.

As far as SN are concerned (Table 5 for the cross sectional study and Table 7 for the prospective study), the variance explained by the biomechanical constraints is smaller or nil and that explained by vibration constraints is greater. The personal exposure acceleration is definitely the major occupational factor, reaching very high levels of significance: POR = 3.55,  $P = 0.0009$  for the existence of SN (cross sectional study) and IOR = 18.45,  $P = 0.0003$  for the development of 'serious' SN (prospective study).

Figure 2 gives the likelihood of development of 'serious' SN as a function of the weighted personal exposure acceleration ( $A_{EPw}$ ), considering a subject of 80 kg, 175 cm tall, in good health, non smoker and without extra occupational activities. The logit is given by is

$$\frac{P}{1-P} = \text{EXP}(-3.6266 + 0.2915 * A_{EPw})$$

This can be approximated by the simple expression  $P = 0.03 \text{EXP}(A_{EPw}/4)$ .

According to this prediction model, the risk of 'serious' SN at the proposed European 'action' value (2.5  $ms^{-2}$ ) is about 6% and at the 'limit' value (5  $ms^{-2}$ ) about 10%.

The analyses with unweighted vibration parameters gave results slightly less significant and odds ratios slightly smaller. Therefore, this study does not provide any argument against the use of this frequency weighting. This use should then be discussed more in

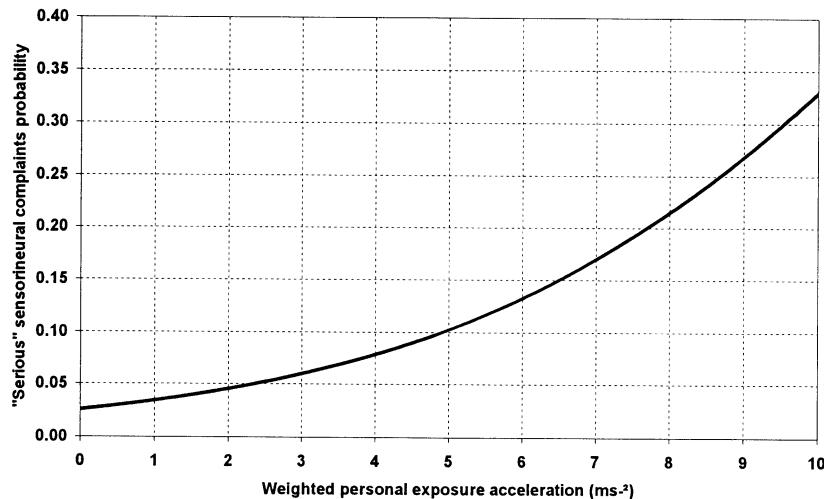


Fig. 2. Likelihood to develop 'serious' SN as a function of the weighted personal exposure acceleration amplitude in  $\text{ms}^{-2}$ .

relation to vascular effects, as done by Bovenzi *et al.* (1994, 1995).

The analyses do not demonstrate any significant relationship with age or seniority at the workplace. This was also the case for osteoarticular effects of vibration for which several papers (Malchaire *et al.*, 1986; Gemne and Saraste, 1987) suggested that these disorders do not appear systematically in the population of exposed workers as an early aging process but, rather, for some subjects apparently predisposed to these problems. The same might be true for neurological disorders that would appear — and maybe progress — only for some individuals. Among the group exposed to vibration and in spite of long seniority and high exposure levels, very few people were classified at the second and third levels of the Stockholm scale. It was then not possible to investigate the evolution of the symptoms with time.

### CONCLUSIONS

The relationships between hand–wrist MS or SN and biomechanical and vibration constraints were studied in a 3-year prospective study (for 'serious' complaints, occurring at least once a week) and in a cross sectional study at the beginning of the period.

In spite of greater biomechanical constraints, the likelihood of 'serious' MS is not significantly greater for the users of vibrating tools. The main association is with the force parameters as noted already in several studies (Silverstein *et al.*, 1987; Malchaire *et al.*, 1996, 1997). On the other hand, vibration exposure is not at all associated and does not appear to play any role, except indirectly through the increase of the biomechanical constraints.

On the contrary, the risk of development of 'serious' SN is remarkably greater (IOR = 28.5) for the workers exposed to vibration, while it appears to be independent of the biomechanical constraints. The

relationship is greater for the incidence (prospective study) than for the prevalence (POR = 4.5) (cross sectional study).

A simple prediction model is proposed for the likelihood of 'serious' SN as a function of the personal exposure acceleration value. This model makes it possible to estimate the risk encountered for different values proposed to limit exposure to hand arm vibration.

Two main results of the study are that the likelihood of SN does not increase with seniority, and the frequency weighted acceleration values makes it possible to better describe the risk of SN than the unweighted values.

*Acknowledgements*—This research was partly supported by a grant from the Federal Services for Scientific, Technical and Cultural Affairs from the Belgian Federal State. The authors want to thank the occupational physicians and the workers who participated in this study.

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