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Maintenance Operations: Workstation Adjustment, Working Posture, and Workers' Perceptions

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In the study maintenance workers were involved in pneumatic wrenching, oxy-gas cutting, and grinding at 5 different heights. Working posture and workers' perceptions were measured. Guidelines on working height were formulated in order to minimize the load on the musculoskeletal system. Data from the present experiment as well as from literature were studied in depth in order to disclose generic mechanisms behind the adoption of working postures during visual-manual operations in relation to workstation adjustment. It was found, for instance, that the working posture was constrained by a strictly followed relationship between gaze inclination and head inclination for-/backwards. Also, the study provided insight into the role of visual interference, viewing distance, manipulation distance, hand grip of the tool, and body support for stability. Concerning evaluation criteria for working postures, it was concluded that neck flexion/extension (i.e., head inclination for-/backwards versus trunk inclination for-/backwards) seems to be the dominant determinant of neck load, as compared to head inclination for-/backwards. Furthermore, the position of the upper arm with respect to the trunk, that is, shoulder flexion/retroflexion in particular, seemed to be a dominant determinant of shoulder and shoulder girdle load, as compared to upper arm elevation.

ergonomics pneumatic wrenching oxy-gas cutting grinding guidelines

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1. INTRODUCTION

Workers at the central maintenance department of the Dutch steel industry Hoogovens IJmuiden showed a large number of low back complaints. These complaints are most probably aggravated or caused by non-optimum (i.e., relatively unfavourable) working postures, which result from the fact that the maintenance objects lie either on the floor or on workbenches and trestles of fixed height. Under these circumstances the varying sizes of the objects hardly ever result in an optimum, that is, most favourable, working height. In order to optimize working posture and reduce the number of complaints, quantitative ergonomic guidelines on working height are needed, in addition to the technical means for creating an optimum height quickly and easily.

This study on maintenance operations (pneumatic wrenching, oxy-gas cutting, and grinding) is one in a series on visual-manual operations, using a standardized research approach (Delleman, 1991). The paper describes the effects of the adjustment of working height with respect to working posture and workers' perceptions. The latter are short-term effects, such as postural discomfort, due to physical load exposure of limited duration (cf. Corlett & Bishop, 1976). The *first* purpose of the paper is to study determinants of working posture (section 1.1), as well as relationships between working posture and workers' perceptions (section 1.3) for the sake of comparison with other visual-manual operations and generalization. Determinants of working posture are to be known for designing a proper workstation, whereas relationships between working posture and workers' perceptions are to be known, for instance, for evaluating existing work situations. The *second* purpose is to formulate ergonomic guidelines for adjustment (and redesign) of maintenance workstations (section 1.2). Matters of work organization (e.g., shift length, work-rest schedule) are recognized as major determinants of musculoskeletal complaints, but will not be a subject of study in this paper. This experimental study is part of a larger project on ergonomic prevention of musculoskeletal disorders of maintenance workers in the steel industry (Dul, Bolijn, Delleman, & Hildebrandt, 1991). The latter publication contains information that was omitted here, for reasons of conciseness.

First of all, somewhat more information on the three operations will be provided, bearing in mind the characteristics of the tools used in the present study (Figure 1), and assuming the right-handedness of the worker. A pneumatic wrench is a tool to tighten or loosen nuts, requiring a considerable

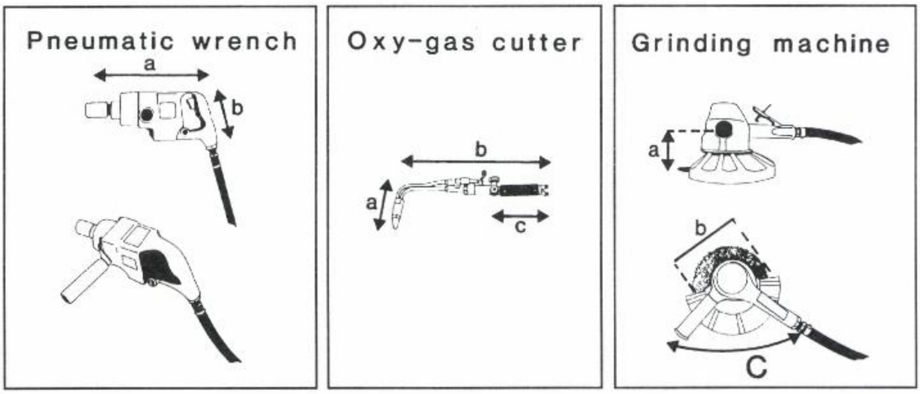

Figure 1. The pneumatic wrench, oxy-gas cutter, and grinding machine that were used in the experiments. Dimensions are presented in Table 2.

lifting force, mainly of the right upper extremity. The left hand is usually held close to the head of the wrench. Operation is characterized by moderate visual demands, that is, though gaze is directed towards the rotating head of the wrench (holding the nut on the bolt), no detailed observation is required.

An oxy-gas cutter is used to cut metal objects along a certain course by a high temperature flame. The object is preferably placed flat on a work-bench, for example, a little over the edge, so that sparks fall on the floor. Oxy-gas cutting is usually a precision operation, that is, requiring maximum stability of nearly the whole body, and characterized by high visual demands. In order to create a stable posture the worker places the left hip against the side of the bench and supports the left elbow on the top. The left hand is held close to the front of the cutter, that is, near the flame, whereas the right hand is at the rear side, close to the oxygen and gas tubes. The flame is primarily moved along the course by continuous slow translation of the right hand. The left hand rotates around the elbow, and merely controls the sideways position and height of the flame.

A grinding machine is used to remove roughnesses from metal objects. It consists of a fast-rotating circular-shaped stone plate within a metal housing, with two handles. Grinding is characterized by repetitive movements of both upper extremities, moderate visual demands, and a considerable lifting force, mainly of the right upper extremity. The demands on the visual system are comparable to those for pneumatic wrenching. The lifting force is needed even for more or less horizontal surfaces, because during operation only the front edge of the rotating plate is in contact with the object.

1.1. Determinants of Working Posture

Hypothetical determinants of working posture relating to working height will be described, following a short exposition on existing guidelines. A determinant is defined as a constraint as regards posture selection by the operator involved. Guidelines on working height in ergonomic handbooks (e.g., Grandjean, 1988) are of a very general nature, that is, for precision work a working height above elbow height is recommended, whereas for heavier work, making use of the weight of the upper part of the body in order to exert a hand force that is directed more or less downwards, a working height below elbow height is recommended. These height recommendations are considered to be of little practical use, and may easily lead to unfavourable working postures, because potential determinants of working posture are only taken care of to the very minimum. In practice questions would immediately arise: What height to choose if hand force were mainly directed upwards (lifting)? What would be the consequence if a tool were involved, requiring a certain way of grasping?

The hypothetical determinants of working posture for pneumatic wrenching, oxy-gas cutting, and grinding are as follows:

- Gaze inclination (all operations),
- Viewing distance (oxy-gas cutting),
  - Manipulation distance (oxy-gas cutting),
  - Horizontal manipulation distance (pneumatic wrenching and grinding),
- Right-hand grip (all operations),
- Stability/body support (oxy-gas cutting).

Firstly, it is hypothesized that for all three operations the head inclination for-/backwards is determined by the gaze direction in the vertical plane (up-/downwards, *gaze inclination*) through a strict relationship, as was found for other operations and tasks (e.g., Brues, 1946; Conrady, Krueger, & Zülch, 1987; Delleman & Berndsen, 1999; Straumann, Haslwanter, Hepp-Reymond, & Hepp, 1991). In addition, for oxy-gas cutting it is hypothesized that a participant will try to retain a favourable distance between the eyes and the target (i.e., the flame), in order to meet the high visual demands. Provided the size of the target is big enough in terms of visual acuity, participants prefer a *viewing distance* of between 50 and 100 cm. The preference exists, most probably, in order to minimize the strain of the extraocular and ciliary muscles, that are responsible for convergence and accommodation of the eyes, respectively (e.g., Akbari

& Konz, 1991; Brown & Schaum, 1980; Grandjean, Hünting, & Pidermann, 1983; Grandjean, Nishiyama, Hünting, & Piderman, 1982; Jaschinski, Heuer, & Kylian, 1998; Jaschinski-Kruza, 1987, 1988, 1990, 1991).

Secondly, it is hypothesized that a participant will try to retain a favourable reach position of the hand(s) with respect to the upper trunk (*manipulation distance*). Due to the relatively heavy weight of the tool in the right hand, for pneumatic wrenching and grinding this postural behaviour would be guided primarily by a minimization of the effect of gravitational force via changes of moment arm (i.e., a minimization of the horizontal component of the manipulation distance). For oxy-gas cutting the postural strategy would be an optimization of the joint positions of the prime mover, which is the right upper extremity (i.e., an optimization of the manipulation distance). In addition, it is hypothesized that for all three tools the working posture is determined by the reasonably rigid *right-hand grip* (for pneumatic wrenching and grinding due to the operation switch at the right handle).

Finally, it seems reasonable to put forward the hypothesis that the body support for *stability* during oxy-gas cutting will determine the working posture.

1.2. Formulation of Guidelines

With the standardized research approach mentioned before, professional participants execute an operation at various adjustments of their workstation. Several variables related to the working posture and the workers' perceptions are measured for each of these experimental conditions. Both types of information have their own specific limitations and advantages regarding the evaluation of experimental conditions and the formulation of guidelines. For example, if, besides gravity, other external forces on the body are known or absent, postures of *individual body segments*, such as the trunk and the upper arms, can be evaluated in terms of musculoskeletal load and the possible consequences for workers' health by the amount of deviation from a neutral posture (i.e., trunk upright, upper arms hanging down). However, the joint evaluation of the postures of various body segments and joints in terms of *total body* musculoskeletal load is not possible. Workers' perceptions have the potential to overcome this limitation. That is, it is assumed that workers are able to present an integral perception by mutual weighing of localized physical perceptions induced by postures of individual body segments and joints. However, concerning workers' perceptions, insight into the reliability and validity of measurements is only available for certain techniques used, and under specific load conditions (Van der Grinten & Smitt, 1992).

Due to the specific limitations and advantages of objective (working posture) and subjective information (workers' perceptions), both types of information are essential and complementary in the process of formulating guidelines. Experimental conditions are not recommended if workers' perceptions are significantly worse than for any other experimental conditions, subject to the basic requirement that the subjective information is supported by (i.e., can be explained by) objective information. In principle, the remaining (best) experimental conditions constitute the guideline.

1.3. Working Posture Versus Workers' Perceptions

The posture of the head and neck segment(s) in the sagittal plane is mostly evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, that is, head/neck inclination for-/backwards (e.g., Chaffin, 1973; Hünting, Grandjean, & Maeda, 1980; Hünting, Läubli, & Grandjean, 1981; Kilbom, Persson, & Jonsson, 1986; Lee, Waikar, Aghazadeh, & Tandon, 1986; Lindberg, Frisk-Kempe, Linderhed, & Eklund, 1993; Snijders, Hoek van Dijke, & Roosch, 1991). This measure or determinant of neck load is to be seen as an equivalent of the force delivered to counteract the gravity force on the segment, where a determinant is defined as the spatial orientation(s) of one or more (linked) body segments disclosing a systematic relationship with musculoskeletal load. It appears however that neck flexion/extension, that is, the for-/backward inclination of the head/neck segment with respect to the for-/backward inclination of the trunk segment, also plays a role with respect to neck load (Bendix & Hagberg, 1984; Delleman & Berndsen, 1999; Delleman & Dul, 1999; Harms-Ringdahl & Schüldt, 1988; Kumar, 1994; Lepoutre, Roger, & Loslever, 1986; Schüldt, Ekholm, Harms-Ringdahl, Arborelius, & Németh, 1986; Schüldt, Ekholm, Harms-Ringdahl, Németh, & Arborelius, 1986). Therefore, in this study both potential determinants of neck load will be closely studied in relation to the workers' physical perceptions for the neck region.

In relation to the previous paragraph, it should be recognized that workers' perceptions for the neck may also be determined by the posture of the shoulder girdle, which affects, for instance, the length of a major neck muscle, that is, the descending part of the trapezius muscle (Van der Helm, 1991). So, there is reason to study workers' perceptions with respect to the neck and the shoulder in close connection.

The posture of the upper arm segment is mostly evaluated by the amount of deviation from the hanging posture or the vertical, that is, upper arm elevation (e.g., Bjelle, Hagberg, & Michaelson, 1979, 1981; Chaffin, 1973; Dul, 1988; Van der Grinten & Smitt, 1992). This measure or determinant of shoulder (girdle) load is to be seen as an equivalent of the force delivered to counteract the gravity force on the segment (for the definition of determinant, refer earlier in the text). In addition, the direction of the elevated upper arm (forwards/sidewards, i.e., projected in the sagittal/frontal plane of the upright trunk, respectively) may play a role with respect to shoulder (girdle) load (Aarås, 1994; Jensen, 1991; Kilbom et al., 1986; Mital & Faard, 1990). Both potential determinants of shoulder (girdle) load will be studied.

Trunk posture in the sagittal plane is evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, that is, trunk inclination for-/backwards (e.g., Aarås, 1994; Jørgensen, 1970; Van der Grinten & Smitt, 1992; Wickstrom, Bhattacharya, & Shukla, 1988). With forward inclination the load on the low back increases. Systematic effects of trunk inclination for-/backwards, however, were found not only in the lumbar region, but also up into the cervico-thoracic region of the head-neck-trunk system (Andersson & Örtengren, 1974; Andersson, Örtengren, Nachemson, & Elfström, 1974). Considering also that head/neck inclination for-/backwards affects thoracic spine curvature (Nakaseko, Morimoto, Nishiyama, & Tainaka, 1993) and relates to complaints of the back and loin (Grandjean et al., 1982; Lee et al., 1986), there is reason to study workers' experiences with respect to the neck and the back in close connection.

The use of a tool in all three operations justifies a close study of the upper extremity posture, that is, especially regarding joint positions, and related workers' perceptions.

2. METHODS

For pneumatic wrenching, oxy-gas cutting, and grinding three separate experiments were set up. The overall approach was identical for all three operations. Deviating methodological approaches will be described for the operation in question. Test participants executed each operation at five different working heights. Working posture and workers' perceptions were measured.

2.1. Participants

Seven males from the Fitting sub-department, Hydraulics/Pneumatics section, participated in the experiments on pneumatic wrenching. In each of the experiments on oxy-gas cutting and grinding 8 males from the Steel Construction and Welding sub-department co-operated. Seven of them were the same for both experiments. For each of these participants both experiments were executed on separate days. Participants were asked to take part according to availability. Table 1 presents several characteristics of the three experimental participant groups. All participants were right-handed.

TABLE 1. Characteristics of the Experimental Participant Groups for Operations Pneumatic Wrenching, Oxy-Gas Cutting, and Grinding (Group Averages and Ranges)

Operation	Age (years)		Stature (cm)		Weight (kg)	
Pneumatic wrenching	32.1	(26–41)	183.3	(172–186)	77.7	(64–84.5)
Oxy-gas cutting	31.6	(21–47)	184.1	(176–194)	81.6	(68–99)
Grinding	28.6	(21–40)	184.4	(178–194)	78.5	(68–90)

2.2. Experimental Task

For pneumatic wrenching the experimental operation consisted of tightening 10 nuts on bolts, followed by loosening the same nuts. This cycle was repeated until the session ended. The bolts were fixed on a metal base, in a horizontal row, their centres 10 cm apart, and directed horizontally towards the participant. For oxy-gas cutting the experimental operation consisted of cutting strips from a long steel plate (25 cm wide and 2.5 cm thick). Fore/aft and left/right positioning of the plate was left up to the participant. For grinding the experimental operation consisted of grinding the top surface of a horizontal steel plate. Table 2 shows the dimensions, net weight, and weights in the right and left hand during operation for the tools used (Figure 1).

TABLE 2. The Characteristics of the Pneumatic Wrench, Oxy-Gas Cutter, and Grinding Machine That Were Used in the Experiments

Tool	Dimensions*	Net Weight (kg)	Weight (kg) in the Hand in a Typical Working Posture	
			Right	Left
Pneumatic wrench	a = 31 cm b = 10 cm	6.0 (+1.0**)	4.5	2.5
Oxy-gas cutter	a = 11.5 cm b = 39.5 cm c = 10 cm	1.0 (+1.0**)	1.5	0.5
Grinding machine	a = 9 cm b = 23 cm C = 100°	4.5 (+0.75**)	3.75*** (3.25****)	1.5*** (1.0****)

Notes. *—visualized in Figure 1, **—the weight of the tube(s) at an average experimental working height, ***—the weight will be reduced by the reaction force from the object during operation, ****—non-operating grinding machine supported on the object at the contact area.

2.3. Independent Variable

The independent variable of this study was working height, that is, relative to elbow height. Elbow height was defined as the distance from the floor to

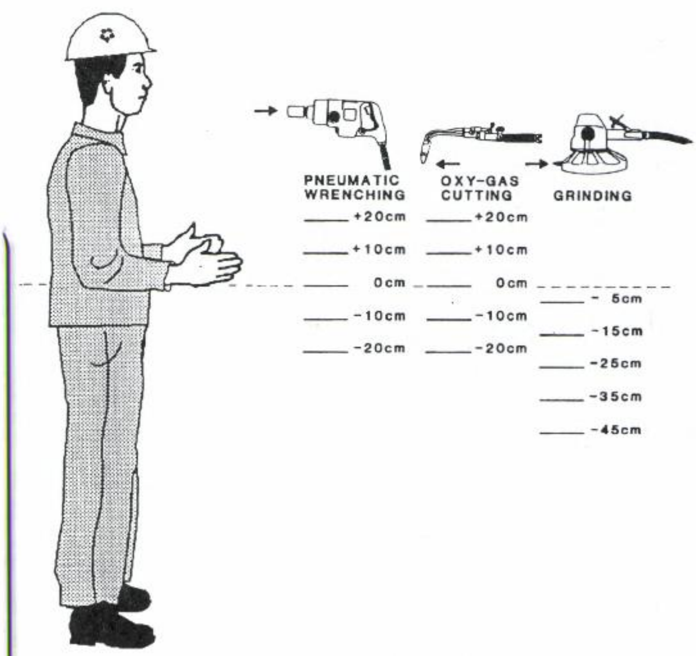

Figure 2. The five experimental working heights for pneumatic wrenching, oxy-gas cutting, and grinding. Elbow height is shown by the horizontal broken line.

the elbow (underside) with the participant standing upright, the upper arms hanging down, and the forearms horizontal (Figure 2). For each operation five levels for working height were selected on the basis of the posture effects seen during a small pilot-study (Figure 2). For pneumatic wrenching working height was defined as the centre of the bolt and nut. Working height levels –20, –10, 0, +10, and +20 cm relative to elbow height were selected. For oxy-gas cutting working height was defined as the height of the flame. Working height levels –20, –10, 0, +10, and +20 cm relative to elbow height were selected. For grinding working height was defined as the height of the contact area of the object surface and the grinding machine. Working height levels –45, –35, –25, –15, and –5 cm relative to elbow height were selected.

2.4. Experimental Procedure

The participants carried out the experimental operations at the central maintenance building. Working height was adjustable by a scissor lift table. Each participant participated in five experimental sessions, each consisting of 5 min of operation. In each session one of the five working heights was presented. A session was followed by a break of at least 10 min. The order of presentation of the working heights was balanced as well as possible over participants and sessions. In total a participant was involved in testing all five experimental working heights for $1^1/_2$ to 2 hrs. The duration of a session was chosen roughly in accordance with the periods of operation during a normal working day.

2.5. Dependent Variables and Measuring Techniques

Working posture and vision characteristics were measured by an opto-electronic VICON-system (Vicon Oxford Metrics, UK). Retro-reflective markers were put on the skin overlying selected body segments and joints, two were on a thin rod attached to a pelvic rig, another two were placed on the upper left and upper right corners of the base of the nuts, as well as on a thin rod on top of the oxy-gas cutter and on top of the grinding machine (Figure 3 and Table 3). The three-dimensional positions of the markers were determined while the participants were in a reference posture (standing upright, symmetric with respect to the sagittal plane, looking straight ahead along the horizontal, arms hanging down along the trunk), as well as during operation at each of the working heights. For pneumatic wrenching data acquisition was restricted to the time intervals during which the actual wrenching occurred (time intervals for transport of the wrench from one bolt to another were excluded).

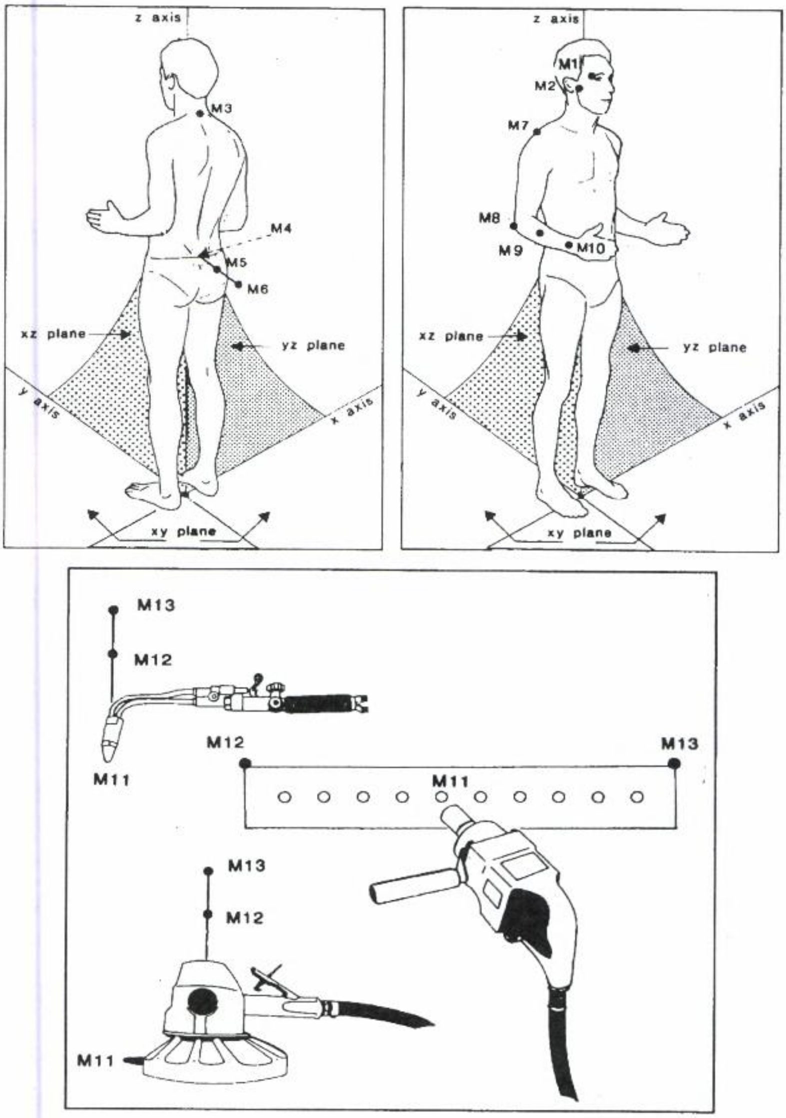

Figure 3. The marker positions for measurement of working posture and vision characteristics (refer also to Table 3).

TABLE 3. Markers: Names and Locations (Refer Also to Figure 3)

Marker	Name	Location
M1	Eye	Near the lateral corner
M2	Ear	Just ventrally off the lobe
M3	Neck	Intervertebral disc C7-T1
M4	Low back	Intervertebral disc L5-S1 (low back location calculated from the locations of M5 and M6)
M5/6	—	On a thin rod attached to a pelvic rig
M7	Shoulder	Acromio-clavicular joint
M8	Elbow	Humero-radial joint
M9	Forearm	Halfway M8 and M10
M10	Wrist	Distal radio-ulnar joint, at the dorsal side (*oxy-gas cutting* and *grinding:* M10 not visible due to the use of gloves; location calculated from the locations of M8 and M9)
M11	Visual target	*Pneumatic wrenching*: the nut on the bolt; *oxy-gas cutting*: the flame; *grinding*: the contact area of the rotating plate and the object (visual target locations calculated from the locations of M12 and M13)
M12/13	—	*Pneumatic wrenching*: on the upper left and upper right corners of the base of the nuts; *oxy-gas cutting*: on a thin rod on top of the oxy-gas cutter; *grinding*: on a thin rod on top of the grinding machine

On the basis of the marker positions various dependent variables with respect to vision, head-neck-trunk, and the right upper extremity were calculated (Table 4). These variables were chosen for testing the effects of the hypothetical determinants of working posture described in the introduction. For data analysis average scores of measurements done within the second half of the session were used.

Workers' perceptions were recorded by a questionnaire, containing four questionnaire modules (scaling-techniques). The modules "Perceived posture" and "Localized postural discomfort" focus on detailed, localized physical perceptions, which may be matched directly with working posture variables. The modules "Estimated endurance time" and "Judgement on working height" focus on integral responses. The modules (A-D) and the dependent variables are described further on.

TABLE 4. Working Posture and Vision: Names and Definitions of Dependent Variables (Refer Also to Table 3 and Figure 3)

Name	Definition
Viewing distance	Distance between M1 and M11
Gaze inclination	Angle between the horizontal plane and the line M1-M11 (a negative value means the participant looks downwards)
Head inclination for-/backwards	Angle between the line M1-M2 and the vertical during operation minus angle between the line M1-M2 and the vertical in the reference posture (a negative value means the head is inclined forwards)
Trunk inclination for-/backwards	Angle between the line M3-M4 and the vertical during operation minus angle between the line M3-M4 and the vertical in the reference posture (a negative value means the trunk is inclined backwards)
Neck flexion/extension	Head inclination for-/backwards (definition above) versus trunk inclination for-/backwards (definition above; a positive value means the neck is flexed)
Manipulation distance	Distance between M3 and M10
Horizontal manipulation distance	Distance between M3 and M10, projected in the horizontal plane
Upper arm elevation for-/backwards	Angle between the line M7-M8 during operation and the line M7-M8 in the reference posture, projected in the XZ plane that was rotated around the vertical in such a way that it included the line M5-M6 (a positive value means the upper arm is elevated forwards)
Upper arm elevation sidewards	Angle between the line M7-M8 during operation and the line M7-M8 in the reference posture, projected in the YZ plane that was rotated around the vertical in such a way that it was perpendicular to the line M5-M6, projected in the horizontal plane (a positive value means the upper arm is elevated outwards)
Elbow flexion	*Pneumatic wrenching*: angle between the lines M7-M8 and M8-M10 during operation minus this angle in the reference posture; *oxy-gas cutting* and *grinding*: angle between the lines M7-M8 and M8-M9 during operation minus this angle in the reference posture
Grip/wrist angle	*Pneumatic wrenching*: angle between the line M8-M10 and the vertical; *oxy-gas cutting* and *grinding*: angle between the line M8-M9 and the line M12-M13

A. Perceived posture. The participant was asked to rate his perception of the posture of the neck, the back, and the right upper extremity, that is, shoulder, upper arm, forearm, and wrist. Directly after the session a written response was given on a 7-point scale (1—*very favourable*, 3—*favourable*, 5—*unfavourable*, 7—*very unfavourable*. Scores of 2, 4, and 6 were available for intermediate responses). The perceived postures of all six body parts mentioned were used as dependent variables.

B. Localized postural discomfort. The participant was asked to rate his postural discomfort in 40 regions shown on a diagram of the rear view of a human body (Figure 4; modified after Corlett & Bishop, 1976), using a scale by Borg (1982) ranging from 0 (*no discomfort*) to 10 (*extreme discomfort, close to maximum*; Van der Grinten & Smitt, 1992). The diagram and the rating scale were positioned in front of the participant.

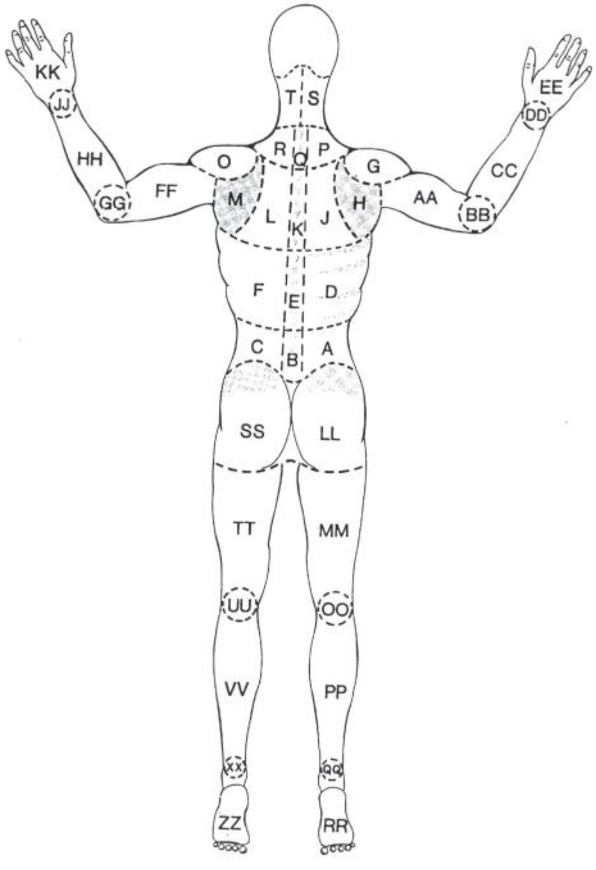

Figure 4. Diagram of the rear view of a human body that was used in the questionnaire module on localized postural discomfort. Forty regions are distinguished.

A verbal response was given at the beginning and at the end of the session. For each body region the score at the beginning was subtracted from the score at the end. The resulting scores for each region were used as dependent variables. Furthermore, the resulting scores for various regions were grouped into larger functional units (Table 5), guided by the information presented in the introduction (the workers involved show low back complaints; furthermore, refer to section 1.3). Finally, an overall dependent variable was constructed, that is, postural discomfort of the whole body, the sum of the resulting scores for all 40 body regions (Table 5). Van der Grinten (1991) and Van der Grinten and Smitt (1992) demonstrated that the variables constructed provide reliable results for comparison of conditions, such as in the present study. Furthermore, for groups of participants reasonably linear relationships were found between gravitational load and discomfort in a body region (e.g., Boussenna, Corlett, & Pheasant, 1982; Van der Grinten & Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g., Manenica, 1986; Meijst, Haslegrave, & Dul, 1995).

TABLE 5. Localized Postural Discomfort: Names and Definitions of Dependent Variables Constructed

Name	Definition (Sum of Resulting Scores for Body Regions Mentioned)
Neck	T, S, R, Q, P
Neck/upper back	T, S, R, Q, P, L, K, J
Low back	C, B, A
Back	L, K, J, F, E, D, C, B, A
Neck/back	T, S, R, Q, P, L, K, J, F, E, D, C, B, A
Neck/shoulder (right side)	S, P, G
Shoulder/arm (right side)	EE, DD, CC, BB, AA, G, H
Whole body	All 40 body regions

C. Estimated endurance time. The participant was asked to estimate, on the basis of his perceptions, how much longer he could continue operation at the experimental working height without difficulty. Directly after the session a written response was given on a 9-point scale (1—*more than 1 working day [8 hrs]*, 2—*½ working day [4 hrs] to 1 working day [8 hrs]*, 3—*2 hrs to ½ working day [4 hrs]*, 4—*1 to 2 hrs*, 5—*30 min to 1 hr*, 6—*20 to 30 min*, 7—*10 to 20 min*, 8—*5 to 10 min*, 9—*less than 5 min*). The estimated endurance time was used as a dependent variable.

D. Judgement on working height. The participant was asked to judge the working height. Directly after the session a written response was given on a 5-point scale (1—*much too low,* 2—*a little too low,* 3—*right,* 4—*a little too high,* and 5—*much too high*). The judgement on working height was used as a dependent variable. For part of the statistical analyses (section 2.6, paired comparisons of working heights) the actual scores on working height given were converted, that is, the amount of deviation from a score of 3 (*right*) was calculated. The reason for this conversion is that a score of 5 is considered as bad as a score of 1 (both were given a conversion score of 2), and a score of 2 as bad as a score of 4 (both were given a conversion score of 1).

2.6. Data Analysis

On the basis of the literature described in section 2.5 (point B), the scale used for determination of localized postural discomfort was considered to have at least interval characteristics. Data on postural discomfort variables as well as on dependent variables with respect to working posture and vision were analyzed by parametric statistical tests. Data on dependent variables with respect to perceived posture, estimated endurance time, and judgement on working height were analyzed by non-parametric (distribution-free) statistical tests, due to the ordinal character of the scales used.

The main effects of working height on the working posture and vision variables, as well as on the variables relating to localized postural discomfort were tested by an Analysis of Variance (ANOVA) for Repeated Measures. Differences between working heights were tested by a post-hoc Tukey test (paired comparisons).

The main effects of working height on the variables relating to perceived posture, estimated endurance time, and judgement on working height were tested by a Friedman Test. Differences between working heights were tested by a Wilcoxon Matched-Pairs Signed-Ranks Test (paired comparisons). The paired comparisons at the variable "judgement on working height" were done on the basis of converted scores (section 2.5, point D).

Paired comparisons for variables relating to workers' perceptions are always done with respect to the working height showing the best result for the particular variable, that is, the optimum working height. The selected level of significance in all tests was $p = .05$ (two-tailed). The description of the results (refer further in the text) will be focused on significant effects of working height. Effects approaching significance ($.05 < p \leq .10$), however, will also be mentioned. Concerning regression equations, correlation is defined as high if the absolute value of the correlation coefficient ≥ .866 (i.e., $R^2 \geq .75$), as moderate if ≥ .707 and <.866 (i.e., $.50 \leq R^2 < .75$), and as low if < .707 (i.e., $R^2 < .50$).

3. RESULTS

3.1. Pneumatic Wrenching

3.1.1. Vision and head-neck-trunk

The *viewing distance* was significantly affected by the working height (Table 6). On average, the distance increased by 5.4 cm for each 10 cm the working height was lowered. For the range of working heights tested all participants show a linear relationship between *gaze inclination* and head inclination for-/backwards with high correlation (Table 7). For each participant, Table 8 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 5 working heights).

TABLE 6. Viewing Distance (VD, cm), Manipulation Distance (MD, cm), and Horizontal Manipulation Distance (HMD, cm) as a Function of Working Height (Average Group Scores)

Variable	Working Height				
Pneumatic wrenching	−20 cm	−10 cm	0 cm	+10 cm	+20 cm
VD	68.0	62.4	56.1	51.1	46.8
MD	62.7	57.2	50.0	44.0	37.9
HMD	20.1	22.1	23.9	24.5	26.3
Oxy-gas cutting	−20 cm	−10 cm	0 cm	+10 cm	+20 cm
VD	41.8	44.2	45.0	46.5	47.9
MD	38.4	39.3	39.5	39.4	37.9
HMD	29.9	30.3	32.4	35.0	35.1
Grinding	−45 cm	−35 cm	−25 cm	−15 cm	−5 cm
VD	84.0	82.1	73.9	66.3	59.3
MD	64.2	61.4	55.6	51.9	50.0
HMD	28.3	32.6	34.4	37.9	42.8

TABLE 7. Head Inclination For-/Backwards Versus Gaze Inclination for Individual Participants

Number of Participant	A	B	*r*	H/G
Pneumatic wrenching				
1	0.58	−8.39	.96	0.73
2	0.91	24.77	.99	0.55
3	1.18	37.16	.94	0.56
4	0.72	8.47	.99	0.59
5	1.10	32.71	.99	0.52
6	1.03	20.80	.94	0.67
7	0.71	10.53	.99	0.53
Oxy-gas cutting				
8	0.95	−13.19	.93	1.24
9	1.14	−1.93	.99	1.19
10	0.97	−6.33	.65	1.13
11	0.86	−5.20	.94	0.98
12	0.98	−8.80	.99	1.17
13	0.38	−32.82	.70	1.13
14	0.83	−17.43	.92	1.17
15	0.93	−10.68	.99	1.17
Grinding				
8	0.70	2.28	.93	0.67
10	0.99	32.93	.93	0.54
11	0.77	7.34	.73	0.67
12	0.73	11.79	.97	0.56
13	0.54	−6.21	.81	0.63
14	0.73	6.48	.56	0.65
15	1.19	43.13	.90	0.63
16	1.14	12.70	.75	0.97

Notes. Head inclination for-/backwards = A * gaze inclination + B (where $n = 5$ working heights), *r*—Pearson correlation coefficient, H/G—head inclination for-/backwards (average of 5 working heights)/gaze inclination (average of 5 working heights). Range of gaze inclinations measured for pneumatic wrenching: −36.6 to −76.9°, range of gaze inclinations measured for oxy-gas cutting: −25.3 to −63.2°, range of gaze inclinations measured for grinding: −57.1 to −85.6°.

Head inclination for-/backwards, *trunk inclination for-/backwards*, and *neck flexion/extension* are significantly affected by the working height (Figure 5). If the working height is lowered from 20 cm above elbow height neck flexion increases, because the head does incline forwards at a higher rate than the trunk (Figure 5a/b). However, at working heights below 0 cm (elbow height) neck flexion is relatively constant, that is, head and trunk do incline forwards at about the same rate.

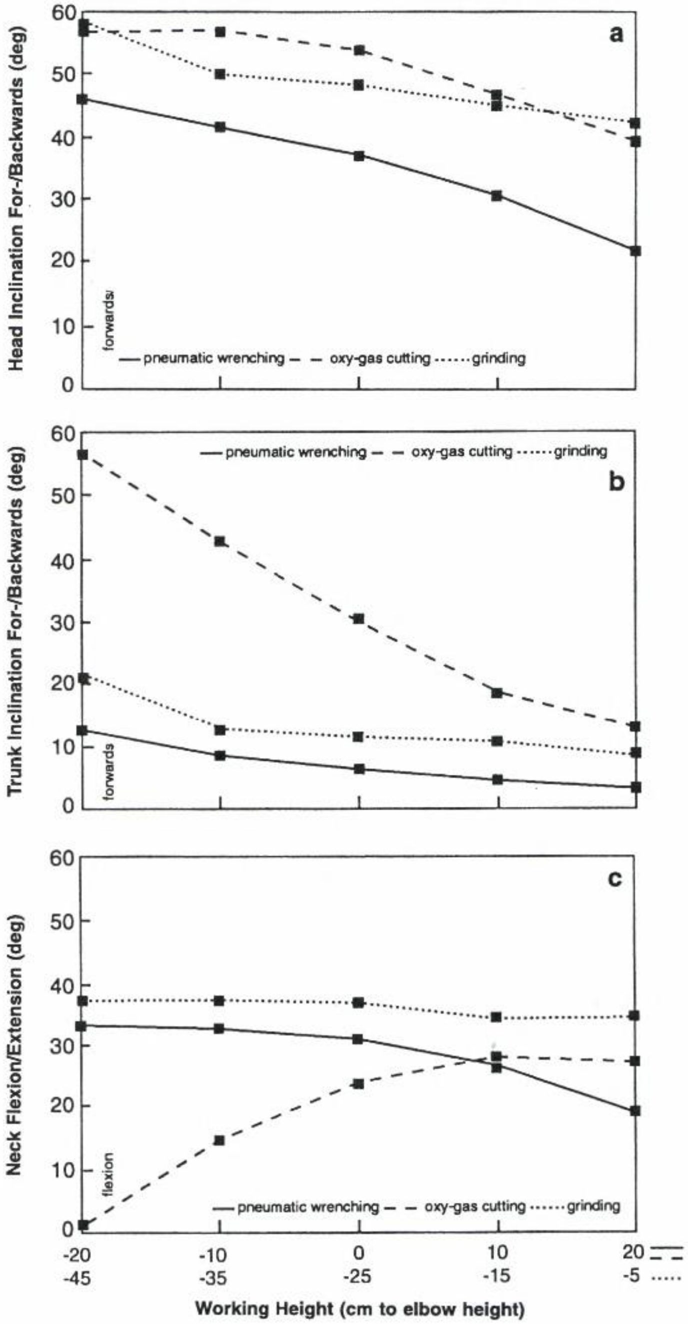

Figure 5. Head-neck-trunk posture variables versus experimental working heights (average group scores): (a) head inclination for-/backwards, (b) trunk inclination for-/backwards, (c) neck flexion/extension.

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in Table 8 (refer also to Figures 6a and 7a).

TABLE 8. Workers' Localized Physical Perceptions: Worse Results ($p \leq .10$) for Various Working Heights with Respect to the Working Height Showing the Best Result for the Particular Variable, That Is, the Optimum Working Height (Mentioned in Brackets)

Working Height	Significant Effects	Effects Approaching Significance (level in brackets)
Pneumatic wrenching		
–20 cm	p.p. neck (+10 cm)	—
+20 cm	—	Judgement on working height ($p = .070$; 0 cm) p.p. upper arm ($p = .040$*; –10 cm; $p = .030$*; –20 cm)
Oxy-gas cutting		
–20 cm	Judgement on working height (0 cm) Estimated endurance time (0 cm) p.p. back (+10 cm) p.p. upper arm (0 cm) p.d. low back (+10 cm)	p.p. shoulder ($p = .070$; 0 cm)
+10 cm	—	p.p. upper arm ($p = .070$; 0 cm)
+20 cm	p.d. whole body (0 cm) p.d. neck/shoulder (–20 cm) p.d. shoulder/arm (0 cm) p.p. shoulder (0 cm) p.p. upper arm (0 cm) p.p. forearm (0 cm)	p.p. wrist ($p = .020$**; 0 cm)
Grinding		
–45 cm	Judgement on working height (–35 cm) p.d. neck/back (–25 cm)	
–25 cm	p.p. wrist (–35 cm)	p.p. forearm ($p = .070$; –35 cm)
–15 cm	p.p. wrist (–35 cm)	p.p. upper arm ($p = .070$***; –35 cm)
–5 cm	p.d. shoulder/arm (–45 cm) p.p. wrist (–35 cm) p.d. whole body (–35 cm)	p.p. upper arm ($p = .040$***; –35 cm) p.p. forearm ($p = .052$; –35 cm)

Notes. p.p.—perceived posture, p.d.—postural discomfort. Variables relating to the upper extremities refer to the right side of the body. Example: at pneumatic wrenching the perceived posture of the neck for working height –20 cm is significantly worse than for its optimum working height (+10 cm). Main effect of working height: *—$p = .080$, **—$p = .052$, ***—$p = .100$.

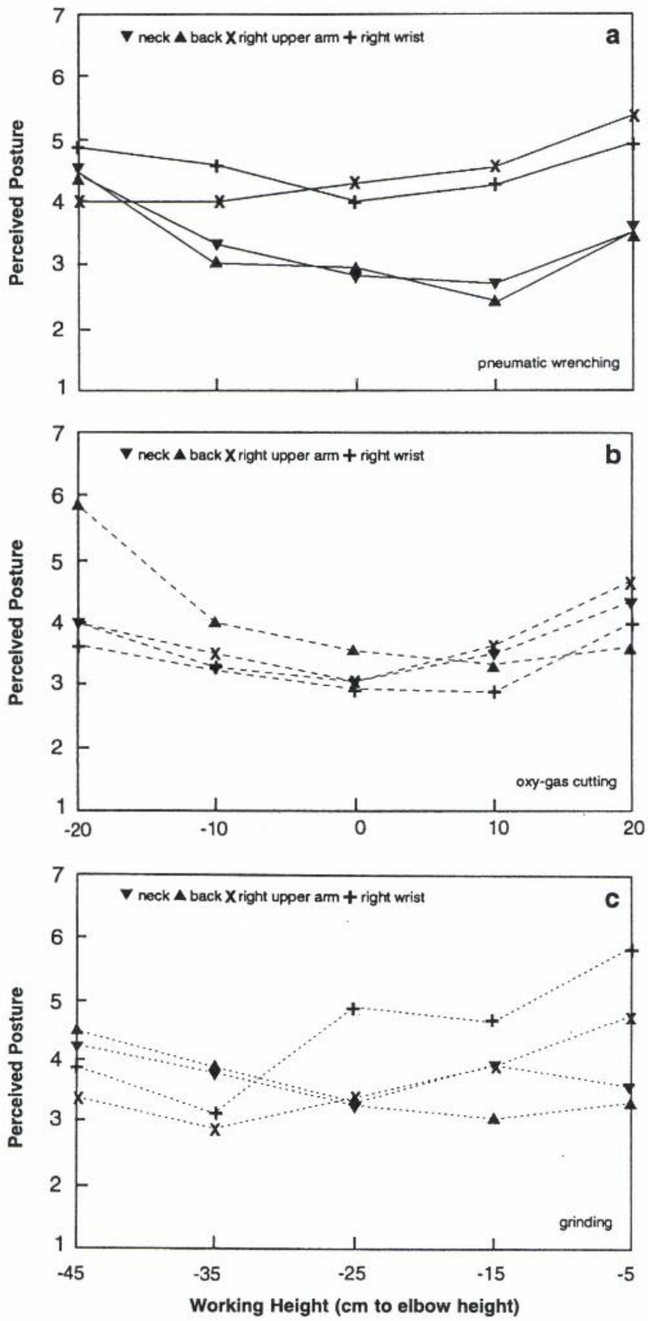

Figure 6. Perceived postures of the neck, back, upper arm, and wrist versus experimental working heights for (a) pneumatic wrenching, (b) oxy-gas cutting, and (c) grinding (average group scores). *Notes.* 1—*very favourable*, 3—*favourable*, 5—*unfavourable*, 7—*very unfavourable.*

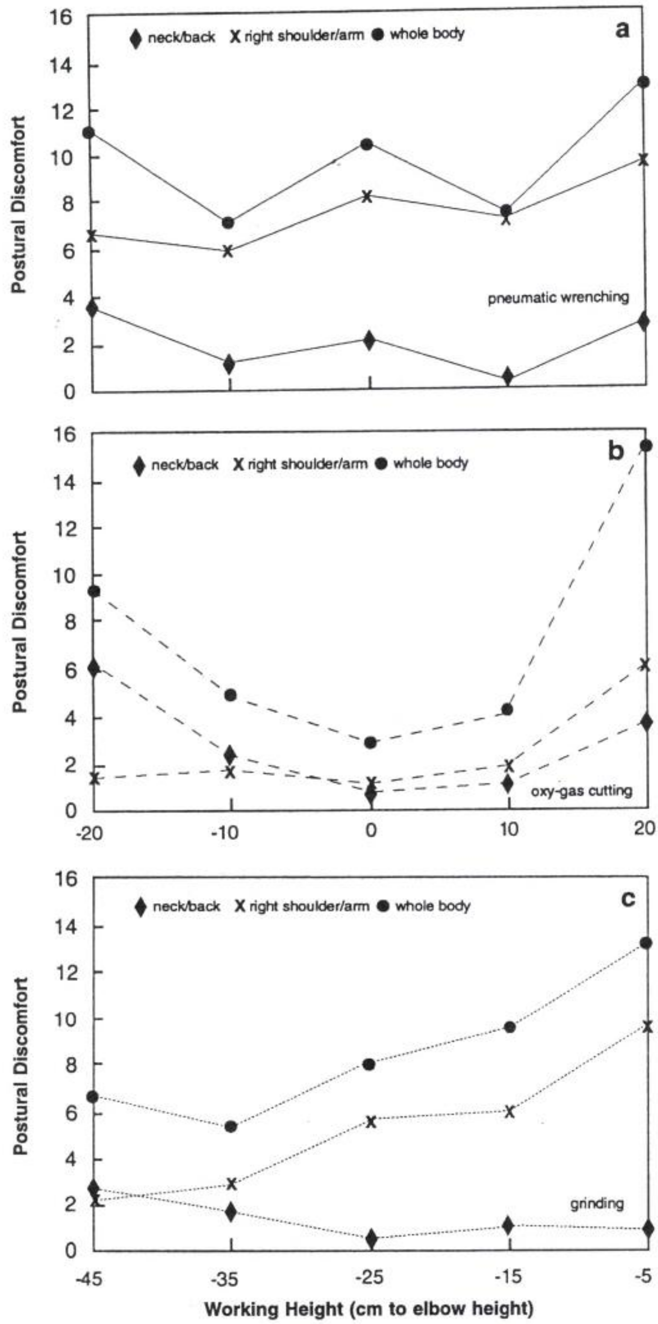

Figure 7. Postural discomfort in the neck/back, in the right shoulder/arm, and of the whole body versus experimental working heights for (a) pneumatic wrenching, (b) oxy-gas cutting, and (c) grinding (average group scores).

3.1.2. Right upper extremity

The *manipulation distance* and the *horizontal manipulation distance* are significantly affected by the working height (Table 6). On average, the manipulation distance increased by 6.3 cm for each 10 cm the working height was lowered. The horizontal manipulation distance for working height −20 cm was smaller than for working heights 0 cm ($p = .06$), +10 cm (significant), and +20 cm (significant). The horizontal manipulation distance for working height −10 cm was significantly smaller than for working height +20 cm.

Upper arm elevation for-/backwards is significantly affected by the working height (Figure 8a). For working height +20 cm the upper arm was less elevated forwards than for working height +10 cm (significant), 0 cm (significant), −10 cm ($p = .0504$), and −20 cm ($p = .06$). *Upper arm elevation*

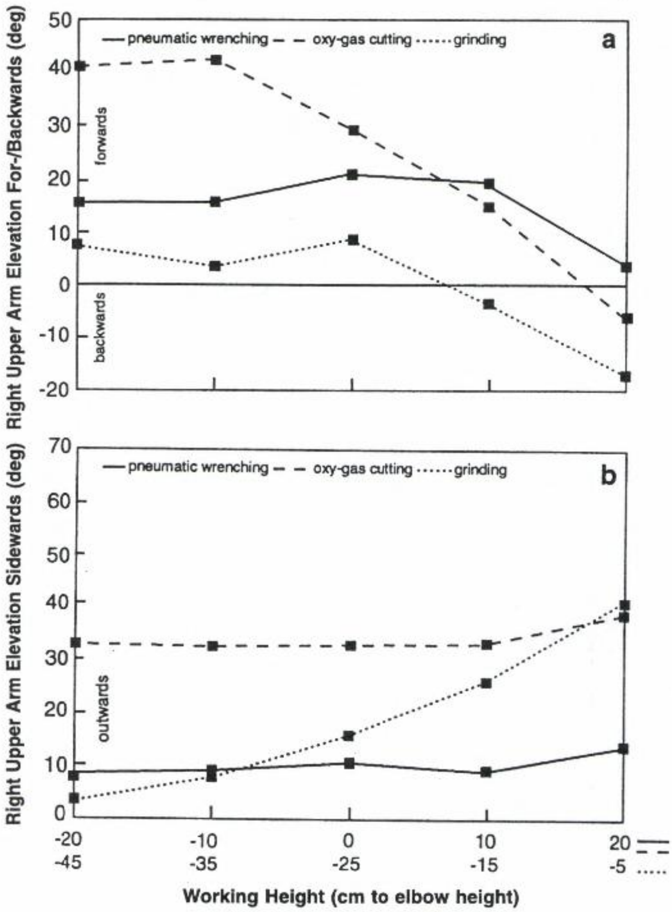

Figure 8. Right upper arm elevation (a) for-/backwards and (b) sidewards versus experimental working heights (average group scores).

sidewards is not affected by the working height (Figure 8b). On average, the upper arm was elevated sidewards 10.1°.

Elbow flexion is significantly affected by the working height (Figure 9). On average, the elbow was 12.9° more extended for each 10 cm the working height was lowered.

The *grip/wrist angle* is significantly affected by the working height (Figure 10). On average, the angle increased by 13.9° for each 10 cm the working height was raised. Video-recordings show that the wrist is increasingly abducted in the ulnar direction at higher working heights.

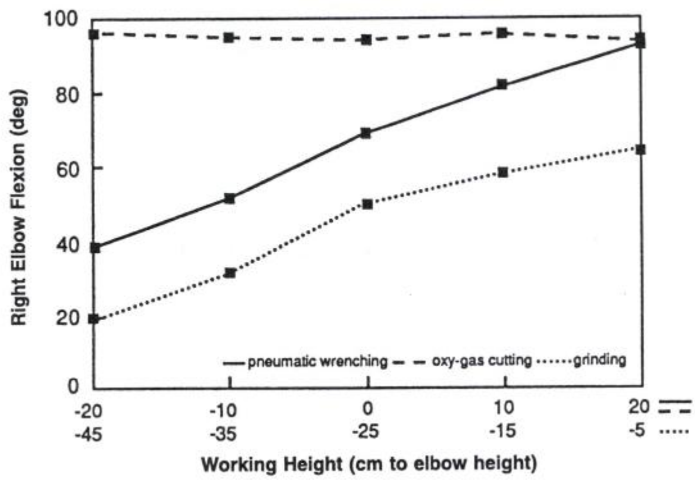

Figure 9. Right elbow flexion versus experimental working heights (average group scores).

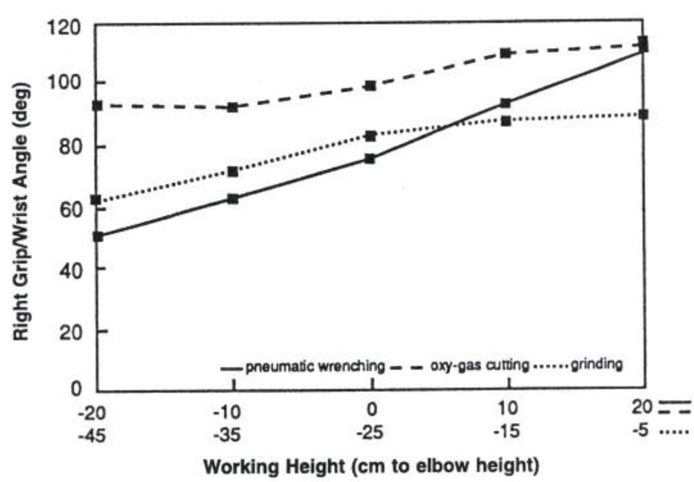

Figure 10. Right grip/wrist angle versus experimental working heights (average group scores).

Effects on *workers' localized physical perceptions* with respect to the right upper extremity are summarized in Table 8 (refer also to Figures 6a and 7a).

3.1.3. Workers' integral perceptions

Effects on *workers' integral perceptions* are summarized in Table 8 (refer also to Figures 11 and 12).

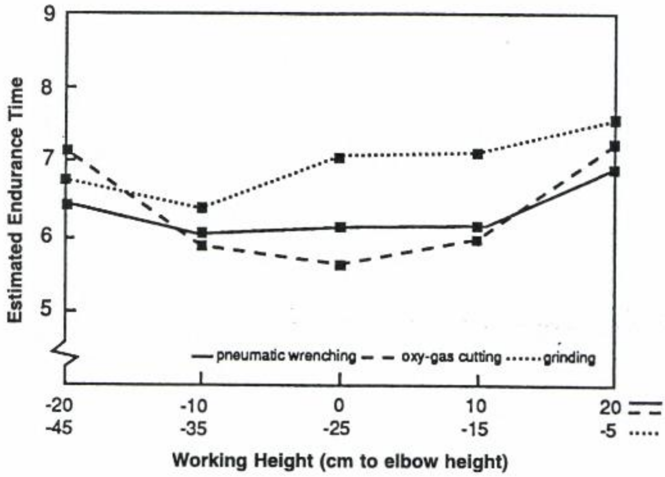

Figure 11. Estimated endurance time versus experimental working heights (average group scores). *Notes.* 5—30 min to 1 hr, 6—20 to 30 min, 7—10 to 20 min, 8—5 to 10 min, 9—less than 5 min.

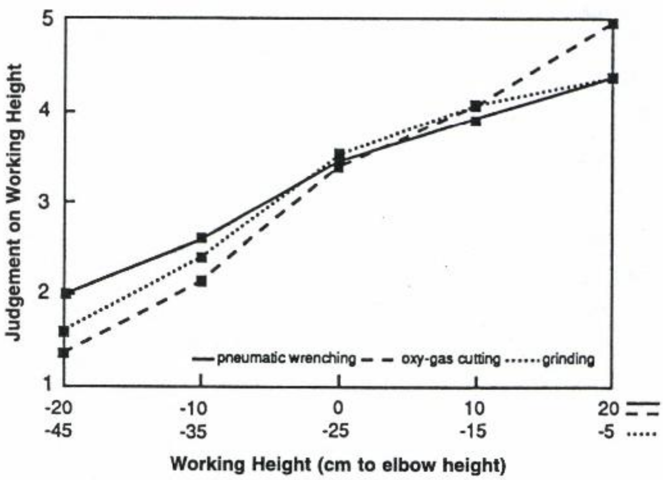

Figure 12. Judgement on working height versus experimental working heights (average group scores). *Notes.* 1—*much too low*, 2—*a little too low*, 3—*right*, 4—*a little too high*, 5—*much too high*.

3.2. Oxy-Gas Cutting

3.2.1. Vision and head-neck-trunk

The *viewing distance* was significantly affected by the working height (Table 6). The distance for working height –20 cm was significantly shorter than for working heights +20 and +10 cm. For the range of working heights tested the majority of the participants show a linear relationship between *gaze inclination* and head inclination for-/backwards with high correlation (Table 7). For each participant, Table 7 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 5 working heights).

Head inclination for-/backwards, trunk inclination for-/backwards, and *neck flexion* are significantly affected by the working height (Figure 5). It turned out, however, that at working heights below 0 cm (elbow height) the head inclination forwards is relatively constant (Figure 5a). Furthermore, above working height 0 cm (elbow height) neck flexion is relatively constant (Figure 5c), that is, head and trunk incline for-/backwards at about the same rate (Figure 5a/b).

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in Table 8 (refer also to Figures 6b and 7b).

3.2.2. Right upper extremity

The *manipulation distance* is not affected by the working height (Table 6). On average, the manipulation distance was 38.9 cm. The *horizontal manipulation distance* is significantly affected by the working height (Table 6). The horizontal manipulation distance for working heights +20 and +10 cm were significantly greater than for working heights –10 and –20 cm.

Upper arm elevation for-/backwards is significantly affected by the working height (Figure 8a). For working height +20 cm the upper arm was significantly less elevated forwards than for all other working heights. For working height +10 cm the upper arm was significantly less elevated forwards than for working heights –10 and –20 cm. *Upper arm elevation sidewards* is not affected by the working height (Figure 8b). On average, the upper arm was elevated sidewards 34.1°.

Elbow flexion is not affected by the working height (Figure 9). On average, the elbow was 93.4° flexed.

The *grip/wrist angle* is significantly affected by the working height (Figure 10). However, at working heights below 0 cm (elbow height) as well as above +10 cm the angle is relatively constant. Video-recordings show that the wrist is increasingly abducted in the ulnar direction at higher working heights.

Effects on *workers' localized physical perceptions* with respect to the right upper extremity are summarized in Table 8 (refer also to Figures 6b and 7b).

3.2.3. Workers' integral perceptions

Effects on *workers' integral perceptions* are summarized in Table 8 (refer also to Figures 11 and 12).

3.3. Grinding

3.3.1. Vision and head-neck-trunk

The *viewing distance* was significantly affected by the working height (Table 6). On average, the distance increased by 7.6 cm for each 10 cm the working height was lowered, until working height –35 cm was reached. For the range of working heights tested the majority of the participants show a linear relationship between *gaze inclination* and head inclination for-/backwards with moderate or high correlation (Table 7). For each participant, Table 7 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 5 working heights).

Both *head inclination for-/backwards* and *trunk inclination for-/backwards* are significantly affected by the working height (Figure 5a/b). If the working height is lowered from 5 cm below elbow height downwards both the head and the trunk incline more forwards at a relatively low rate, until working height –35 cm is reached. Below this height both variables incline more forwards at a much higher rate.

Neck flexion/extension is not significantly affected by the working height (Figure 5c), because the head and the trunk do incline forwards/backwards at about the same rate.

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in Table 8 (refer also to Figures 6c and 7c).

3.3.2. Right upper extremity

The *manipulation distance* and the *horizontal manipulation distance* are significantly affected by the working height (Table 6). All pairwise comparisons of working heights on manipulation distance disclosed significant differences, except for working height –45 cm versus working height –35 cm, and working height –15 cm versus working height –5 cm ($p > .10$ for both comparisons). On average, the horizontal manipulation distance decreased by 3.4 cm for each 10 cm the working height was lowered.

Upper arm elevation for-/backwards is significantly affected by the working height (Figure 8a). For working height –5 cm the upper arm was significantly less elevated forwards than for working heights –45, –35, and –25 cm. *Upper arm elevation sidewards* is significantly affected by the working height (Figure 8b). Elevation sidewards for working height –5 cm differed significantly from the elevation sidewards for all other working heights. Elevation sidewards for working height –15 cm differed from the elevation sidewards for working heights –25 cm ($p = .06$), –35 cm (significant), and –45 cm (significant). Elevation sidewards for working height –25 cm differed significantly from the elevation sidewards for working height –45 cm.

Elbow flexion is significantly affected by the working height (Figure 9). All pairwise comparisons of working heights disclosed significant differences, except for working height –5 cm versus working height –15 cm, and working height –15 cm versus working height –25 cm ($p > .10$ for both comparisons).

The *grip/wrist angle* is significantly affected by the working height (Figure 10). However, at working heights above –25 cm the angle is relatively constant. Video-recordings show that the wrist is flexed at these heights.

Effects on *workers' localized physical perceptions* with respect to the right upper extremity are summarized in Table 8 (refer also to Figures 6c and 7c).

3.3.3. Workers' integral perceptions

Effects on *workers' integral perceptions* are summarized in Table 8 (refer also to Figures 11 and 12).

4. DISCUSSION

4.1. Head-Neck-Trunk Posture

Nakaseko et al. (1993) and Delleman and Berndsen (1999) described the association between the for-/backward inclination of the head/neck segment and the for-/backward inclination of the thoracic region of the trunk (i.e., thoracic spine curvature). Figures 5a and 5b and video recordings indicated that for pneumatic wrenching and for grinding (working height –35 cm and upwards) the trunk inclination for-/backwards measured originates from the for-/backward inclination of its thoracic region. On the basis of the aforementioned observations, it was hypothesized that trunk inclination for-/backwards may be determined by head inclination for-/backwards. In order to understand this relationship, various curve types were selected to find the best fit for five data pairs (group averages for working heights) for pneumatic wrenching as well as for four data pairs for grinding. For both operations an exponential curve was the best, whereas the curves were about the same. Therefore, a third curve was fitted based on the nine data pairs, which resulted in the following relationship, with high correlation: $\ln(Y) = 0.055 * X - 0.2$, where X is head inclination for-/backwards, and Y is trunk inclination for-/backwards. The close relationship between head inclination for-/backwards and trunk inclination for-/backwards is reflected by the workers' perceptions, that is, the perceptions of the neck and back posture are tightly connected (Figures 6a and 6c).

It was hypothesized that the body support for *stability* during oxy-gas cutting would determine the working posture. The results show that the for-/backward inclination of the trunk is largely affected by positioning the left elbow on the table top for support (Figure 5b). That is, in particular for working heights –20, –10, and 0 cm, where the left upper arm almost vertical, that is, an elevation of about 10° (Dul et al., 1991). At the lowest experimental working height, that is, –20 cm, the great amount of trunk inclination for-/backwards (on average 57°) together with a pre-determined head inclination for-/backwards (refer to the first paragraph of section 4.2), led to a very small neck flexion (close to extension), which is known to be a relatively unfavourable posture of the neck (Delleman & Berndsen, 1999). The selection of such posture leads to the conclusion that stability is a determinant of the working posture.

At all three operations neck flexion seems to reach a maximum (Figure 5c), most likely an extreme position of the range of motion. A direct comparison of the maximum flexion angles found is only possible for oxy-gas cutting and grinding, because in the experiments on these operations 7 participants were the same (Table 7; i.e., participants 8 and 10–15). At maximum the group averages for these 7 participants were 29.1° for oxy-gas cutting (working height +20 cm), and 36.0° for grinding (working height –45 cm). One reason for the difference seems to be that during oxy-gas cutting at higher working heights (i.e., 10 and 20 cm above elbow height) the possibility for bending the thoracic region of the spine forwards is limited, simply due to obstruction by the table. Because head inclination for-/backwards is made possible partly by bending the thoracic spine forwards (refer to the first paragraph of this section), the maximum neck flexion is not as high as without the limitation.

4.2. Vision

4.2.1. Gaze inclination

Gaze inclination is made up of two complementary components: head inclination for-/backwards and the up-/downward orientation of the eye with respect to the head/orbit. The majority of the participants show a linear relationship with moderate or high correlation (Table 7). For each operation, however, this relationship differs among individuals considerably (Table 7; parameter A). In 6 out of 23 cases even a contribution of head inclination for-/backwards to gaze inclination above 100% was found. The most likely cause for this phenomenon seems to be that the regression lines were based on too small a range of gaze inclinations (i.e., on average 26.1, 21.3, and 17.6° for the participant groups involved in pneumatic wrenching, oxy-gas cutting, and grinding, respectively) or based on too small a number of data pairs (i.e., 5), or both, creating a greater variability than actually present and affecting slopes and correlation coefficients of the regression lines. Therefore, taking into account the correlation coefficients calculated, gaze inclination is considered to be a determinant of head inclination for-/backwards.

At the range of gaze inclinations measured for pneumatic wrenching, that is, –36.6 to –76.9°, estimates based on data presented by Brues (1946) show that the contribution of head inclination for-/backwards to gaze inclination is 47 to 56% (average group score). For gaze inclinations from horizontal down to –50°, data by Conrady et al. (1987) disclosed a slightly higher contribution, that is, about 55–60% (average group score). The actual contribution of head inclination for-/backwards to gaze inclination for participants 2, 3, 5, and 7 match with the range obtained from the data presented by Brues, whereas the figures for the other 3 participants are slightly to somewhat higher (Table 7; parameter H/G). The actual contribution of head inclination for-/backwards to gaze inclination for participants 2, 3, and 4 matches with the range obtained from the data by Conrady and colleagues, whereas the actual contribution is slightly lower for participants 5 and 7, and somewhat higher for participants 1 and 6.

At the range of gaze inclinations measured for grinding, that is, –57.1 to –85.6°, estimates based on data presented by Brues (1946) show that the contribution of head inclination for-/backwards to gaze inclination is 51 to 59% (average group score). The actual contribution for participants 10 and 12 match with the range obtained from the data presented by Brues, whereas the Figures for participants 8, 10, and 13–15 are slightly to somewhat higher (Table 7; parameter H/G). Video observations suggested that the relatively high contribution of head inclination for-/backwards at participant 16 (accompanied by a somewhat asymmetric neck posture) may have been selected in order to prevent sparks from touching unprotected skin at the chest, neck (front side), and face.

Only for oxy-gas cutting a serious deviation from the data found at the literature is present. At the range of gaze inclinations measured in this study, that is, –25.3 to –63.2°, estimates based on data presented by Brues (1946) show that the contribution of head inclination for-/backwards to gaze inclination is 44 to 51% (average group score). For gaze inclinations from horizontal down to –50°, data by Conrady et al. (1987) indicated 55–60% (average group score). All 8 participants show a considerably higher contribution (Table 7; parameter H/G). For 7 of them even a contribution above 100% was found. This means that during operation the eye is rotated slightly upwards with respect to the head/orbit as compared to its position in the reference posture. Video observations showed that the participants adjusted their dark glasses (Figure 13) while standing with the head and trunk upright, as about the reference posture. Participants confirmed that during adjustment the round pieces of glass are centred at the accessory gaze direction. By further questioning it was found out during operation the eyes are directed somewhere upwards from the centre of the pieces of glass (i.e., the eyes were rotated upwards with respect to the head/orbit), in order to avoid light reflecting from the inside of the glass. This unfavourable effect is caused by the particular orientation of glasses with respect to the head (Figure 13). That is, because the glasses were designed for work at a smelting-furnace, demanding an upwardly directed gaze. According to the participants, goggles are not preferred during oxy-gas cutting, because they get steamy and do not allow for unprotected vision as easily as by looking underneath the dark glasses used now. Finally, it is remarkable that for participants showing a linear relationship of head inclination for-/backwards and gaze inclination with moderate or high correlation, on average the head created 95% of a *gaze change* (Table 7; parameter A), leaving hardly any role for the eye. Apparently, the effective range of motion of the eyes is severely reduced, or in other words, visual interference by parts of the glasses reflecting light as well as by the frame at the upper edge is nearby.

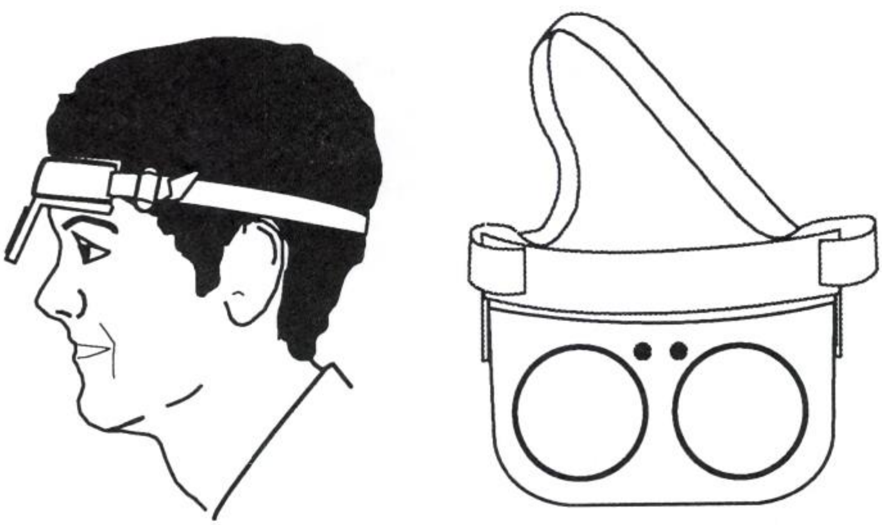

Figure 13. The dark glasses worn during oxy-gas cutting.

4.2.2. Viewing distance

For oxy-gas cutting it was hypothesized that a worker would try to retain a favourable viewing distance. However, a systematic variation of the viewing distance with working height was found (Table 6). Therefore, it cannot be concluded that the viewing distance is a determinant of working posture. The greater viewing distance at a higher working height is a result of the eyes moving away from the target (flame) as the head, the trunk, or both get more upright (Figure 5a/b). The notion that the viewing distance is a result of the head inclination for-/backwards (refer also to section 4.2.1), the trunk inclination for-/backwards, or both, is supported by data, touch-typing VDU (Video Display Unit) operation (Delleman & Berndsen, 1999), pneumatic wrenching, and grinding. Finally, it should be remarked that there is no reason to say that the viewing distance during oxy-gas cutting is unimportant, considering the much wider range of viewing distances for pneumatic wrenching and grinding (Table 6).

4.3. Right Upper Extremity Posture

4.3.1. Manipulation distance

For pneumatic wrenching and grinding it was hypothesized that a worker would try to retain a favourable horizontal manipulation distance. However, a systematic variation of this distance with working height was found (Table 6). Therefore, it cannot be concluded that the horizontal manipulation distance is a determinant of working posture. Apparently, the weight of the pneumatic wrench in the right hand (i.e., 4.5 kg; Table 2) did not affect the working posture. For the grinding machine no conclusion can be drawn regarding the weight in the right hand, because the reaction force from the object during operation is not known.

For oxy-gas cutting it was hypothesized that a worker would try to retain a favourable manipulation distance. This hypothesis was confirmed (Table 6; refer also to Figure 9 for the constant elbow flexion). So, it can be concluded that the manipulation distance is a determinant of working posture.

4.3.2. Grip/wrist angle and upper arm elevation

For all three tools used it was hypothesized that the working posture would be determined by a reasonably rigid right-hand grip. For pneumatic wrenching this hypothesis was not supported, because a systematic variation of the right grip/wrist angle with working height was found (Figure 10). This leaves unexplained why the upper arm is less elevated forwards for working height +20 cm than for all other working heights (Figure 8a). Probably at this height, the grip/wrist angle would have come close to a maximum, but the upper arm prevents such by moving more backwards and slightly more sidewards (Figures 8a and 8b), thereby moving the forearm and wrist into a more favourable posture.

For oxy-gas cutting the right grip/wrist angle seems to move towards a maximum, when raising the working height to elbow height +20 cm

(Figure 10). At the same time, the upper arm elevation forwards is reduced (Figure 8a), supporting the hypothesis described before. Remarkably, the postural effects at working height +20 cm show a strong resemblance to pneumatic wrenching, that is, a maximum or nearly maximum grip/wrist angle (Figure 10), almost zero upper arm elevation for-/backwards (Figure 8a), and a slightly increased upper arm elevation sidewards (Figure 8b).

For grinding the right grip/wrist angle seems to have reached a maximum at working heights –25 cm and higher (Figure 10). At the same time, in particular upper arm elevation forwards is reduced (Figure 8a), supporting the hypothesis described before.

Comparing Figures 8a and 8b, it seems that the sideward elevation of the upper arm increases most when the upper arm is elevated backwards (cf. the results for grinding and the results for pneumatic wrenching and oxy-gas cutting).

As far as the right upper arm is concerned, the data of the present study gave reason to have a closer look at the relationship between posture and workers' localized perceptions. For pneumatic wrenching the perceived posture of the upper arm for working height +20 cm was found to be worse than for the optimum working height −10 cm (Table 8; effect approaching significance). The small upper arm elevation measured, which was also about the same for all heights (Dul et al., 1991; Figure 8), is not considered to be a reasonable explanation for these relatively unfavourable perceptions. It seems more likely, however, that the position of the upper arm with respect to the trunk plays a role in this matter, that is, the upper arm approaches a shoulder retroflexion position, because upper arm elevation for-/backwards gets close to zero (Figure 8b), while the trunk is about upright (Figure 5b).

For oxy-gas cutting the perceived posture of the upper arm for working heights +10 and +20 cm was found to be worse than for the optimum working height 0 cm (Table 8; effect approaching significance and significant, respectively). The upper arm elevation for both working heights was not significantly greater than for the other working heights (Dul et al., 1991; refer also to Figure 8). So, also here the upper arm elevation does not seem to play a role with respect to the relatively unfavourable workers' perceptions. Again, the position of the upper arm with respect to the trunk seems a more likely explanation, that is, for working height +20 cm in particular the upper arm is close to a shoulder retroflexion position, because upper arm elevation backwards (Figure 8a) and trunk inclination forwards (Figure 5b) are about equal. Furthermore, for oxy-gas cutting it was found that the perceived posture of the upper arm for working height –20 cm significantly worse than for the optimum working height 0 cm (Table 8). No such result was found for working height –10 cm. Because the upper arm elevation was the same for working heights –20 and –10 cm (Figure 8), elevation itself is not a likely explanation for the workers' perceptions relating to working height –20 cm. The fact that the rather great angle between the upper arm and the trunk at working height –10 cm (that is mainly shoulder flexion, defined as the sum of upper arm elevation forwards and trunk inclination forwards) gets even greater at working height –20 cm (cf. Figures 8 and 5b), points at this parameter for being a reasonable explanation.

For grinding the perceived posture of the upper arm for working heights –15 and –5 cm was found to be worse than for the optimum working height –35 cm (Table 8; both effects approaching significance). Basically, these results can be explained by the greater upper arm elevation (Dul et al., 1991; Figure 8) as well as by the position of the upper arm with respect to the trunk, that is, the upper arm approaches or has reached a shoulder retroflexion position, because the upper arm is elevated backwards (Figure 8a), while the trunk is close to the upright posture. Though the upper arm elevation measured still seems to be rather small (40–45° at maximum). Bjelle et al. (1981) found upper arm elevation (i.e., forward flexion and abduction in their terminology, but it was deduced from the authors' description that actually the amount of deviation from the hanging posture or the vertical was measured) above 60° to be significantly more frequent as well as sustained for a longer duration in workers with acute shoulder-neck pains than in matched controls. Also here, it seems likely that the position of the upper arm with respect to the trunk plays a dominant role concerning workers' perceptions, because of its resemblance to the postures found for pneumatic wrenching and oxy-gas cutting.

4.4. What Determines Neck Load?

Two potential determinants of neck load were studied, that is, head inclination for-/backwards and neck flexion/extension. Below the data on these posture variables will be related to the data on perceived posture of the neck, in order to add to the existing knowledge on the possible dominance of one of both variables (refer to the introduction). Data on postural discomfort for the neck (not shown in this paper) do strongly resemble the data on perceived posture of the neck.

First of all, it should be emphasized that a significant effect of working height on the perceived posture of the neck could only be demonstrated for pneumatic wrenching, and not for oxy-gas cutting ($p = .15$) and grinding ($p = .31$). Still, some remarkable tendencies can be seen in the data. For this, a distinction is made between so-called favourable working heights (i.e., the number of participants who gave a score ≤3 is greater than the number of participants who gave a score ≥5) and unfavourable working heights (i.e., the number of participants who gave a score ≥5 is greater than the number of participants who gave a score ≤3). On the basis of this classification for pneumatic wrenching working height –20 cm (Figure 6a) is unfavourable (refer also to Table 8), whereas all other heights are favourable; for oxy-gas cutting (Figure 6b) working height +20 cm is unfavourable, working heights +10, 0, and −10 cm are favourable, and working height –20 cm is ambiguous (3 participants gave score of 3, 2 gave score of 4, and 3 gave score of 5); for grinding (Figure 6c) working height –45 cm is unfavourable, whereas all other heights are favourable.

At the favourable working heights mentioned above the head is inclined forwards, that is, average inclinations roughly between 20 and 60° (Figure 5a). This range does not match the most favourable head inclinations suggested in the literature, that is, less than 15° inclined forwards (Chaffin, 1973) or even inclined backwards (De Wall, Van Riel, Aghina, Burdorf, & Snijders, 1991, 1992; Snijders et al., 1991). In itself this does not make the role of head inclination for-/backwards as a determinant (or the dominant determinant) of neck load unlikely. It may be that with the present experimental setup (5 min of operation) a working height only tends to be unfavourable at a rather great amount of head inclination forwards (refer to Figures 5a and 6, at the lowest working height for all operations and the perceived postures of the neck). If this were true, a higher working height, with a lower amount of head inclination forwards (Figure 5a), would always have to be relatively favourable. However, then the fact that for oxy-gas cutting working height +20 cm is most unfavourable (1 participant gave score of 3, 2 participants score of 4, and 5 participants score of 5) is left unexplained. So, it seems that the head inclination for-/backwards is not the dominant determinant of neck load. All unfavourable working heights though can be explained by the neck flexion/extension. At each of these heights (–20 cm for pneumatic wrenching, +20 cm for oxy-gas cutting, and –45 cm for grinding) a relatively unfavourable, extremely flexed, neck posture seems to be reached (Figure 5c). Neck flexion/extension also does seem to explain the ambiguous result for working height –20 cm for oxy-gas cutting. At this height neck flexion is rather small (close to extension), which is known to be a relatively unfavourable neck posture (Delleman & Berndsen, 1999). From the aforementioned it seems that the neck flexion/extension is the dominant determinant of neck load, as compared to the head inclination for-/backwards.

In view of the aforementioned reasoning one should always be aware that the workers' perceptions for the neck may equally well be determined by factors that were not studied here. The posture of the shoulder girdle, for example, is such a factor, that is, affecting the length of a major neck muscle (trapezius, descending part; Van der Helm, 1991). Knowing that the posture of the shoulder girdle depends on the elevation of the upper arm (Pronk, 1991; Van der Helm, 1991), the latter asked for a closer look. For pneumatic wrenching at the relatively unfavourable working height –20 cm as well as for grinding at the relatively unfavourable working height –45 cm it was found that the upper arm elevation was rather small, and among the smallest of all experimental conditions (Dul et al., 1991; refer also to Figure 8). Also, no clearly unfavourable workers' perceptions for the shoulder/upper arm region were found (Figures 6a and 6c). So, for both operations at least the upper arm elevation does not seem to play a role with respect to the remarkable workers' perceptions for the neck, discussed in the previous paragraph. For oxy-gas cutting at the relatively unfavourable working height +20 cm the relatively unfavourable perceptions for the upper arm posture (section 4.3.2) may have had an effect on perceptions for the neck.

5. FORMULATION OF GUIDELINES

The second purpose of the paper was to formulate ergonomic guidelines for adjustment (and redesign) of maintenance workstations. For this, results on working posture and workers' perceptions are to be discussed regarding their mutual relationships in the process of evaluation of experimental working heights. In the case of a recommended working height range the borders of this range are formed by the lowest and highest experimental working heights that can be recommended on the basis of the criteria described in the introduction to this paper. This excludes working heights outside the recommended range that might be found acceptable if tested experimentally. Theoretically, it can be expected that the actual acceptable range is somewhat greater than the currently recommended range. However, the exact borders of this actual range cannot be determined on the basis of the present study. Consequently, the smallest possible height range was recommended. Doing so, the recommended range also constitutes safe limits.

5.1. Pneumatic Wrenching

Only very few significant effects of working height (or effects approaching significance) were found (Table 8). Nevertheless, the results on estimated endurance time indicate a working height range between –10 to +10 cm for recommendation (Figure 11). The judgements on working heights –10 and 0 cm were closest to the qualification *right*, that is, tending to qualifications *a little too low* and *a little too high*, respectively (Figure 12). Results on postural discomfort of the whole body disfavour working height 0 cm (Figure 7a), in addition to disfavouring working heights –20 and +20 cm. For working height –20 cm the neck posture was found to be significantly more unfavourable than for its particular optimum working height (Table 8). This localized physical perception is supported by the results on working posture (section 4.4). For working height +20 cm the right upper arm posture was found to be more unfavourable than for its particular optimum working height (Table 8; effect approaching significance). This localized physical perception is supported by the results on working posture (section 4.3.2). Acting only according to the criteria described in the introduction to this paper (i.e., experimental conditions are not recommended if workers' perceptions are significantly worse than for any other experimental conditions), one would decide not to exclude working height +20 cm for recommendation. Nevertheless, it is considered best not to recommend this height, because judgements of all participants were either *much too high* or *a little too high*. Furthermore, for practical reasons an upper limit for a recommendation is desirable. The results discussed above lead to the conclusion that within a recommended work height range from 10 below to 10 cm above elbow height, a working height of 5 to 10 cm below elbow height is to be preferred.

5.2. Oxy-Gas Cutting

The results on estimated endurance time and postural discomfort of the whole body indicate a working height between –10 and +10 cm for recommendation (Figures 11 and 7b, respectively). The judgement on working height 0 cm (elbow height) was closest to the qualification *right*. The judgements on working heights −10 and +10 cm were given qualifications *a little too low* and *a little too high* respectively. For working heights −20 and +20 cm quite a number of variables disclosed that localized physical perceptions were significantly worse than for their particular optimum working height (Table 8). These perceptions are supported by the results on working posture of the related body segments and joints (Figures 5, 8, and 10; refer also to section 4.3.2 and 4.4). In accordance with the criteria described in the introduction to this paper (i.e., experimental conditions are not recommended if workers' perceptions are significantly worse than for any other experimental conditions), working heights −10 and +10 cm should not be excluded for recommendation. Here, it was considered best to do so, but also to emphasize a preference for working height 0 cm, because for working height −10 cm the judgements of a majority of participants (5 out of 8) were either *much too low* or *a little too low*, whereas for working height +10 cm judgements of a majority of participants (6 out of 8) were *much too high* or *a little too high*. The results discussed above lead to the conclusion that a strong preference exists for a working height at elbow height within the recommended working height range from 10 cm below to 10 cm above elbow height.

5.3. Grinding

The results on estimated endurance time and postural discomfort of the whole body show that −35 cm is the optimum, that is, most favourable, working height (Figures 11 and 7c, respectively). The judgements on working heights −35 and −25 cm were closest to the qualification *right*, that is, tending to qualifications *a little too low* and *a little too high*, respectively (Figure 12). Working heights −25 cm and upwards led to significantly worse workers' perceptions for the right upper extremity than lower working heights (Table 8). These localized physical perceptions are supported by the results on working posture (Figures 8 and 10; refer also to section 4.3.2). Working height −45 cm led to significantly worse workers' perceptions for the neck and back than working heights −25 cm and higher (Table 8). These localized physical perceptions are supported by the results on working posture (Figure 5; refer also to section 4.4). The results discussed above lead to the conclusion that a working height 35 cm below elbow height, that is, approximately knuckle height for the participants involved, is recommended.

6. CONCLUSIONS

Concerning the hypotheses and experimental conditions tested, the following conclusions were drawn:

1. the gaze inclination is a determinant of head inclination for-/backwards (*pneumatic wrenching* and *grinding*);
2. visual interference (related to the gaze inclination) is a determinant of head inclination for-/backwards (*oxy-gas cutting*);
3. the viewing distance is *not* a determinant of working posture (*oxy-gas cutting*);
4. the horizontal manipulation distance is *not* a determinant of working posture (*pneumatic wrenching* and *grinding*);
5. the manipulation distance is a determinant of working posture (*oxy-gas cutting*);
6. the hand grip of the tool used is a determinant of working posture, most probably due to the orientation of the grip (*oxy-gas cutting* and *grinding*), or the position of the operation switch (*grinding*), or both;
7. body support for stability is a determinant of working posture (*oxy-gas cutting*);
8. the position of the upper arm with respect to the trunk, that is, shoulder flexion/retroflexion in particular, seems to be a dominant determinant of shoulder and shoulder girdle load, as compared to upper arm elevation (*all operations*);
9. neck flexion/extension seems to be the dominant determinant of neck load, as compared to head inclination for-/backwards (*all operations*);
10. for *pneumatic wrenching* a working height between 10 below and 10 cm above elbow height is recommended, whereas a working height of 5 to 10 cm below elbow height is to be preferred;
11. for *oxy-gas cutting* a strong preference exists for a working height at elbow height, whereas a working height range between 10 below and 10 cm above elbow height is recommended;
12. for *grinding* a working height 35 cm below elbow height, that is, approximately knuckle height, is recommended.

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