Working postures

prediction and evaluation

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The experimental data presented in chapters 4–7 of this thesis stem from research conducted between 1988 and 1992 at TNO Prevention and Health for the 'Stichting Sectorbeleid Meubelindustrie' (branch organization of the furniture industry in the Netherlands), the Dutch Ministry of Social Affairs and Employment, the European Coal and Steel Community, Hoogovens IJmuiden, and the 'Raad van Overleg in de Metaal- en elektrotechnische industrie' (consultative board of the metal and electrotechnical industry in the Netherlands). The printing of this thesis was financially supported by TNO Human Factors Research Institute.

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VRIJE UNIVERSITEIT

Working postures
prediction and evaluation

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Contents

"We have reached a stage where we are now able to measure posture with a high degree of accuracy, but have not yet had time to use this research capability to develop an understanding of human behaviour in different work activities which would allow us to specify the criteria for 'good working postures' or to predict the postures which will actually be adopted by operators in industry."

Christine M. Haslegrave, 1994, p. 796

Chapter 1

Introduction

This thesis is about working posture, i.e. the spatial orientation of body segments, or the sequence of orientations adopted over time, while performing a work task/operation[1]. About one-third of the workers in the European Union are involved in painful or tiring positions for more than half their working day, and close to 50% of the workers are exposed to repetitive hand or arm movements for such a duration (The European Foundation for the Improvement of Living and Working Conditions, 1996). To date, workstation designers cannot see the effects of a design on working posture before a mock-up/prototype is available. At that moment, usually the margin for creating the conditions required for adopting favourable postures is still very limited. Posture prediction at an early design phase, i.e. at the CAD screen, would enhance full consideration of ergonomics among other design aspects as well as reduce time-to-market and costs for proper workstation design. For prediction, however, the determinants of working postures have to be known, where a determinant is defined as a constraint as regards posture selection by the worker involved.

The purpose of this thesis is to describe determinants of working postures (chapters 2 and 8), as well as evaluation criteria for working postures (chapters 3 and 9; figure 1.1). In chapters 8 and 9 data from the literature (chapters 2 and 3) will be brought together with data from a series of studies on visual-manual operations (chapters 4–7), using a standardized research approach (Delleman, 1991). These studies describe the effects of the adjustment of workstations 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 and Bishop, 1976). Combining detailed posture records of body segments and localized physical perceptions may generate evaluation criteria for working postures. Insight into determinants of working postures may be gained by geometric invariants observed at worker-workstation interactions, as well as by exploring why workers adopt certain postures that are rated relatively unfavourable by themselves. It is considered worth mentioning that whole-body movements (such as in picking up an object from the floor), as well as exertion of great forces will not be studied in this thesis.

[1] Key terms can be found in a glossary near the end of this thesis.

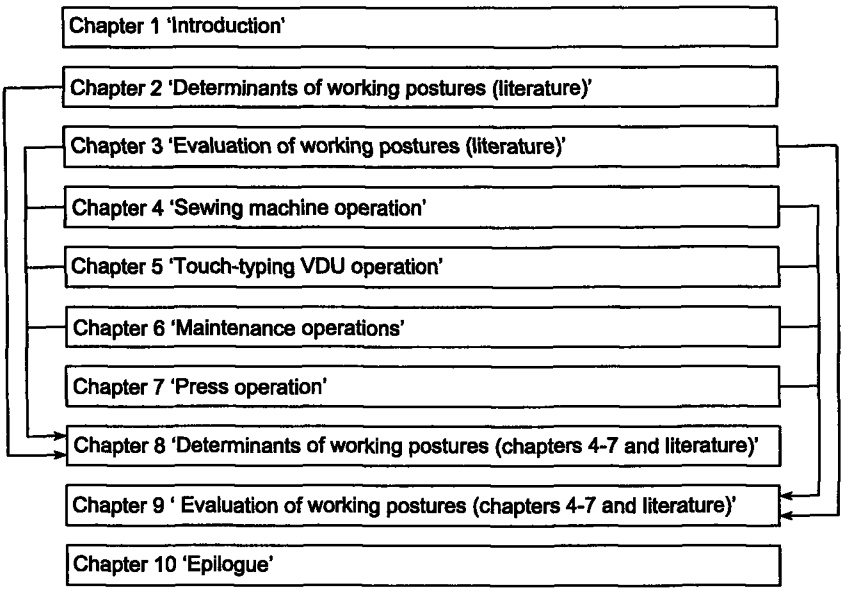

Figure 1.1 Thesis set-up. Arrows show the streams of information.

This thesis serves as an exploration stage for the development of a posture prediction and evaluation tool for designers of workstations. Knowledge of the determinants that lead workers to adopt a particular working posture increases the feasibility of posture prediction. In other words, once it is found that actually selected postures follow certain rules, posture may be predicted on the basis of workstation, worker, and operation characteristics. As posture and movement are related to musculoskeletal load and task performance, means of prediction offer the opportunity for designing proper workstations. In the future postural determinants and evaluation criteria may be incorporated in man-models working in connection with CAD-systems, along with other information concerning workers that is of importance to a designer (cf. Chaffin *et al.*, 1970). This thesis may contribute to the introduction of more ergonomics into designers' practice. Users of ergonomically designed workstations are likely to benefit in terms of task performance (improvement of productivity and quality of work), as well as in terms of less discomfort/fatigue, sick leave, and disability caused by musculoskeletal load.

Chapter 2

Determinants of working postures (literature)

2.1 Introduction

A working posture is determined by the characteristics of the worker, the workstation, and the operation. Table 2.1 contains the hypothetical determinants that are treated in this thesis. Concerning the sense-systems, the main attention will be on the eyes/vision. Regarding the capabilities of motor-systems one may, for example, think of joint ranges of motion, strength, and endurance. It is recognized that many other determinants may be involved in posture selection in general, e.g. the level of skill, and psychosocial factors such as stress, boredom, and tradition/culture.

Table 2.1 Hypothetical determinants of working postures.

Worker
- dimensions, spatial position and orientation, and mass (body segment, whole body)
- capabilities of motor-systems
- capabilities of sense-systems

Workstation (transport means, machines, furniture, tools/objects*)
- dimensions, spatial position and orientation, and mass

Operation
- vision
  - gaze direction and viewing distance (spatial position of target with respect to head/eyes)
  - interface with visual target (angle between line of sight (gaze direction) and target surface, visual interference)
- control (hand, foot)
  - reach direction and reach distance (spatial position of target with respect to spine/thorax/shoulder girdle or pelvis)
  - interface with target, i.e. actuator/tool/object (type and orientation of grip/contact)
  - direction and magnitude of external force exertion
- stability (body segment, whole body)
  - interface with workstation (type of body support)

* In a wider sense, a workstation includes fixtures, fittings, floor, walls, and ceiling.

Determinants of working posture may be active as regards the postural space and/or as a postural strategy. Both concepts will be defined below and exemplified following the determinants mentioned in table 2.1. After that, key hypotheses/models as regards postural behaviour are described.

Postural space

A postural space is defined as all working postures that can be adopted voluntarily and momentarily, given a set of physical limitations. Basically, each space is determined by the ranges of motion of body joints and eyes (within the head/orbit). During operation, a range of motion may be reduced by personal protective equipment, such as glasses, clothing, etc. Furthermore, the capability of the eyes in terms of visual acuity may affect the space by limiting the range of viewing distances. Dimensions, spatial position and orientation of a workstation and a worker may affect the postural space, simply by mutual physical interference. Worker dimensions also include personal protective equipment, such as shoes, clothing, helmet, etc. The operation to be performed may pose demands on vision, hand/foot control, and/or stability. That is, all three types of demand can be characterized by interfaces with the workstation, affecting the postural space. For instance, vision requires a minimum angle between the line of sight (gaze direction) and the surface of a visual target as well as the absence of interference of the line of sight. Control may require a certain type and orientation of grip/contact. Stability in terms of a balanced posture of the whole body always requires a base of one or more points/areas of support at the workstation, while stability in terms a fixed posture of a body segment may require additional support.

Postural strategy

Within the postural space, a worker needs to meet vision and/or control demands concerning the position of the target with respect to the body, described here in terms of spherical coordinates by a direction and a distance. A hand position, for example, may be realised by many combinations of orientations of the forearm, the upper arm, the shoulder girdle, and the trunk. Most likely, a worker will prefer a selection of these, guided by an underlying principle (cf. Bernstein, 1967; for analogous considerations concerning external force exertion, cf. Haslegrave, 1994). A postural strategy is defined as a systematic relationship disclosed between the determinant in question and working posture.

Key hypotheses/models

Evershed (1970), Korein (1985), and Case *et al.* (1990) hypothesized that a body segment will only be moved, if a target cannot be reached by all segments located more distally. Hsiao and

Keyserling (1991) hypothesized that a proximal segment (i.e. closer to the buttock-seat interface) would show a greater tendency to stay close to a neutral posture than a distal segment, whenever movement of segments was necessary in order to view or reach a target. The model by Hsiao and Keyserling includes two- and three-dimensional segments, each defined by measurement points (all mounted at the skin, except for the visual target; table 2.2). The hypothesis by Hsiao and Keyserling was tested at a variety of target positions by measuring the posture of body segments (except for the shoulder girdle) and classifying them as within or outside neutral ranges (table 2.3). A neutral range is defined as the part of the maximum range of motion which presents minimal discomfort to the joints and adjacent body segments. However, the neutral ranges defined are highly questionable. That is, the literature does not provide a proper basis for quantifying to this extent (cf. chapter 3). It would have been much more appropriate if the authors would have done without and presented the actual data on joint positions while viewing or reaching a target. Moreover, to a large extent the experimental data for target positions were presented as average scores. Therefore, only very few systematic relationships between target position and working posture can be disclosed. Still, even when such a relationship was found, sometimes doubts remained as regards the conclusions to be drawn. That is, from the authors' description it could not be deduced a) whether or not the seat of the chair could swivel, i.e. rotate around a vertical axis, and b) whether or not the chair was fixed to the floor. This means for example that if a rotation of the pelvis around the vertical axis is measured, it is not clear whether subjects prefer rotating the pelvis with respect to the seat or prefer swivelling the seat, instead of using other body segments for viewing or reaching a target.

Table 2.2 Segments and measurement points from the model by Hsiao and Keyserling (1991).

Segment	Measurement points
Line of sight	visual target, and halfway between both eyes
Head/neck	halfway between both eyes, left tragion (approximately the earhole), right tragion, and 2nd thoracic vertebra (from the authors' description it is not clear which of these four points were actually used)
Trunk	2nd thoracic vertebra, suprasternale notch, and 5th lumbar vertebra
Pelvis	5th lumbar vertebra, left hip joint, and right hip joint
Hand	medial side of the wrist, lateral side of the wrist, and a non-specified point at the back of the hand
Forearm	olecranon, medial side of the elbow, lateral side of the elbow, medial side of the wrist, and lateral side of the wrist (from the authors' description it is not clear which of these five points were actually used)

Upper arm	anterior side of the lesser tubercle of the shoulder joint, posterior side of the greater tubercle of the shoulder joint, olecranon, medial side of the elbow, and lateral side of the elbow (from the authors' description it is not clear which of these five points were actually used)

Table 2.3 Neutral ranges defined by Hsiao and Keyserling (1991). The ranges are defined relative to a neutral posture, i.e. an upright head/neck, trunk and pelvis, symmetric with respect to the sagittal plane, the upper arms hanging downwards, forearms pointed forwards, parallel to the sagittal plane and perpendicular to the upper arms, hand palms facing the sagittal plane, no radial/ulnar deviation or flexion/extension of the wrist. The head/neck was defined as upright, when the Frankfurt plane was parallel to the horizontal.

Neutral ranges	
Vertical viewing angle	between 45° downwards and 15° upwards (line of sight with respect to the Frankfurt plane)
Horizontal viewing angle	between 15° to the left and 15° to the right (line of sight with respect to the head/neck sagittal plane)
Head/neck vertical angle	between 45° flexion and 45° extension (i.e. head/neck with respect to trunk)
Head/neck twist/rotation angle	between 20° to the left and 20° to the right (i.e. head/neck with respect to trunk)
Head/neck lateral bending angle	between 20° to the left and 20° to the right (i.e. head/neck with respect to trunk)
Trunk flexion-extension	between 30° flexion and 30° extension (i.e. trunk with respect to pelvis)
Trunk twist/rotation angle	between 20° to the left and 20° to the right (i.e. trunk with respect to pelvis)
Trunk lateral bending angle	between 20° to the left and 20° to the right (i.e. trunk with respect to the pelvis)
Wrist flexion-extension	between 15° flexion and 15° extension (i.e. hand with respect to forearm)
Wrist deviation angle	between 5° radial deviation and 15° ulnar deviation (i.e. hand with respect to forearm)
Forearm rotation angle	between 30° pronation and 90° pronation (hand with respect to upper arm)
Elbow angle	between 45° flexion and 110° flexion (i.e. forearm with respect to upper arm)
Shoulder flexion-retroflexion	between 45° flexion and 27° retroflexion (i.e. upper arm with respect to trunk); N.B. the authors use the term extension instead of the term retroflexion

Shoulder adduction-abduction	between 45° abduction and 20° adduction (i.e. upper arm with respect to trunk)
Shoulder internal-external rotation	between 45° medial rotation and 20° lateral rotation (i.e. upper arm with respect to trunk)
Pelvis rotation angle	no rotation around the vertical axis*
Pelvis shifting distance	no horizontal shift (translation)*

* N.B. the authors use the term hip instead of the term pelvis.

The model by Jung *et al.* (1992;1995) includes four segments on the left as well as on the right side of the upper body, i.e. the hand, the forearm, the upper arm, and the trunk. Remarkably, no shoulder girdle segment is included in the model. The left and right side of the upper body are independent. Joints connecting a segment to a proximal adjacent segment have either one or three degrees of freedom and accessory ranges of motion (table 2.4). A hand segment and a forearm segment are connected at the wrist. A forearm segment and an upper arm segment are connected at the elbow. An upper arm segment and a trunk segment are connected at the shoulder. A trunk segment is connected to a non-specified segment (most likely the upper leg) at the hip. Wrist ulnar/radial deviation and forearm pronation/supination are not included in the model. Although the authors' descriptions were not always complete, it is very likely that the ranges of motion are defined with respect to the so-called anatomical position, i.e. standing upright, head facing forward, symmetric with respect to the sagittal plane, arms hanging down with palms facing forward. For posture prediction purposes, the model calculates, for each range of motion separately, the deviation of the segment from the centre, divides it by the maximum deviation from the centre (both in radians), takes the square, and multiplies by a penalty, i.e. ((deviation/maximum deviation) squared) * penalty. The resulting scores for the eight ranges of motion are summed. The model predicts that the upper body posture with the lowest sum will be chosen by subjects in reality. The sizes of the penalties mentioned above are 25 for trunk flexion, 2100 for trunk lateral bending, 1500 for trunk twisting, 150 for shoulder flexion/retroflexion, and 1 for the other four ranges of motion. Without giving any more detailed information, the authors state that these particular penalty sizes were selected using simulations based on anthropometric characteristics of the segments involved, in order to prevent discontinuous (non-smooth) joint motions. Despite this vague description, the model gives us the opportunity the compare postural predictions with actual reaching behaviour.

Table 2.4 Joint ranges of motion defined by Jung *et al.* (1992;1995). Each range of motion has its own maximum deviation from the centre (e.g. 91° for upper arm abduction-adduction).

Ranges of motion	
Wrist flexion-extension	between 90° flexion and 99° extension (i.e. hand with respect to forearm); centre at 4.5° extension
Elbow flexion-extension	between 0° flexion and 142° flexion (i.e. forearm with respect to upper arm); centre at 71° flexion
Shoulder flexion-retroflexion	between 188° flexion and 61° retroflexion (i.e. upper arm with respect to trunk); centre at 63.5° flexion; N.B. the authors use the term extension instead of the term retroflexion
Shoulder abduction-adduction	between 134° abduction and 48° adduction (i.e. upper arm with respect to trunk); centre at 43° abduction
Shoulder rotation	between 97° medial rotation and 34° lateral rotation (i.e. upper arm with respect to trunk); centre at 31.5 medial rotation
Trunk flexion	between 0° flexion and 90° flexion (i.e. trunk with respect to upper leg); centre at 45° flexion
Trunk lateral bending	between 45° to the left and 45° to the right (i.e. trunk with respect to upper leg); centre at 0°
Trunk rotation	between 60° twisting to the left and 60° to the right (i.e. trunk with respect to upper leg); centre at 0°

The BOEMAN model (Springer, 1969; Healy, 1971; Katz, 1972) resembles the model by Jung and colleagues. Unfortunately, the postural behaviour predicted by the former model could not be studied, because no quantitative description was presented. The same is true for the models by Kilpatrick (1970;1972; refer to § 2.3.1), and Rosenbaum *et al.* (1995; refer to § 2.3.1). In general, it is concluded from the literature that very few models provide enough quantitative information for predicting 3D upper body postural behaviour. In addition, authors' descriptions were not always complete, in particular as regards definitions (e.g. Hsiao and Keyserling, 1991; Jung *et al.*, 1992;1995). Furthermore, every now and then identical terms have different definitions in the literature.

In the remaining part of this chapter determinants of working postures will be described along the lines of the operation characteristics mentioned before, i.e. vision (§ 2.2), hand control (§ 2.3), and stability (§ 2.4), as well as by their interactions (§ 2.5, including foot control). In each section data from the literature will be described. The aim is to present a broad overview, without unnecessarily going into the details of the various studies. Descriptions will mainly be of a kinematic nature. The research questions emerging can be found in § 2.6.

2.2 Vision

Here, vision is described as the position of a target with respect to the head/eyes[2], i.e. in terms of spherical coordinates by a gaze direction (line of sight; § 2.2.1), and a viewing distance (§ 2.2.2). Furthermore, effects of the interface with a visual target (angle between line of sight and target surface, visual interference) are described (§ 2.2.3). No descriptions concerning saccadic eye movements[3] are included.

2.2.1 Gaze direction

Gaze is directed towards a target by re-orienting the eye in the head/orbit, and/or by re-orienting various body segments. Studies on the relationship between gaze direction and working posture either focus on the horizontal gaze direction (left/right), on the vertical gaze direction (up/down), or on a combination of both, i.e. an oblique gaze direction. The vertical gaze direction is usually described as gaze inclination, i.e. the angle between the gaze direction and the horizontal plane.

Oblique gaze direction

Nakayama (1983) described quite clearly two fundamental laws of human eye rotation. Donders' law states that each gaze direction is associated with one and only one orientation of the eye in the orbit. While obeying Donders' law, Listing's law for the eyes in the head (figure 2.1) is much more specific, i.e. stating that the eye uses only two out of its three degrees of rotational freedom while re-directing gaze. The eye rotates around axes that all lie in one head-fixed plane. This so-called Listing's plane (figure 2.1) is roughly somewhat tilted forwards with respect to the frontal plane of the upright head[4] (Hore *et al.*, 1992; Radau *et al.*, 1994; for a review of conditions affecting Listing's plane orientation, refer to Crawford and Vilis, 1995), as well as perpendicular to a primary gaze direction. Gaze changes occur without rotation around the latter axis when viewing distant targets. Listing's law also holds during vision at close range, where Listing's plane rotates temporally in each eye, that is, in a direction opposite to the vergence-mediated

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[2] The studies found in the literature do use various base points, i.e. the centre of the head, one of the eyes, or the so-called mid-eye position (halfway between both eyes). Descriptions of gaze direction and viewing distance concern either a reference posture (e.g. head/neck and trunk/pelvis upright), or the posture while actually viewing the target.

[3] Saccadic eye movements are fast jumps of short duration from one position to another which direct the fovea to an object of interest.

[4] The head defined as upright, when the Frankfurt plane is parallel to the horizontal.

change of gaze direction towards the nose (e.g. Mok *et al.*, 1992; Minken and Van Gisbergen, 1994).

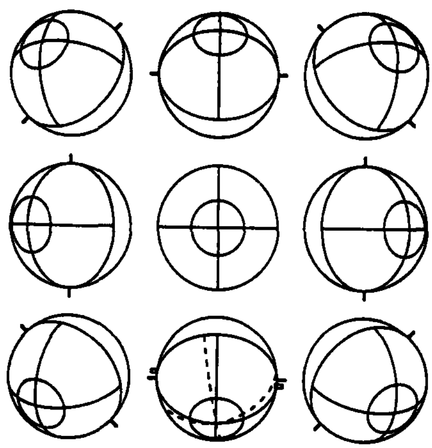

Figure 2.1 Listing's law for the eye in the head. The nine eye orientations drawn in solid lines accord with Listing's law, because they are attainable by rotating from a primary orientation (centre) about axes lying in Listing's plane (the plane of the paper). The orientation drawn in dashed lines at bottom centre does not fit Listing's law, because the rotation to this orientation from the primary orientation occurs about an axis tilted out of Listing's plane. Reprinted from Vision Research, 30, Tweed, D. and Vilis, T., Geometric relations of eye position and velocity vectors during saccades, 111-127, Copyright (1990), with kind permission from Elsevier Science Ltd, The Boulevard, Langford Lane, Kidlington, 0X5 1GB, UK.

Straumann *et al.* (1991) and Tweed and Vilis (1992) have shown an analogue of Listing's law for the head, i.e. during head-free gaze changes (trunk upright and stationary) the facing direction of the head, that is, the direction in which the nose points, changes by rotations around axes that all also lie in one plane. This plane is perpendicular to the primary facing direction, which is approximately the normal head posture for viewing a target at eye level straight ahead. No rotation around the axis of the primary facing direction was demonstrated. The results of both studies were obtained for target positions up to 70° eccentric from a central target. However, for somewhat more eccentric targets (70° to 90°), Glenn and Vilis (1992) disclosed for each gaze direction a rather unique amount of rotation of the head around the axis of the primary facing direction. Changes of head orientation are constrained to a twisted surface of rotation axes instead of to a plane[5]. This means that the analogue of Listing's law for the head is violated, while the analogue of Donders' law for the head is upheld. It seems that the head behaves more like a so-called Fick gimbal, i.e. a rotational system in which a horizontal axis is nested within a fixed vertical axis (figure 2.2). According to Misslisch *et al.* (1994) the rotation of the head around the axis of the primary facing direction depends primarily on its for-/backward and left/right orientation of the head relative to the trunk and is largely independent of the trunk's orientation relative to gravity (45° inclination for-/backwards, as well as 45° inclination sidewards, were tested). In other words, in the case of trunk inclination the head's constraining surface appears to be trunk-fixed. Radau *et al.* (1994) indicated that the head's constraining surface is also trunk-fixed for chest rotation around a vertical axis while fixating at targets positioned up to 135° to the left or right. In the latter study 40–50% of the horizontal gaze direction was created by re-orienting the head with respect to the chest (Vilis, 1996). Turning the trunk with respect to the head through a much smaller angle (30° to the left or to the right) still led to the conclusion that the head's constraining surface is a space-fixed local Listing's plane (Straumann *et al.*, 1991). According to Straumann (1996) space-fixed local Listing's planes and global trunk-fixed surfaces are, in principle, not contradictory. That is, the orientation of the local Listing's planes changes according to the workspace, and the composition of all these planes would probably result in a trunk-fixed surface similar to the one found by Vilis and co-workers.

Straumann *et al.* (1991) and Glenn and Vilis (1992) found that during oblique gaze shifts (without chest/trunk movement), the eye makes predominantly vertical movements (within the head/orbit), whereas the head makes predominantly horizontal movements, presumably in order to minimize work done against gravity. Glenn and Vilis (1992) positioned visual targets at each corner and at the centre of a square (with sides vertical or horizontal). For the head the average ratio of vertical and horizontal components (v/h) was 0.54 for movements to targets at 70° eccentricity and 0.50 for targets at 90° eccentricity, whereas for the eye (within the orbit/head) the average v/h was 2.51 for movements to targets at 70° eccentricity and 1.42 for targets at 90° eccentricity.

Hsiao and Keyserling (1991; refer to § 2.1 for a general critique) studied postural behaviour of seated subjects, during continuous/static viewing for two minutes at each of nine target positions (either 0°, 30° or 60° to the right, and either 60° down, 0°, or 60° up). It was hypothesized that a proximal segment (i.e. closer to the buttock-seat interface) would show a greater tendency to stay close to a neutral posture than a distal segment, whenever movement of segments was necessary in order to view a target. The posture of body segments (including the

[5] Apparently, while studying small sections of a curved surface, the surface easily appears flat (Straumann *et al.*, 1991; Tweed and Vilis, 1992).

eyes) was measured and classified as within or outside neutral ranges. Indeed, looking at the overall result for all target positions tested, the trunk was found to have a greater neutral tendency than the head/neck. However, contrary to the hypothesis, the eyes (line of sight with respect to the head) had the greatest neutral tendency of all. The least neutral tendency of all was found for the pelvis, i.e. on average about 80% of the movement to get the gaze onto a target to the right was created by rotation of the pelvis around the vertical axis (it is not clear whether subjects rotated the pelvis with respect to the seat or used a swivelling seat).

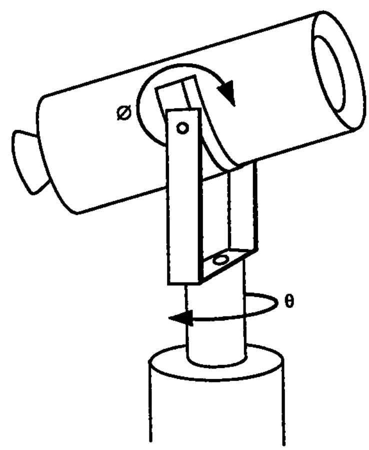

Figure 2.2 Fick gimbal system, exemplified by a telescope. Rotations around vertical and horizontal axes are denoted by Θ and ϕ, respectively. Reprinted from Nakayama (1983), with kind permission from the author.

Radau *et al.* (1994) studied eye, head, and chest orientation of standing subjects (feet fixed only), while fixating a visual target at each of 12 positions (either 45°, 90°, or 135° to the left or right, and either 45° down or 45° up). It was found that the ratio of vertical to horizontal components for the eye (within the orbit/head) is generally greater than 1. The chest, by contrast, moved almost entirely in the horizontal direction, whereas the head performed an intermediate role. The horizontal component of gaze is created on average 50–60% by the chest and 40–50% by the head with respect to the chest, leaving the eye with little to contribute and near its centre position within the head/orbit (Vilis, 1996). The results of Radau and colleagues concerning vertical gaze direction support the main hypothesis by Hsiao and Keyserling (1991), stating that a proximal segment would show a greater tendency to stay close to a neutral posture (upright trunk, upright head/neck) than a distal segment, whenever movement of segments is necessary in order to view a target. Bearing in mind the experimental results by Radau and colleagues, it is very likely that

Hsiao and Keyserling were not able to demonstrate that the eyes have the least neutral tendency, because of the extremely great neutral range defined (i.e. the line of sight between 45° of rotation downwards and 15° of rotation upwards from the Frankfurt plane). The results of Radau and colleagues concerning horizontal gaze direction disclosed that a distal segment shows a greater tendency to stay close to a neutral posture than a proximal segment (i.e. eyes versus head, as well as head versus chest), which is totally opposite to the main hypothesis by Hsiao and Keyserling (1991).

Horizontal gaze direction (left/right)

The studies to be described in this section were carried out under trunk/chest-fixed conditions. Given less restricted circumstances, Radau *et al.* (1994) and Hsiao and Keyserling (1994) showed that the trunk/chest and pelvis, respectively, contribute considerably to get the gaze onto an eccentric target (§ 2.2.1, sub *oblique gaze direction*).

The relationship between target eccentricity in the horizontal gaze direction and head posture is rather linear for subjects on a group level (e.g. Gresty, 1974; Barnes, 1979; Rossetti *et al.*, 1993; Volle and Guitton, 1993). Gresty (1974) asked subjects to fixate at various visual targets positioned on an arc between about 80° to the left and 80° to the right of the straight forward gaze direction (i.e. eyes in the straight-ahead position in the orbit). On average, the head contributed 75-84% to get the gaze onto target. For about the same arc, Barnes (1979) found an average 78-80% for the subjects studied (on estimate the 95% confidence interval equals 25% on average). For a limited range of horizontal gaze direction (targets positioned between 25° to the left and 25° to the right) also Straumann *et al.* (1991) stated that gaze is directed mainly by head movement. The same result was obtained by Volle and Guitton (1993) for target positions up to 110° to the left or to the right of various initial head postures (the gaze direction initially always straight forward with respect to the trunk). Rossetti *et al.* (1994) measured head contribution while viewing at various targets on an arc between the straight forward gaze direction (i.e. eyes in the straight-ahead position in the orbit) and 80° to the right of it. It was hypothesized that the pointing performance would be best at a 90% head contribution. On average this figure was confirmed by their experimental data, while individual contributions were said to vary between 50% and 100%. Until now we have seen studies showing that on average a relatively large share of the horizontal gaze direction is contributed by the head. However, there are also studies mentioning much lower contributions. For targets positioned 40° and 55° to the left and 40° and 55° to the right of the straight forward gaze direction (i.e. eyes in the straight-ahead position in the orbit), Bartz (1966) found that the head contributed on average between 15% and 35% to get the gaze on target. For less eccentric target positions, i.e. on an arc between 40° to the left and 40° to the right, Biguer *et al.* (1984) disclosed an average contribution of about 60% (all individual values below 67%). The same result was found by Biguer and Prablanc (1981). For targets 10°, 30°, and 50° away from the straight forward gaze direction, Uemura *et al.* (1980) disclosed head contributions of 93%, 64%, and 62%, respectively.

Delreux *et al.* (1991) described an average head contribution of about 60-65% (most individual values between 40% and 80%) after centrifugal movements, i.e. more exorotation of the head at the final orientation. Remarkably final orientations after centripetal movements showed on average about a 100% head contribution. This phenomenon is called midline attraction (Fuller, 1992), i.e. attraction of the eyes to the straight-ahead orientation within the orbit.

Especially the studies by Delreux *et al.* (1991), Fuller (1992), and Rossetti *et al.* (1994) disclosed quite an intersubject variability. According to Delreux *et al.* and Fuller this supports the existence of so-called head movers and eye movers (non-head movers), as introduced by Afanador and Aitsebaomo (1982) and confirmed by Roll *et al.* (1986). Furthermore, various possible reasons for the variability observed were mentioned by Delreux *et al.* and Fuller, such as the behavioural/-experimental situation, target eccentricity, and initial alignment of head and gaze (i.e. eyes in the straight-ahead position in the orbit). The latter was said to induce an awareness/arousal effect leading to a greater head contribution to get the gaze on target. According to Fuller (1992), under the condition that head and gaze were initially aligned, about the same range of head contributions were found in the studies mentioned above. However, if head and gaze were not aligned at the start of a gaze shift, the head contribution to get the gaze on target ranged from about 0% to 70% for the same subjects (target positions tested ranging from 40° to the left to 40° to the right).

Vertical gaze direction (up/down, gaze inclination)

Under trunk-fixed conditions, Brues (1946) measured head inclination for-/backwards on a range of gaze inclination between straight down and straight up, with intervals of 22.5°. Figure 2.3 shows the mean results of 21 subjects. Because gaze inclination is equal to the sum of head inclination for-/backwards and up-/downward orientation of the eye with respect to the head/orbit by definition, the data disclose that while looking forward between 22.5° below and 22.5° above the horizontal, a change of gaze inclination is created by approximately 45-55% through head inclination for-/backwards. The contribution by the head gradually increases up to 80-85% when gaze changes occur between 70° and 90° to the horizontal (i.e. close to looking steeply up or down). This effect of target eccentricity seems to play a role in the changing ratios of vertical and horizontal components for the head and the eyes measured by Glenn and Vilis (1992; refer to the section on oblique gaze direction). In figure 2.3 at gaze inclinations -90°, -67.5°, -45°, -22.5°, 22.5°, 45°, 67.5°, and 90° the contribution of head inclination for-/backwards to gaze inclination is approximately 60%, 52%, 49%, 42%, 47%, 56%, 61%, and 66%, respectively. From a typical result of a gaze-pursuit task (with instructions to keep the back against the chair), as presented by Straumann *et al.* (1991), it was estimated that the contribution of head inclination for-/backwards to gaze inclination is about 55-60% for targets positioned between 25° below and 25° above the horizontal. This result was confirmed for gaze inclinations between horizontal and 50° below horizontal by data on a reading task with an upright trunk (Conrady *et al.*, 1987). For the gaze range studied, the data of Conrady and colleagues showed a rather linear relationship between gaze inclination and head inclination for-/backwards.

At the literature described above the gaze inclination turned out to be a determinant of working posture as a postural strategy. That is, all three studies show about the same relationship between gaze inclination and head inclination for-/backwards, given a stationary trunk. None of the tasks studied seemed to put moderate/high demands on hand control. Therefore, one question remaining is whether the strategy disclosed also holds at visual-manual operations under trunk-free conditions.

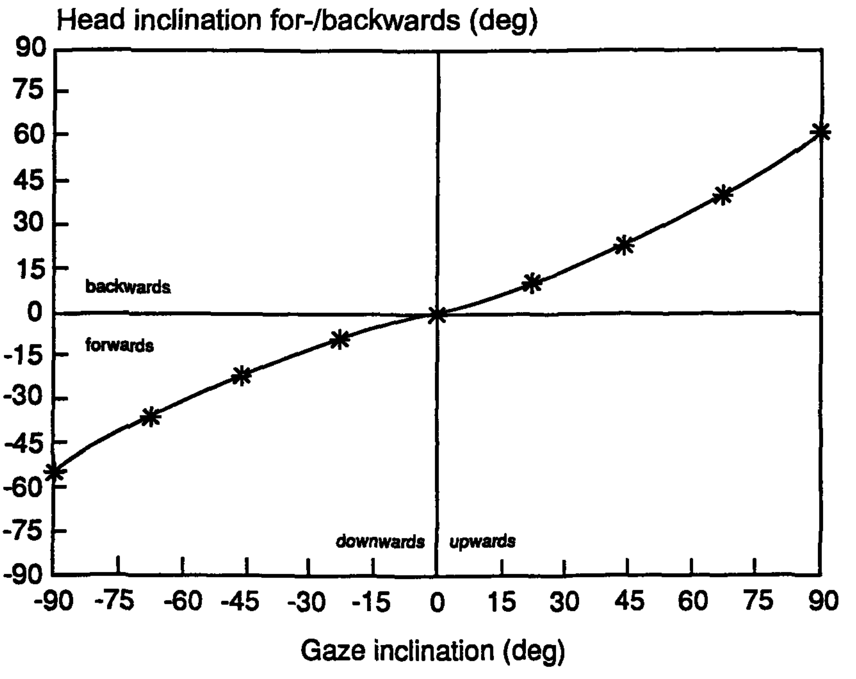

Figure 2.3 The relationship between gaze inclination and head inclination for-/backwards (average group scores; n = 21), taken from a study by Brues (1946). Original data were modified in such a way that at a gaze inclination equal to 0° (horizontal), head inclination for-/backwards equals 0° (upright).

2.2.2 Viewing distance

Subjects prefer a distance between the eyes and a target roughly between 50 cm and 100 cm, provided the size of the target is big enough in terms of visual acuity. The preference exists, most probably, in order to minimize the strain of the extraocular and ciliary muscles, which are responsible for convergence and accommodation of the eyes, respectively (e.g. Brown and Schaum, 1980; Grandjean *et al.*, 1982;1983; Jaschinski-Kruza, 1987;1988;1990;1991; Jaschinski *et al.*, 1998; Akbari and Konz, 1991).

One question remaining is whether the viewing distance is a determinant of working posture as regards the postural space (the capacity of the eyes in terms of visual acuity limits the range of distances) and/or as a postural strategy (workers may try to retain a favourable distance under various conditions).

2.2.3 Interface with visual target

The interface with a visual target is described by *the angle between the line of sight (gaze direction) and the surface of the target*, and sometimes by *visual interference*. A sloping desk, for instance, is most likely meant to improve viewing conditions by means of greater angle between the line of sight and the desk or the surface of the visual target on the desk. In general, it is expected that a desk slope created by a rotation of the desk around its front edge results in a more upright posture of the head and trunk, without elevating the arms (i.e. loading the shoulder region) any further, simply because the elbow is not forced to be raised due to contact with the desk surface. This way, a desk slope may resolve a classic problem presented by table height changes, i.e. either a more upright (presumably better) head and trunk posture, and a more elevated (presumably worse) posture of the upper arms is created, or vice versa.

One question remaining is whether the angle between the line of sight (gaze direction) and the surface of the target is a determinant of working posture as regards the postural space (due to a minimum angle required) and/or as a postural strategy (workers may try to retain a favourable angle under various conditions). Visual interference, on the contrary, is a determinant of working posture only as regards the postural space, i.e. interference of the line of sight reduces the range of postures possible. The question remaining is whether visual interference actually occurs in visual-manual operations, or, in other words, whether postural effects of interference can be demonstrated.

2.3 Hand control

Here, hand control is described as the position of a target with respect to the spine/thorax/shoulder girdle[6], i.e. in terms of spherical coordinates by a reach direction (§ 2.3.1), and a reach distance (§ 2.3.2). The latter section will also describe hand trajectories, which usually include simultaneous changes of reach direction and reach distance. Furthermore, effects of the interface (type and orientation of grip/contact) with an actuator, tool or object (§ 2.3.3) are described. Aspects of force exertion are included in the section on reach distance (§ 2.3.2).

2.3.1 Reach direction

Straumann *et al.* (1991; also Hepp *et al.* 1992) showed an analogue of Listing's law for the arm, i.e. the reach direction of the arm changes by rotations around axes that all lie in one plane. This result was obtained for a small range of target positions, i.e. up to 25° from a central target. However, for more eccentric targets, Hore *et al.* (1992) and Miller *et al.* (1992) disclosed that changes of arm orientation are constrained to a curved surface of rotation axes instead of to a plane, like that found for the head (cf. § 2.2.1, sub *oblique gaze direction*). Here also the arm seems to behave more like a Fick gimbal. Miller *et al.* (1992) indicated that the arm's constraining surface is space-fixed for an upright trunk posture, where the centre of a 30° wide range of targets was positioned 30° upwards or 30° downwards from the horizontal. This result was confirmed by Hore *et al.* (1992) for trunk inclination between 30° backwards and 50° forwards, and a 60° wide range[7] of target positions centred at the horizontal. Remarkably, the head's constraining surface did not appear to be space-fixed, but trunk-fixed (cf. § 2.2.1, sub *oblique gaze direction*). Misslisch *et al.* (1994) mention that the constraining surface for the arm may be space-fixed because the mechanics of rotating the large mass require more consideration of gravity. Straumann *et al.* (1991) showed that the arm's constraining surface is approximately space-fixed for rotation of the upright chest around a vertical axis up to 60° from the forward direction, and a 50° wide range of target positions. That is, for target positions ranging from 25°

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[6] The studies found in the literature do use various base points, i.e. on the shoulder girdle (e.g. at the skin overlying the acromion) or on the spine (at the skin overlying a particular vertebra). Descriptions on reach direction and reach distance concern either a reference posture (e.g. head/neck and trunk/pelvis upright, upper arms hanging down), or the posture while actually reaching. In the latter case, the studies found keep the trunk and shoulder girdle approximately fixed and equal to the reference posture mentioned above.

[7] In the study by Hore *et al.* (1992), 60° wide ranges as well as 90° wide ranges were used. For this particular part of their study, the authors did not specify the range of pointing directions tested. Considering the flexion/retroflexion range of motion of the upper arm with respect to the trunk, it is most likely that a 60° wide range was used.

to the left and 85° to the right of the forward direction. However, according to the study by Miller *et al.* (1992) the constraining surface was definitely not space-fixed for about the same range of target positions, i.e. from 15° to the left and 90° to the right of the forward direction. No reasonable explanation for this discrepancy was found, other than that for the subjects involved in the latter study the limits of the shoulder joint may have been approached (a phenomenon mentioned by Straumann *et al.*, 1991).

The studies by Straumann *et al.* (1991), Hore *et al.* (1992), and Miller *et al.* (1992) were performed at a fully extended or slightly flexed elbow, while the trunk was kept fixed. According to Hepp *et al.* (1992), at these reach distances, the orientation of the arm's constraining plane changed little with reach distance, while upper extremity kinematics are similar to 'visual grasping' with eye and head (cf. § 2.2.1). Hepp and colleagues also stated that great rotations around the longitudinal axis of the upper arm are made while reaching with the upper arm close to the body. A resemblance appears to the effects found during vision at close range (e.g. Mok *et al.*, 1992; Minken and Van Gisbergen, 1994). For relatively short reach distances (i.e. elbow at half and two-thirds of full extension), a quantitative description on arm orientation was presented in a pilot study by Verriest *et al.* (1994). On the basis of a spherical coordinate system, the rotation of the upper extremity segments around the line shoulder-finger tip is related to its reach direction and distance through a linear regression model. The great rotations around the the longitudinal axis of the upper arm mentioned above by Hepp *et al.* (1992) indicate that changes of arm orientation are not always constrained to a surface of rotation axes. Donders' law, as applied to the arm, states that every spatial position of the hand corresponds to a unique posture of the arm. Hepp *et al.* (1992), Soechting *et al.* (1995), Gielen *et al.* (1997), and Desmurget *et al.* (1998) demonstrated that the arm posture at a final hand position depends on the starting position of the hand, and that, consequently, Donders' law is violated. According to Soechting *et al.* (1995) final arm postures can be predicted on the basis of the strategy aiming for minimizing the work done to transport the hand from the starting position to the final position. Rosenbaum *et al.* (1995) postulated that reaching behaviour is guided by knowledge gained by a subject about postures adopted earlier at final hand positions ('stored postures'), that is, in terms of spatial accuracy costs (the extent to which stored postures miss the current target) and travel costs (how expensive it will be to move to the stored postures from the starting posture). Fisher *et al.* (1997) quantified the travel costs in this so-called knowledge model on the basis of the weight of the body segments moved by a rotation at the hip, by a rotation at the shoulder, as well as by a rotation at the elbow (all in the sagittal plane). Some of the predictions from the model were supported by experiments on subjects moving the hand from one location to another, via a third location or not. That is, the least rotation was found at the joint moving the greatest weight, i.e. the hip. Furthermore, postures at a preceeding hand location affected postures at a succeeding location. Subjects seemed to minimize the differences between hip joint positions at successively reached locations of the hand. It also turned out that the velocity of the movement affected the postures at the so-called via location mentioned above, which was located away from the straight line between the initial and final locations of the hand.

Hsiao and Keyserling (1991; refer to § 2.1 for a general critique) studied postural behaviour of seated subjects, during continuous/static reaching for two minutes at each of nine target positions (either 60° to the right, 0°, or 60° to the left, and either 60° down, 0°, or 60° up). These positions were tested at three reach distances, i.e. approximately 40, 70, and 100 cm (16, 28, and 40 inches) away from vertebra T2. It was hypothesized that a proximal segment (i.e. closer to the buttock-seat interface) would show a greater tendency to stay close to a neutral posture than a distal segment, whenever movement of segments was necessary in order to reach a target. The posture of body segments (with the exception of the shoulder girdle) was measured and classified as within or outside neutral ranges. Indeed, looking at the overall result for all combinations of reach directions and distances tested, the trunk showed a greater neutral tendency than the upper extremity segments. However, contrary to the hypothesis, the least neutral tendency of all was found for the pelvis. More specifically, the vertical position of the target clearly showed most effect on shoulder flexion, while the target's horizontal position mostly affected the rotation of the pelvis around the vertical axis (it is not clear whether subjects rotated the pelvis with respect to the seat or used a swivelling seat). For main effects of reach distance, refer to § 2.3.2.

According to the experimental data presented by Hsiao and Keyserling (refer above) subjects are more likely to show rotation of the pelvis around the vertical axis, than to twist their trunk during continuous/static reaching. The model on reach posture of the upper body by Jung *et al.* (1992;1995; § 2.1) does not include the possibility of rotation of the pelvis around the vertical axis. However, the model makes trunk twisting (and trunk lateral bending) the least likely option to be used by subjects in order to reach a target[8]. In that way, the model supports the postural behaviour observed by Hsiao and Keyserling. Contrary to the model by Jung and colleagues, the model by Kilpatrick (1970;1972)[9] calculates both rotation of the pelvis around the vertical axis

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[8] That is, due to the relatively high penalties associated with these particular motions of the trunk (refer to § 2.1).

[9] The model by Kilpatrick (1970;1972) includes, amongst others, the links AP and PT, as well as two links TC (left and right side of the body), where A is the mid-acetabular point, or the midpoint of a line passing through the acetabular points on the right and left side of the pelvis, P is the intervertebral joint L5/S1, T is the vertebra T4, and C is a sternoclavicular joint. What is called 'rotation of the pelvis around the vertical axis' in the main text, is the angle between the projection of the link AP on the horizontal (XY) plane, and the X-axis. What is called 'twisting of the trunk' in the main text, is the axial rotation of the link PT with respect to 'rotation of the pelvis around the vertical axis' described above. Axial rotation of the link PT is based upon the orientation of the link(s) TC.

and twisting of the trunk on the basis of the reach position(s) of the left and/or right hand in space. Unfortunately, no conclusions could be drawn on the postural behaviour of these two parameters, because no quantitative description of the model was presented.

2.3.2 Reach distance

Several researchers studied the effects of reach distance on upper body posture. For seated subjects, Hsiao and Keyserling (1991; refer to § 2.1 for a general critique; refer to § 2.3.1 for details of the experimental set-up) showed that the reach distance affected trunk flexion, shoulder flexion, elbow flexion, as well as pelvis shifting (it is not clear whether subjects shifted the pelvis with respect to the seat or shifted the seat). In particular, subjects shifted their pelvis when a target location was too far away (roughly more than two-thirds of length of the upper extremity). The mathematical relationships between the reach distance and the posture of an individual body segment, were not presented.

Snyder *et al.* (1971) published experimental data on the relationship between the spatial end position of the elbow and the spatial positions of various skin surface markers on the upper body (position of the feet and buttock fixed during standing and sitting, respectively). The spatial orientation of the trunk and the upper arm was studied[10], while moving the elbow straight forward virtually along a series of end positions, starting from an upright trunk posture, with the upper arm hanging down. It turned out that initially most of the forward 'movement' of the elbow was created by upper arm elevation forwards, while the trunk inclines forwards at a slow rate. While 'moving' the elbow further forwards, the upper arm reaches a maximum and the trunk gradually takes over (cf. Kaminski *et al.*, 1995; Mark *et al.*, 1997; Zhang and Chaffin, 1997; Fisher *et al.*, 1997; Vaughan *et al.*, 1998). It appeared that during standing the contribution of the trunk was a little smaller than when sitting.

Predictions from the model by Jung *et al.* (1992;1995; § 2.1) were studied for a series of forward reach positions of the hand at about elbow height, starting from an upright trunk posture, with the upper arm hanging down and the forearm and hand reaching straight forward. Calculations on the basis of the authors' description of the model showed that reaching straight forward from this starting position, initially will be performed by trunk inclination forwards, and

[10] Snyder *et al.* (1971) use an orthogonal coordinate system. The vertical constitutes the Z-axis. The YZ, XZ and XY planes are parallel to the frontal, sagittal, and transversal planes of the upright trunk, respectively. For the purpose of analysing upper body posture, trunk inclination for-/backwards is defined as the angle between the line CL (through the skin surface markers at the 7th cervical vertebra and the 5th lumbar vertebra) during task execution and the line CL in the neutral posture (trunk upright), projected in the XZ-plane, whereas upper arm elevation for-/backwards is defined as the angle between the line AE (through the skin surface markers at the right acromion and the elbow) during task execution and the line AE in the neutral posture (upper arm hanging down), projected in the XZ-plane.

not by upper arm elevation forwards. Clearly this is not supported by the data from Snyder *et al.* (1970).

Two elements missing in the model by Jung and colleagues are in fact included in the model by Kilpatrick (1970;1972), i.e. pelvis shifting, for which the necessity was demonstrated by Hsiao and Keyserling (refer above), and shoulder girdle posture. The experimental data from Snyder *et al.* (1971), as well as a comparison of predicted and actual postures by stick figures from Jung *et al.* (1995), demonstrates the importance of including a shoulder girdle segment.

One question remaining is whether adopting an upper extremity posture is guided by an optimization of the upper extremity joint positions, or by a minimization of the effect of gravitational force via changes of moment arm (besides the weight of the upper extremities, there may be also a weight at hand). The existence of the former postural strategy would be supported by a constant reach position of the hand(s) with respect to the upper trunk during operation (*manipulation distance*), while the existence of the latter would be supported by a constant horizontal component of the manipulation distance (*horizontal manipulation distance*). The manipulation distance may also be a determinant of working posture as regards the postural space (i.e. the distance is limited by the ranges of motion of the upper extremity joints).

Hand trajectories

Soechting and Flanders (1991a/b) reviewed the literature on the trajectory (path) of the hand during point-to-point movements. They concluded that some trajectories are straight, others are (slightly) curved, but there is little intra- and intersubject variability (e.g. Morasso, 1981; Soechting and Lacquaniti, 1981; Lacquaniti and Soechting, 1982; Atkeson and Hollerbach, 1985; Lacquaniti *et al.*, 1986). Uno *et al.* (1989) have shown that a model based on the minimum change of joint torque can account for the various trajectories observed. For horizontal movements Dornay *et al.* (1996) showed similar results when using a minimum muscle-tension change model. The equilibrium point hypothesis (e.g. Fel'dman, 1966; Bizzi *et al.*, 1984)[11], as well as the minimum jerk[12] model (e.g. Hogan, 1984; Flash and Hogan, 1985) predicts straight trajectories only. In their reviews Soechting and Flanders also concluded that hand trajectories are invariant of movement velocity (Soechting and Lacquaniti, 1981; Lacquaniti *et al.*, 1982; Atkeson and Hollerbach, 1985), as well as invariant of a weight up to 2.5 kg in the hand (Lacquaniti *et al.*, 1982; Atkeson and Hollerbach, 1985). However, Pollick and Ishimura (1996) showed that for

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[11] According to the hypothesis the nervous system uses the spring-like properties of muscles. A movement is started by changing the equilibrium point (the muscle length at which the muscle generates no force) from a value appropriate for the initial posture to a value appropriate for the final posture.

[12] Jerk is a change of acceleration.

point-to-point movements at maximum velocity the curvature of the hand trajectory is inversely related to movement velocity. Furthermore, the two studies on the effect of weight in the hand concern movements in a vertical plane. For movements in a horizontal plane, Uno *et al.* (1989) showed that a variable spring force on the hand (i.e. between 3.3 N and 10.4 N) drastically changed the hand trajectory.

2.3.3 Interface with actuator/tool/object

Many times the importance of an adequate *type and orientation of grip/contact with an actuator, tool, or any other object* has been stressed (e.g. Tichauer, 1978; Schulze *et al.*, 1991; Hepp *et al.*, 1992; Karlqvist *et al.*, 1994; Hedge and Powers, 1995; Marras *et al.*, 1995).

For various visual-manual operations Eastman and Kamon (1976), Bendix and Hagberg (1984), Magnusson and Örtengren (1987), Bridger (1988), De Wall *et al.* (1991), and Freudenthal *et al.* (1991) showed that a desk inclined towards the operator induces a more upright posture of the head, neck, and trunk, as well as a more lordotic lumbar spine posture (Bendix and Hagberg, 1984; Bridger, 1988). The studies to be described below give reason to suppose that these positive postural effects of a desk slope are not supported by the majority of operators themselves when a hand tool is involved (pencil, knife, screwdriver), which indicates an interface problem. Bendix and Hagberg (1984) tested a flat desk, a 22° desk slope, and a 45° desk slope. A rating for acceptability favoured the steepest desk for reading. For writing the opposite was favoured. That is, the 45° desk slope received a negative rating (i.e. 'very bad'), while the 22° desk slope and the flat desk were rated 'neutral' and close to 'very good', respectively. Also for writing, Bridger (1988) disclosed that a 15° desk slope was found slightly more comfortable than a flat desk. Taking the latter two studies together, it seems that for writing a desk slope becomes a problem beyond a certain steepness. On the basis of data presented in a study on meat-cutting by Magnusson and Örtengren (1987), for the majority of butchers no improvement on an overall comfort-discomfort scale was found when comparing a 5-8° desk slope to a flat desk. Douwes and Delleman (1992, also Douwes *et al.*, 1992) revealed that during assembly work an object inclined 10° towards the operator was judged 'not good' by 6 out of 8 operators involved, due to the extra force needed to tilt the vertically-aligned balanced pneumatic screwdriver used and an unfavourable right wrist posture.

In a literature review and various experimental studies, Van der Vaart (1995) described postural behaviour in grasping and operating rotary controls. Concerning the experiments he uses the terms CAR (i.e. combined upper arm rotations, defined as the rotation of the arm segments around the line shoulder-wrist) and SUP (i.e. forearm pronation/supination). While rotating an O-control (figure 2.4) subjects almost always used SUP and CAR movements in a fixed ratio. Three different 'tactics' were identified, each characterized by a particular ratio of SUP and CAR movements. There is a general preference for using SUP rather than CAR, but the latter is nearly always used. The full range of CAR was only used when SUP approached the end of its range of motion. This behaviour supports the hypothesis that subjects prefer using a distal body segment instead of a proximal one (refer to § 2.1). In rotating a T-control or an L-control (figure 2.4) the thumb either points to one end of the cylinder or to the other. It was found that the grip used can be predicted accurately if the initial orientation and magnitude of the required rotation are known. The ratio of SUP and CAR movements depends on the grip used and the orientation of the control halfway between its initial and final orientations.

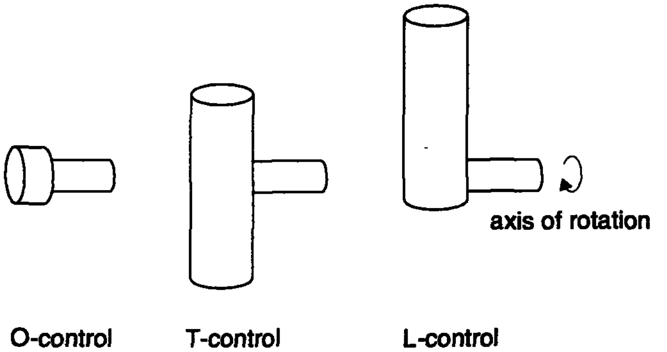

Figure 2.4 Schematic side view of three types of rotary controls. Reprinted from Van der Vaart (1995), with kind permission from Delft University Press.

One question remaining is whether the type and orientation of grip/contact with an actuator/tool/object is a determinant of working posture as regards the postural space (due to a limited set of types/orientations) and/or as a postural strategy (workers may try to retain a favourable type/orientation under various conditions).

2.4 Stability

Any working posture needs a stable base, created by one or more *interfaces with the workstation*. This section focuses on sitting posture, i.e. on the posture effects of buttock/upper legs, back, and foot support.

Keegan (1953) was among the first to describe the effect of hip and knee angles on pelvis inclination for-/backwards and lumbar spine curvature (lordosis/kyphosis). That is, the pelvis inclines more backward and lumbar lordosis decreases, when hip flexion increases or knee flexion decreases. Keegan stated that this postural adaptation is caused by the limited length and consequent pull of the hamstrings[13]. Support for this statement is found in the studies by Bridger *et al.* (1989a/b) and Eklund and Liew (1991)[14]. According to Bridger *et al.* (1989a), for-/backward inclination of the pelvis and lumbar spine curvature are linearly related. For common sitting postures (i.e. hip and knee flexion of 60°-90°)[15], Eklund and Liew (1991) showed that hip flexion is approximately three times more powerful than knee flexion in changing lumbar spine curvature. Lumbar spine curvature is affected by the for-/backward inclination of the seat (e.g. Bendix and Biering-Sørensen, 1983; Bendix, 1984; Mandal, 1985). In the latter studies, each change of experimental seat inclination was accompanied by a re-adjustment of seat height, in order to keep the upper legs aligned with and supported by the top surface of the seat. It might be thought that the effects of seat inclination for-/backwards on lumbar spine curvature are mediated by the amount of hip flexion. Bridger *et al.* (1989a), however, disclosed that, in addition to hip flexion, seat inclination for-/backwards itself also affects lumbar spine curvature (cf. Bridger *et al.*, 1989b). Considering the linear relationship between lumbar spine curvature and pelvis inclination for-/backwards, it seems likely that the latter is directly affected by the seat inclination for-/backwards. This points to an effect of gravity, leading to a stable posture for the pelvis by 'rocking' over the ischial tuberosities (Branton, 1969; refer also to Schoberth, 1962; Corlett and Eklund, 1984).

If the back is positioned against a backrest, for instance by simply instructing subjects to do so, the lumbar spine curvature will be more lordotic, relative to the amount the lumbar support protrudes forwards (cf. Andersson *et al.*, 1979). However, during operations at a table desk (reading, writing, assembling, etc.), where the head and (upper) trunk are more or less inclined forwards, the presence of a lumbar support may easily induce (or, so to say, invite for taking) a more kyphotic lumbar spine curvature, to obtain a stable posture (Bendix *et al.*, 1996).

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[13] Keegan (1953) showed X-ray photographs of a subject lying on his side in order to support his statement, without quantifying muscle lengths (distances between attachment points) and angles between the lower leg, upper leg, pelvis, and lumbar vertebrae.

[14] Eklund and Liew (1991) demonstrated the effects of hip angle and knee angle on lumbar curvature for subjects lying on the side, thus keeping effects of gravity constant. Therefore, it became more likely that the hamstrings are a cause of the postural adaptation mentioned.

[15] Hip flexion is absent (0°), when the upper leg and the trunk are in line. Knee flexion is absent (0°), when the lower leg and the upper leg are in line.

Inadequate means for foot support may be expected to have an effect on lumbar spine curvature as well, mediated by the leg posture, i.e. knee and hip angles, required to create support anyway. Such a non-optimum (i.e. relatively unfavourable) situation usually occurs when seat height is raised in order to create an adequate working height for the visual-manual operation carried out (De Moraes, 1992). On the basis of the variation of foot positions observed, there is a need for relatively large foot rests, with a flat part at the side close to the worker and slanted parts at the other three sides (Windberg *et al.*, 1989; De Moraes, 1992).

An interface with the workstation (type of body support) for creating a stable posture is a determinant of working posture as regards the postural space, i.e. an interface either reduces the range of postures possible or makes a different range of postures possible (e.g. the reach envelope of the hands is enlarged by fixating the lower body, for instance at the feet by friction between the footwear used and the floor, as well as at the upper legs or pelvis by leaning against a stable workstation). One question remaining is whether particular types of body support, other than described above in relation to sitting (for instance upper extremity support), actually occur in visual-manual operations, that is, whether their effects as regards the postural space can be demonstrated.

2.5 Interactions of vision, control, and stability demands

Spine posture may be affected by *vision demands* (through head posture), by *hand control demands* (through upper extremity posture), by *foot control demands* (through lower extremity posture), and/or by *stability demands* (e.g. through sitting/standing posture). Not so much is known about the combined effects of these demands.

According to Nakaseko *et al.* (1993) head/neck inclination for-/backwards affects thoracic spine curvature (a 'top-down' effect), whereas raising or lowering the upper legs when sitting affects lumbar spine curvature (a 'bottom-up' effect, cf. § 2.4). Bendix and Hagberg (1984) and Bridger (1988) showed that a desk inclination even affected lumbar spine posture (top-down, cf. § 2.3.3), while such an effect can also be seen for forward reaching in the results presented by Bendix *et al.* (1988). Bottom-up and top-down effects on lumbar spine posture were found to be independent (Bridger, 1988). Grandjean *et al.* (1982) showed that head/neck inclination for-/backwards is associated with complaints of the back and loin (top-down). Andersson and Örtengren (1974) and Andersson *et al.* (1974) demonstrated that the effects on muscle activity of backward trunk inclination (with adequate support) were found not only in the lumbar spine, but also up into the cervico-thoracic region of the spine (bottom-up). It may be expected that the effects mentioned (complaints, electromyographic activity) do play a role in the process of selecting a working posture.

One question remaining is whether hand control demands or vision demands are the dominant determinant of working posture, knowing that the hand - forearm - upper arm - shoulder girdle chain and the eye - head - cervical spine chain meet at the top end of the thoracic spine.

2.6 Research questions

The literature studied led to the following research questions, that are to be answered by a series of studies on visual-manual operations described in chapters 4–7:

- Vision
  - Is the *gaze inclination* a determinant of working posture as a postural strategy?
  - Is the *viewing distance* a determinant of working posture as regards the postural space and/or as a postural strategy?
  - Is the interface with the visual target, in terms of the *angle between line of sight (gaze direction) and target surface,* a determinant of working posture as regards the postural space and/or as a postural strategy?
  - Is the interface with the visual target, in terms of *visual interference*, a determinant of working posture as regards the postural space?
- Hand control
  - Is the *manipulation distance* a determinant of working posture as regards the postural space and/or as a postural strategy?
  - Is the horizontal component of the manipulation distance (*horizontal manipulation distance*) a determinant of working posture as a postural strategy?
  - Is the interface with the target, i.e. actuator/tool/object (*type and orientation of grip/contact*) a determinant of working posture as regards the postural space and/or as a postural strategy?
- Stability
  - Is the interface with the workstation (*type of body support*) a determinant of working posture as regards the postural space?
- Interactions of vision, control, and stability demands
  - Are vision demands or hand control demands the dominant determinant of working posture?

Chapter 3

Evaluation of working postures (literature)

3.1 Introduction

A working posture is currently being evaluated mainly by regarding various body segments independently. Concerning trunk posture in the sagittal plane, this evaluation relies on experimental, biomechanical modelling, and epidemiological studies relating low back load and health complaints to the amount of deviation from the upright posture or the vertical, i.e. trunk inclination for-/backwards (e.g. Jørgensen, 1970; Wickstrom *et al.*, 1988; Van der Grinten and Smitt, 1992; Aarås, 1994), whereas the evaluation of the upper arm posture relies on similar types of studies relating shoulder (girdle) load and health complaints to the amount of deviation from the hanging posture or the vertical, i.e. upper arm elevation (e.g. Chaffin, 1973; Bjelle *et al.*, 1979;1981; Dul, 1988; Van der Grinten and Smitt, 1992). The posture of the head and/or neck segment in the sagittal plane is mostly evaluated on the basis of experimental, biomechanical modelling, and epidemiological studies relating neck load and health complaints to the amount of deviation from the upright posture or the vertical, i.e. head/neck inclination for-/backwards (e.g. Chaffin, 1973; Hünting *et al.*, 1980;1981; Kilbom *et al.*, 1986; Lee *et al.*, 1986; Snijders *et al.*, 1991; Lindberg *et al.*, 1993). All these measures or determinants of musculoskeletal load are to be seen as an equivalent of the force delivered to counteract the gravitational force on the body 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. From the literature, however, it also appeared that some additional determinants of neck load and shoulder (girdle) load may be of importance in posture evaluation (§§ 3.2 and 3.3). The research questions emerging can be found in § 3.4, while § 3.5 elaborates on the role of various research methods in the process of generating evaluation criteria for working postures.

3.2 Head/neck posture

Bendix and Hagberg (1984) mentioned that neck flexion/extension, i.e. the for-/backward inclination of the head/neck segment with respect to the for-/backward inclination of the trunk segment, may play a role with respect to neck load. This notion is supported by various studies.

Kumar (1994) found that a reduction of neck inclination forwards led to an increase of discomfort. From the data presented by Lepoutre *et al.* (1986) it can be concluded that a greater spinal curvature at vertebra T1 (equivalent to more neck flexion) is associated with reduced fatigue and pain at the neck. Schüldt *et al.* (1986a/b) showed that, at a constant neck inclination for-/backwards (with respect to the vertical), electromyographic activity of various neck muscles was reduced by an increase of neck flexion (created by a backward inclination of the thoraco-lumbar spine). It is likely that the lower electromyographic activity at a greater neck flexion represents a more favourable neck posture from a biomechanical viewpoint (e.g. concerning muscle moment arms and length-tension characteristics). Harms-Ringdahl and Schüldt (1988) found that maximum neck extensor moment was highest at a slightly flexed neck posture (halfway between the neutral and maximum flexed neck postures), that is, significantly different from an extended posture, but not being significantly different from both the neutral posture (subject sitting upright and looking straight forward) and the much flexed posture (near maximum neck flexion). Considering also that head/neck inclination for-/backwards is associated with for-/backward inclination of the thoracic region of the trunk (Nakaseko *et al.*, 1993) and complaints at the low back (Grandjean *et al.*, 1982; Lee *et al.*, 1986), as well as that systematic electromyographic effects of trunk inclination for-/backwards were found not only in the lumbar region, but also up into the cervico-thoracic region of the head-neck-trunk system (Andersson and Örtengren, 1974; Andersson *et al.*, 1974), there is enough reason to study head/neck inclination for-/backwards in relation to trunk inclination for-/backwards (neck flexion/extension), in addition to head/neck inclination for-/backwards. Therefore, in chapters 4-7 both potential determinants of neck load will be studied. However, one should be aware that neck load may equally well be determined by other factors. The posture of the shoulder girdle, for example, is such a factor, i.e. 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 posture of the upper arm (Pronk, 1991; Van der Helm, 1991), at least the latter warrants a closer look in relation to neck load.

3.3 Upper arm posture

In addition to the amount of elevation of the upper arm, 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. Epidemiological data on musculoskeletal illness/sick-leave among workers assembling parts for telephone exchanges, obtained by Aarås (1994), indicate that for an acceptable working posture, median upper arm elevation forwards should be less than 15° and median upper arm elevation sidewards less than 10°. Data on workers in an electronics manufacturing industry, presented by Kilbom *et al.* (1986), suggest a stronger relationship between upper arm elevation sidewards and the severity of musculoskeletal disorders than for upper arm elevation forwards. In an experimental study Mital and Faard (1990) demonstrated that, with an upright trunk, the maximum force for isokinetic pulling in a horizontal plane is affected by the direction of the elevated upper arm, that is, a gradual reduction from the sagittal plane to the frontal plane of the trunk was found (intermediate directions were tested at 30° intervals). It may be assumed that the range of upper arm elevations gone through during force exertion is about the same for all directions tested, since the subjects started pulling from the same horizontal reach distance. Also in the case of an upright trunk, Jensen (1991) measured higher intramuscular pressure in the supraspinatus muscle for 30° upper arm elevation in the sagittal plane of the trunk than for 30° upper arm elevation in the frontal plane of the trunk.

3.4 Research questions

The literature studied led to the following research questions, that are to answered by a series of studies on visual-manual operations described in chapters 4–7:

- Is neck flexion/extension a determinant of neck load, that is to be used as an evaluation criterion for working postures, besides the traditionally used for-/backward inclination of the head and/or neck segment?
- Is the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively) a determinant of shoulder (girdle) load, that is to be used as an evaluation criterion for working postures, besides the traditionally used elevation of the upper arm?

3.5 Research methods

The results of experimental, biomechanical modelling and epidemiological studies are complementary in the process of establishing the relationship between working posture on the one hand, and musculoskeletal load and health complaints on the other. All research methods presented in the literature on this relationship have their limitations. For instance, electromyographic activity and intramuscular pressure do not address the load on passive structures, such as ligaments, while biomechanical models mostly lack validation experiments on their predictions in this respect. Furthermore, data on maximum force exertion do in fact concern load capacity, and provide no more than indications about the actual musculoskeletal load. Epidemiological research may disclose the role of working posture as a risk factor for musculoskeletal disorders (long-term health complaints), but for practical reasons the detail of exposure levels that can be studied is most often considerably less than in experimental research. The series of studies on visual-manual operations in chapters 4–7 provide localized physical perceptions of workers (short-term health complaints) in relation to working posture. Here, the general characteristics of the methods used will be described. Detailed descriptions can be found in §§ 4.2, 5.2, 6.2, and 7.2. In the four studies following working posture is determined by an opto-electronic system, measuring the positions of retro-reflective markers attached to various body segments. The spatial orientations of the segments are described to a large extent by a projection onto a plane of the orthogonal coordinate system used. Such an approach was considered most realistic at the workstations and operations studied, due to the relatively large number of markers to be detected and the body-mounted marker support constructions required for a full three-dimensional description of working posture. For determining the localized physical experiences two scaling techniques are used, i.e. on localized postural discomfort and on perceived posture. Insight into the validity and reliability of these measurements is only available with respect to the former technique and a limited set of load conditions. That is, for groups of subjects reasonably linear relationships were found between gravitational load and discomfort (e.g. Boussenna *et al.*, 1982; Van der Grinten and Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g. Manenica, 1986; Meijst *et al.*, 1995). Van der Grinten (1991) and Van der Grinten and Smitt (1992) demonstrated that the technique for measurement of localized postural discomfort provides reliable results for the mutual comparison of working postures. However, it turned out as well that the absolute discomfort levels vary from time to time. On the basis of the literature described above, the scale used for measuring discomfort was considered to have at least interval characteristics. For measurement of perceived posture an ordinal scale is used. Basically, a standardized research approach as used in the four chapters following, may generate evaluation criteria for working postures. However, given the apparent insufficient reliability of absolute levels of localized postural discomfort, the ordinal character of the rating scale for perceived posture, and the varying experimental circumstances among the studies on the visual-manual operations following (e.g. durations of operation), it seems realistic to expect that the workers' perceptions to be obtained may indicate, confirm, or establish the mere presence of additional determinants of musculoskeletal load, without allowing us to go into a quantitative description of working postures for evaluation purposes (refer to § 3.4).

Chapter 4

Sewing machine operation
Workstation adjustment, working posture, and workers' perceptions

At a traditional sewing machine workstation professional operators worked at ten different combined adjustments of table height, desk slope, and pedal position. Working posture and workers' perceptions were measured. Two guidelines were formulated in order to minimize the load on the musculoskeletal system during operation, i.e. (1) the table desk should be adjusted between 5 and 15 cm above elbow height in a seated posture, (2) the table desk should be given a slope (indication: 10°) and the pedal should be positioned as far under the table as considered comfortable (indication: pedal axis behind the needle). Data from the present experiment as well as from the 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. During sewing machine operation the working posture was constrained by a strictly followed relationship between gaze inclination and head inclination for-/backwards. It was revealed that, while the pedal position allowed for moving closer to the needle, operators used this opportunity only when a 10° desk slope was present. Several hypotheses on this postural behaviour have been presented. Furthermore, it is demonstrated that at various visual-manual operations a slope effect is in fact a height effect. Neck flexion/extension (i.e. for-/backward inclination of the head and/or neck segment versus for-/backward inclination of the trunk segment) was found to be a determinant of neck load, that is to be considered in future research, besides the traditionally measured head/neck inclination for-/backwards.

4.1 Introduction

Several studies have shown that operators of sewing machines report discomfort in the left shoulder, the neck, the back, and the lower extremities (e.g. Vihma *et al.*, 1982; Wick and Drury, 1986; Blåder *et al.*, 1991). These complaints may be caused or aggravated by the seated working posture which is characterized by an elevated left upper arm posture, a forward inclined posture of the head and trunk, and non-optimum (i.e. relatively unfavourable) ankle and knee angles, respectively. At a traditional sewing machine workstation, the body posture is constrained by (1) the eyes for visual control of the work, (2) the hands for directing the sewing material, and (3) the feet for (speed) control of the machine. In order to improve the working posture and reduce the number of complaints, quantitative guidelines for the adjustment of the workstation are needed which take these postural constraints into account.

This study on sewing machine operation 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 the workstation (i.e. desk height, desk slope, and pedal position) 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 and Bishop, 1976). The *first* purpose of the paper is to study determinants of working posture (§ 4.1.1), as well as relationships between working posture and workers' perceptions (§ 4.1.3) for the sake of comparison with other visual-manual operations and generalization. The *second* purpose is to formulate ergonomic guidelines for adjustment (and redesign) of sewing machine workstations (§ 4.1.2). 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.

4.1.1 Determinants of working postures

Table 4.1 shows hypothetical determinants of working posture during sewing machine operation, where a determinant is defined as a constraint as regards posture selection by the operator involved.

Table 4.1 Hypothetical determinants of working posture.

Desk height	→ viewing distance*	(eyes)	→ head inclination for-/backwards
	→ gaze-desk angle*	(eyes)	→ head inclination for-/backwards
	→ gaze inclination*	(eyes)	→ head inclination for-/backwards
	→ manipulation distance	(hands)	→ trunk inclination for-/backwards
	→ obstruction by the desk	(hands)	→ upper arm elevation
Desk slope	→ gaze-desk angle	(eyes)	→ head inclination for-/backwards
	→ visual target height	(eyes)	refer above at *
	→ manipulation distance and horizontal manipulation distance	(hands)	→ trunk inclination for-/backwards
Pedal position (fore/aft)	→ hip-workstation fore/aft distance	(feet)	→ trunk inclination for-/backwards

An arrow stands for 'affects'. The item in brackets refers to the body system that is supposed to be involved in constraining the working posture.

These determinants will be described successively on the basis of the three workstation characteristics to be studied, starting with desk height. So far, it has only been shown that for sewing a desk height 5 cm above elbow height induces a better working posture than lower desks (Dul *et al.*, 1988). Here, it is hypothesized that at higher desks either a more upright head posture is adopted by an operator in order to retain a favourable viewing distance from the needle, or that the head is inclined more forwards to preserve a favourable gaze angle to the sewing material at the desk. Provided the size of the target is big enough in terms of visual acuity, subjects prefer a viewing distance roughly between 50 cm 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. Brown and Schaum, 1980; Grandjean *et al.*, 1982;1983; Jaschinski-Kruza, 1987; 1988; 1990; 1991; Jaschinski *et al.*, 1998; *Akbari and Konz, 1991). It may also be that an operator is subject to a strict relationship between* on the one hand gaze inclination (up-/downwards) and on the other its complementary components — head inclination for-/backwards and the up-/downward orientation of the eye with respect to the head/orbit. This relationship described by Brues (1946; cf. Conrady *et al.*, 1987; Straumann *et al.*, 1991) implies that if gaze is inclined less downwards (as may be expected at higher desks), the head is inclined less forwards at a certain percentage of gaze change. Probably a more upright head posture is accompanied by a more upright trunk posture, and vice versa. Apart from the mechanisms described, it is likely that at higher desks an operator will try to retain a favourable manipulation distance, i.e. the average reach position of the hands with respect to the upper trunk within one sewing movement. This postural behaviour may be guided by an optimization of the upper extremity joint positions (i.e. an optimization of the manipulation distance), or, due to the weight of the upper extremities, 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). Furthermore, concerning the upper arms, it is likely that these have to be raised at higher desks in order to prevent the elbow from colliding with the desk.

Wick and Drury (1986) have demonstrated that the forward inclination of the head/neck and trunk of an operator manufacturing shoes at a so-called single-needle post sewing machine was reduced considerably by introducing various changes, including an 11° inclination of the machine towards the operator, and a pedal that could be positioned anywhere on the floor by the operator, according to her own preference.

Analogous to the presumable (partial) effect of the machine inclination towards the operator described above, the effects of a sloping desk in various operations have been published (Eastman and Kamon, 1976; Bendix and Hagberg, 1984; Magnusson and Örtengren, 1987; Bridger, 1988; De Wall *et al.*, 1991; Freudenthal *et al.*, 1991), but never to our knowledge was a reasonable mechanism presented to explain it. Here, it is hypothesized that a sloping desk either creates a more favourable gaze angle to the sewing material at the desk, or that it creates a covert height effect in the case that the visual target (needle tip) is raised as a consequence of a desk rotation around its front edge. The essence of a desk slope created in such a way is that the desk front edge remains in the same position. Therefore, it is likely that no extra upper arm elevation occurs, because the elbow is not forced to be raised due to contact with the desk surface. In summary, it is expected that a desk slope created by a rotation around its front edge may result in a more upright posture of the head and trunk, without elevating the arms (i.e. loading the shoulder region) any further. This way, a desk slope may resolve a classic problem presented by desk height changes, i.e. either a more upright (presumably better) head and trunk posture and a more elevated (presumably worse) posture of the upper arms is created, or vice versa. Finally, it should be recognized that if the desk is given a slope, the needle tip will also change position in the fore/aft direction. It is likely that here also an operator will try to retain a favourable reach position of the hands with respect to the upper trunk, i.e. guided by a minimization of the effect of gravity on the various upper extremity segments via changes of moment arm (i.e. a minimization of the horizontal component of the manipulation distance).

On the basis of the likely (partial) effect of the pedal position as described by Wick and Drury (1986), it may be expected that the pedal position in the fore/aft direction affects the possibility of sitting nearer to or farther from the workstation, thereby affecting trunk posture.

4.1.2 Formulation of guidelines

With the standardized research approach mentioned above, professional workers execute an operation at various adjustments of their workstation. Several variables relating to the working posture and the workers' perceptions have been measured for each of these experimental conditions. Both types of information have their own specific limitations and advantages regarding the evaluation of experimental conditions. For example, in the case that, 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 and 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 (that is, can be explained by) objective information. In principle, the remaining (best) experimental conditions constitute the guideline.

4.1.3 Working posture versus workers' perceptions

The posture of the head and/or neck segment in the sagittal plane is mostly evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, i.e. head/neck inclination for-/backwards (e.g. Chaffin, 1973; Hünting *et al.*, 1980;1981; Kilbom *et al.*, 1986; Lee *et al.*, 1986; Snijders *et al.*, 1991; Lindberg *et al.*, 1993). 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, i.e. 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 and Hagberg, 1984; Lepoutre *et al.*, 1986; Schüldt *et al.*, 1986a;b; Harms-Ringdahl and Schüldt, 1988; Kumar, 1994). 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, i.e. 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, i.e. upper arm elevation (e.g. Chaffin, 1973; Bjelle *et al.*, 1979; 1981; Dul, 1988; Van der Grinten and 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 above). In addition, the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively) may play a role with respect to shoulder (girdle) load (Kilbom *et al.*, 1986; Mital and Faard, 1990; Jensen, 1991; Aarås, 1994). 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, i.e. trunk inclination for-/backwards (e.g. Jørgensen, 1970; Wickstrom *et al.*, 1988; Van der Grinten and Smitt, 1992; Aarås, 1994). 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 and Örtengren, 1974; Andersson *et al.*, 1974). Considering also that head/neck inclination for-/backwards affects thoracic spine curvature (Nakaseko *et al.*, 1993) and relates to complaints of the back and loin (Grandjean *et al.*, 1982; Lee *et al.*, 1986), there is reason to study workers' perceptions with respect to the neck and the back in close connection.

4.2 Methods

In the laboratory ten sets of experimental conditions were tested. Test subjects worked for a certain amount of time at each set of conditions. Working posture and workers' perceptions were measured.

4.2.1 Subjects

Five female operators (average age 41 years, range 34-47; average stature 170 cm, range 167-175) from the furniture industry participated in the experiments. They were familiar with the sewing task (average experience 12 years, range 2.5-18).

4.2.2 Experimental task and procedure

At a traditional adjustable sewing machine workstation, the operators performed their normal sewing task in ten experimental sessions of 45 minutes followed by breaks of 15 minutes. In each session one of the ten sets of experimental conditions was presented. The first day consisted of three sessions and the following two days of either three or four sessions. The order of presentation of the sets of experimental conditions was balanced over subjects, days, and sessions. Prior to the first session each operator selected a seat height at which pedal operation was comfortable. For this, visual cues from the desk and the sewing machine were hidden by a blanket. The individual seat height and pedal inclination were constant during the experiments, but the operator was free to choose the fore/aft position of the chair.

The duration of an experimental session was chosen roughly in accordance with the average of continuous work periods seen during a normal working day, i.e. periods without leaving the workstation for materials transport, visits to the toilet, and official breaks. It is assumed that the experimental results are valid for regular daily task execution, as workers' perceptions in terms of postural discomfort are linearly related to the duration of postures (refer to § 4.2.4, sub B). In other words, it is expected that the subjective differences to be found between particular workstation adjustments remain as they are if the duration of task execution is increased.

4.2.3 Independent variables

The ten sets of experimental conditions consisted of different combinations of desk height, desk slope, and pedal position. The desk heights (height of the desk front edge) tested were related to the individual elbow height of the operator (figure 4.1):

- 5 cm above (+5cm)
- 10 cm above (+10cm)
- 15 cm above (+15cm).

These specific adjustments were chosen because they link up with the adjustments tested by Dul *et al.* (1988), i.e. -5 cm, 0 cm, and +5 cm relative to elbow height. Elbow height was defined as the distance from the floor to the elbow (underside) with the operator sitting upright, the upper arms hanging down, and the forearms horizontal (figure 4.1).

The desk slopes tested were related to the horizontal (figure 4.1):

- no slope (0°)
- 10° slope towards the operator.

The condition 0° is in accordance with the desk slope at the industrial workstation of each operator.

The pedal positions tested were defined as the horizontal fore/aft position of its rotation axis related to the needle tip (figure 4.1):

- 4 cm to the operator's side of the needle tip (-4cm)
- 6 cm to the opposite side of the needle tip (+6cm).

The condition -4cm is in accordance with the average pedal position at the operators' own industrial workstations (all five individual adjustments at the operator's side of the needle tip).

A complete block design (3 * 2 * 2) turned out to be impracticable. In preparing the experiments, two sets of experimental conditions (with desk height +5cm and pedal position +6cm, desk slopes 0° and 10°) appeared to cause problems due to lack of leg space, and were excluded. The remaining ten sets of experimental conditions were tested.

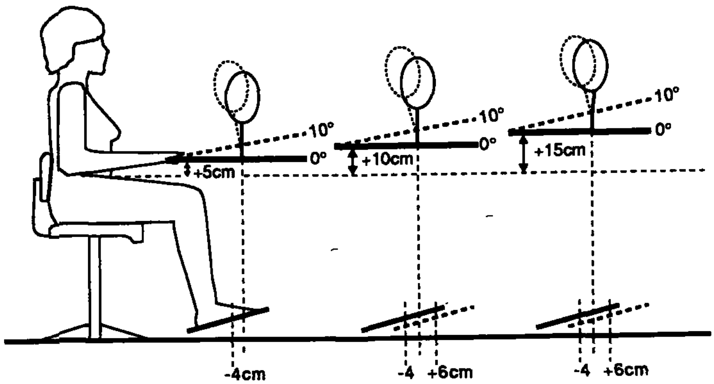


Figure 4.1 The 10 sets of experimental conditions. Elbow height is shown by the horizontal broken line. The needle position is shown by the vertical broken line.

4.2.4 Dependent variables and measurement techniques

Working posture and *vision characteristics* were measured by an opto-electronic VICON-system. Retro-reflective markers were put on the skin overlying selected segments and joints, as well as on the workstation (figure 4.2 and table 4.2). Concerning the upper extremities, markers were on the left side only, due to the left shoulder complaints reported by operators (refer to the introduction). The three-dimensional positions of the markers were determined while the operators were in a reference posture (sitting 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 set of experimental conditions, i.e. while the machine was running, the working posture being constrained by the workstation adjustment studied. For data analysis averages over two full sewing cycles within the last 15 minutes of an experimental session were used.

On the basis of the marker positions various dependent variables with respect to vision, head-neck-trunk, and lower/upper extremities were calculated (table 4.3 and figure 4.2). In accordance with the hypothetical effects of desk height, desk slope, and pedal position described in the introduction, most of these dependent variables describe the sagittal plane posture of the head/spine/pelvis. This flexible system is usually divided into two segments, i.e. the head/neck and the trunk (including the pelvis). The segregation between these segments is made at the C7-T1 spine level, because the spine flexion/extension movement range increases considerably above this level as compared to the thoracic spine (White and Panjabi, 1978). The head/neck segment may be segregated in a head segment and a neck segment (Hünting *et al.*, 1980). In the introduction to this paper it was stated that two potential determinants of neck load were to be studied, i.e. head/neck inclination for-/backwards and neck flexion/extension (for-/backward inclination of the head and/or neck segment with respect to for-/backward inclination of the trunk segment). On the basis of the segregations mentioned above, trunk inclination for-/backwards represents the total flexion/extension between the hip joint and the vertebra T1, while head inclination for-/backwards equals the total flexion/extension between the hip joint and the head. Neck inclination for-/backwards equals trunk inclination for-/backwards plus the neck-trunk angle, or head inclination for-/backwards minus the head-neck angle. Besides the neck-trunk angle and the head-neck angle, the head-trunk angle also is a measure of neck flexion/extension, i.e. the latter giving insight into the total flexion/extension above the vertebra T1 relative to the total flexion/extension between the hip joint and the vertebra T1. By segregating the head/neck segment into a head segment and a neck segment more information on the flexion/extension mechanism in the cervical spine may be gained. The head-neck angle and the neck-trunk angle indicate whether neck flexion/extension takes place more or less in the upper part or in the lower/middle part of the cervical spine, respectively.

Table 4.2 Markers; names and locations (also refer to figure 4.2).

Marker	Name	Location
M1	needle	tip*
M2	eye	near the lateral corner
M3	ear	just ventrally of the lobe
M4	neck	intervertebral disc C7-T1
M5	hip	upper edge of the greater trochanter
M6	left shoulder	acromioclavicular joint
M7	left upper arm	caudal insertion of the deltoid muscle

*A virtual marker. Its position was calculated from the location of a real marker on the top of the machine.

Table 4.3 Working posture and vision; names and definitions of dependent variables (refer also to table 4.2 and figure 4.2).

Name	Definition
Viewing distance	distance between M1 and M2, projected in the XZ plane
Gaze inclination	angle between the horizontal and the line M1-M2, projected in the XZ-plane (a negative value means the operator looks downward)
Head inclination for-/backwards	angle between the line M2-M3 during operation and the line M2-M3 in the reference posture, projected in the XZ-plane (a negative value means the head is inclined forwards/downwards)
Neck inclination for-/backwards	angle between the line M3-M4 during operation and the line M3-M4 in the reference posture, projected in the XZ-plane (a negative value means the neck is inclined forwards/downwards)
Trunk inclination for-/backwards	angle between the line M4-M5 during operation and the line M4-M5 in the reference posture, projected in the XZ-plane (a negative value means the trunk is inclined backwards)
Hip-needle fore/aft distance	distance between M5 and M1 along the X-axis
Head-neck angle	head inclination for-/backwards (definition above) versus neck inclination for-/backwards (definition above) (a positive value means the upper neck segment is flexed)
Neck-trunk angle	neck inclination for-/backwards (definition above) versus trunk inclination for-/backwards (definition above) (a positive value means the lower/middle neck segment is flexed)
Head-trunk angle	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 M4 and M1
Horizontal manipulation distance	distance between M4 and M1 along the X-axis of the coordinate system
Left upper arm elevation for-/backwards	angle between the line M6-M7 during operation and the line M6-M7 in the reference posture, projected in the XZ-plane (a positive value means the upper arm is elevated forwards)
Left upper arm elevation sidewards	angle between the line M6-M7 during operation and the line M6-M7 in the reference posture, projected in the YZ-plane (a positive value means the upper arm is elevated outwards)

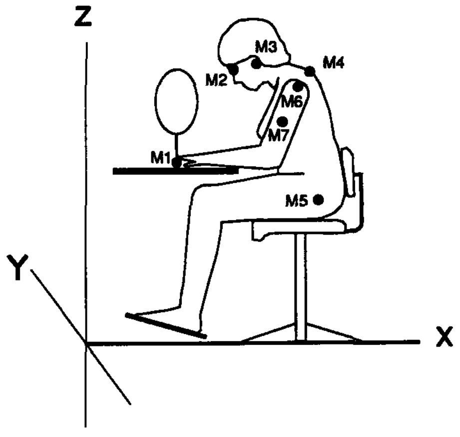


Figure 4.2 The marker positions for measurement of working posture and vision characteristics (refer also to table 4.2). The orthogonal axes shown represent the coordinate system used. The Y-axis is aligned parallel to the desk front edge. The Z-axis is vertical. The XZ-plane corresponds to the sagittal plane of the operator's body. The YZ-plane corresponds to the frontal plane of the operator's body.

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, that may be matched directly with working posture variables. The modules 'Estimated endurance time' and 'Judgement on workstation adjustment' focus on integral responses. The modules (A–D) and the dependent variables are described below.

A Perceived posture

The operator was asked to rate her perception of the posture of the neck, back, left shoulder, right shoulder, left upper arm, right upper arm, left lower leg, right lower leg, left foot, and right foot. Directly after the session a written response was given on a seven-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 10 body parts mentioned were used as dependent variables.

B Localized postural discomfort

The operator was asked to rate her postural discomfort in 30 regions shown on a diagram of the rear view of a human body (figure 4.3; modified after Corlett and Bishop, 1976), using a scale ranging from 0 (no discomfort) to 5 (very severe discomfort) (Corlett and Bishop, 1976). A written 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 4.4), guided by the information presented in the introduction (various health complaint locations; furthermore, refer to § 4.1.3). Finally, an overall dependent variable was constructed, i.e. postural discomfort of the whole body, the sum of the resulting scores for all 30 body regions (table 4.4). 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 subjects reasonably linear relationships were found between gravitational load and discomfort in a body region (e.g. Boussenna *et al.*, 1982; Van der Grinten and Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g. Manenica, 1986; Meijst *et al.*, 1995).

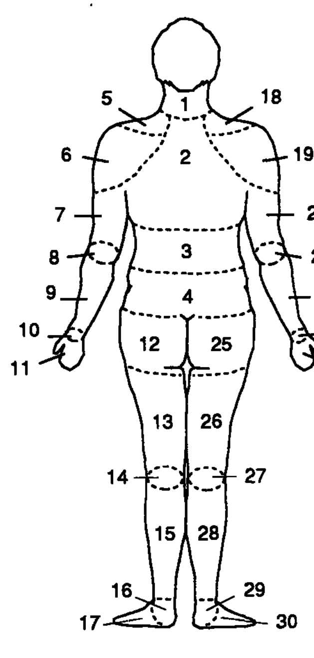


Figure 4.3 Diagram of the rear view of a human body, which was used in the questionnaire module on localized postural discomfort.

Table 4.4 Localized postural discomfort; names and definitions of dependent variables constructed.

Name	Definition (sum of resulting scores for body regions mentioned)
Neck	1, 5, and 18
Neck/upper back	1, 2, 5, and 18
Back	2, 3, and 4
Upper neck/back	1, 2, 3, and 4
Neck/back	1, 2, 3, 4, 5, and 18
Left shoulder/neck	5 and 6
Right shoulder/neck	18 and 19
Left leg	12–17
Right leg	25–30
Whole body	1–30

C Estimated endurance time

The operator was asked to estimate, on the basis of her perceptions, how long she could operate at the experimental workstation adjustment without difficulty during a regular working day. Directly after the session a written response was given on a five-point scale (1 = more than 8 hours, 2 = 6–8 hours, 3 = 4–6 hours, 4 = 2–4 hours, 5 = less than 2 hours). The estimated endurance time was used as a dependent variable.

D Judgement on workstation adjustment

Firstly, the operator was asked to judge the desk height. Directly after the session a written response was given on a five-point scale (1 = much too low, 2 = a little too low, 3 = right, 4 = a little too high, and 5 = much too high). Secondly, the operator was asked to judge the desk slope. Directly after the session a written response was given on a five-point scale (1 = much too steep, 2 = a little too steep, 3 = right, 4 = a little too flat, and 5 = much too flat). Thirdly, the operator was asked to judge the pedal position. Directly after the session a written response was given on a five-point scale (1 = much too close, 2 = a little too close, 3 = right, 4 = a little too far away, and 5 = much too far away). The judgements on desk height, desk slope, and pedal position were used as dependent variables. For part of the statistical analyses (§ 4.2.5, paired comparisons of sets of experimental conditions) the actual scores given were converted, i.e. 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). Finally, the operator was asked to judge the whole workstation adjustment as compared to her own workstation adjustment in industry (one operator was not asked for this judgement because she usually worked at various workstations during a regular working day in industry). Directly after the session a written response was given on a five-point scale (1 = much better, 2 = a little better, 3 = equal, 4 = a little worse, and 5 = much worse). The judgement on the whole workstation adjustment was used as a dependent variable.

4.2.5 Data analysis

The data on working posture and workers' perceptions are statistically tested to determine main and interaction effects of desk height, desk slope, and pedal position, as well as to determine differences between sets of experimental conditions (paired comparisons).

On the basis of the literature described in § 4.2.4 (at B), the scale used for determination of localized postural discomfort was considered to have at least interval characteristics, whereas the scale used for determination of estimated endurance time has ratio characteristics by definition. Data on both these dependent variables as well as on those with respect to working posture and vision were analysed by parametric statistical tests. Data on dependent variables with respect to perceived posture and judgement on workstation adjustment were analysed by non-parametric (distribution-free) statistical tests, due to the ordinal character of the scales used.

The main and interaction effects of desk height and/or desk slope on the working posture and vision variables, as well as on the variables relating to localized postural discomfort and estimated endurance time were tested by an Analysis of Variance (ANOVA) for Repeated Measures (3 * 2 design). Furthermore, the main and interaction effects of desk height (+10cm and +15cm), desk slope, and pedal position on the variables mentioned above were tested by an ANOVA for Repeated Measures (2 * 2 * 2 design). Differences between sets of experimental conditions were tested by a post-hoc Tukey test (paired comparisons).

The effect of desk height on the variables relating to perceived posture and judgement on workstation adjustment (except for whole workstation adjustment, because of the non-identical individual desk heights in industry for the five operators to compare with) were tested at both desk slopes (pedal position -4cm) by a Friedman test. Differences between sets of experimental conditions were tested by a Wilcoxon Matched-pairs Signed-ranks Test (paired comparisons). The paired comparisons for the variables judgement on desk height, desk slope, and pedal position were done on the basis of converted scores (§ 4.2.4, sub D).

The selected level of significance in all tests was $p=.05$ (two-tailed). The description of the results (refer below) will be focussed on significant (combined) effects of desk height, desk slope, and pedal position. Effects approaching significance ($.05 < p \leq .10$), however, will also be mentioned. In the case of effects on variables measured by an ordinal scale (perceived posture and judgement on workstation adjustment), these will be mentioned if the majority of operators favour a certain set of experimental conditions instead of another and no one opposes this. Concerning regression equations, correlation is defined as high if the absolute value of the correlation coefficient $\geq .8660$ (i.e. $R^2 \geq .75$), as moderate if $\geq .7071$ and $< .8660$ (i.e. $.50 \leq R^2 < .75$), and as low if $< .7071$ (i.e. $R^2 < .50$).

4.3 Results

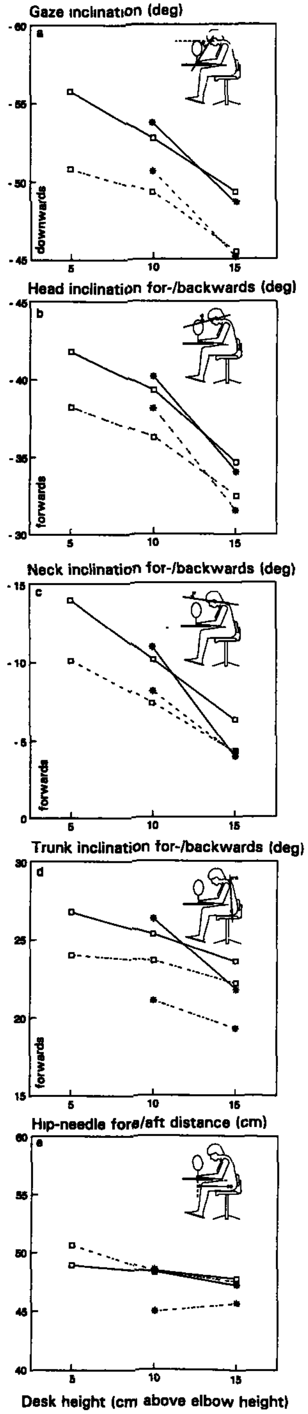
§ 4.3.1 contains results for working posture and the related workers' localized physical perceptions for vision, head-neck-trunk, and lower extremities. In § 4.3.2 working posture and the related workers' localized physical perceptions for the upper extremities will be described. In § 4.3.3 workers' integral perceptions are presented.

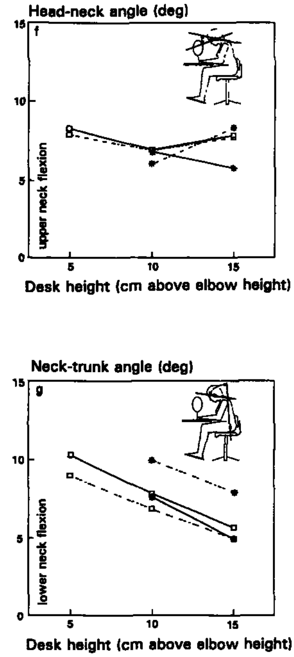
4.3.1 Vision, head-neck-trunk, and lower extremities

Figure 4.4 shows the head-neck-trunk posture in relation to gaze inclination at the one end, and in relation to the hip-needle fore/aft distance at the other (§ 4.4.1 contains a short non-statistical description on the basis of the effects of desk height, desk slope, and pedal position).

4.3.1.1 Head inclination for-/backwards and gaze inclination

Head inclination for-/backwards is closely related to gaze inclination (figures 4.4a and 4.4b). Within the range of experimental conditions tested all operators show a linear relationship with moderate or high correlation (table 4.5). For each operator, table 4.5 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 10 sets of experimental conditions).





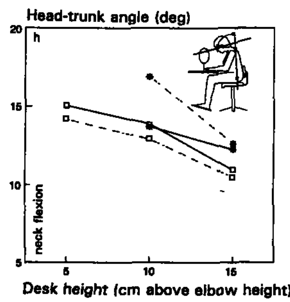


Figure 4.4 Posture and vision variables versus experimental conditions (average group scores). a. gaze inclination; b. head inclination for-/backwards; c. neck inclination for-/backwards; d. trunk inclination for-/backwards; e. hip-needle fore/aft distance; f. head-neck angle; g. neck-trunk angle; h. head-trunk angle. -□- = desk slope 0° and pedal position -4cm; -∗- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --∗-- = desk slope 10° and pedal position +6cm. For variables c, f, and g arbitrary units are used, due to loss of data on the reference posture.

Table 4.5 Head inclination for-/backwards versus gaze inclination for individual operators. Head inclination for-/backwards = A * gaze inclination + B (where n = 10 sets of experimental conditions); #: number of operator; r: Pearson correlation coefficient. H/G: head inclination for-/backwards (average of 10 sets of experimental conditions)/gaze inclination (average of 10 sets of experimental conditions). Range of gaze inclinations measured: -41.9° to -59.2°.

#	A	B	r	H/G
1	.92	-5.96	.76	1.03
2	1.04	26.91	.94	.54
3	.91	7.65	.85	.75
4	.88	13.23	.80	.60
5	1.27	26.14	.95	.72

4.3.1.2 Viewing distance

At working height +5cm the viewing distance is greater than at working heights +10cm (p=.07), and +15cm (significant) (figure 4.5a).

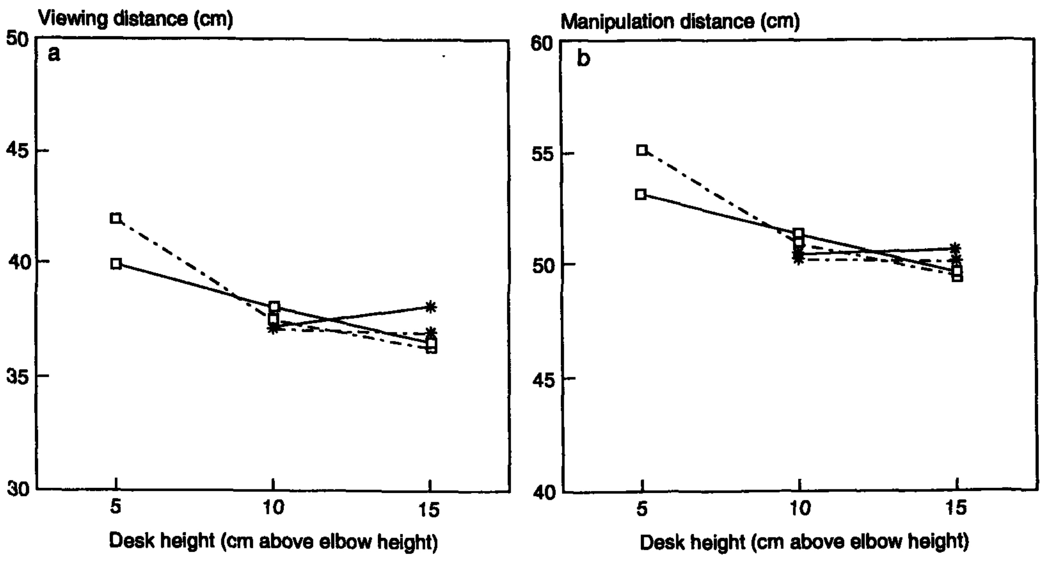


Figure 4.5 Viewing distance (a) and manipulation distance (b) versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position -4cm; -*- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --*-- = desk slope 10° and pedal position +6cm.

4.3.1.3 Head and neck inclination for-/backwards

Desk height +15cm causes a significantly more upright head posture than desk heights +10cm and +5cm (figure 4.4b). Changing the desk height from +10cm to +15cm causes a significantly greater effect on head inclination for-/backwards for pedal position +6cm than for pedal position -4cm. Desk slope 10° leads to a significantly more upright head posture as compared to desk slope 0° (figure 4.4b).

Desk height +15cm causes a significantly more upright neck posture than desk heights +10cm and +5cm (figure 4.4c).

4.3.1.4 Neck flexion/extension

At pedal position +6cm the head-trunk angle is significantly greater than at pedal position -4cm (figure 4.4h). At working height +5cm the neck-trunk angle is greater than at working height +15cm (figure 4.4g, p=.06). At pedal position +6cm the neck-trunk angle is greater than at pedal position -4cm only in the case of desk slope 10° (figure 4.4g, --*-- vs. --□--, p=.08). At desk height +10cm, based on perceived neck posture desk slope 10° and pedal position +6cm is favoured instead of desk slope 10° and pedal position -4cm (figure 4.6a, --*-- vs. --□--, 3 operators in favour and 2 ties, p=.11).

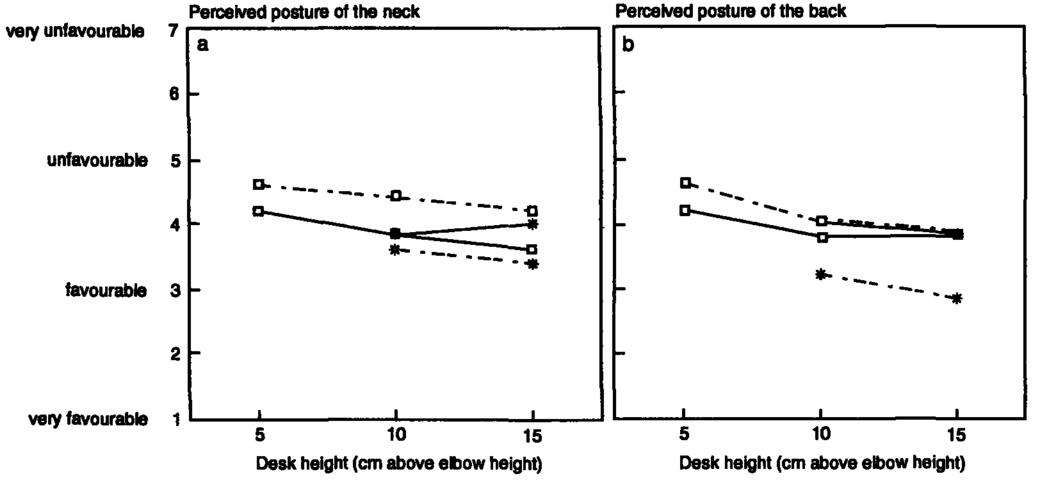


Figure 4.6 Perceived postures of the neck (a) and the back (b) versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position -4cm; -*- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --*-- = desk slope 10° and pedal position +6cm.

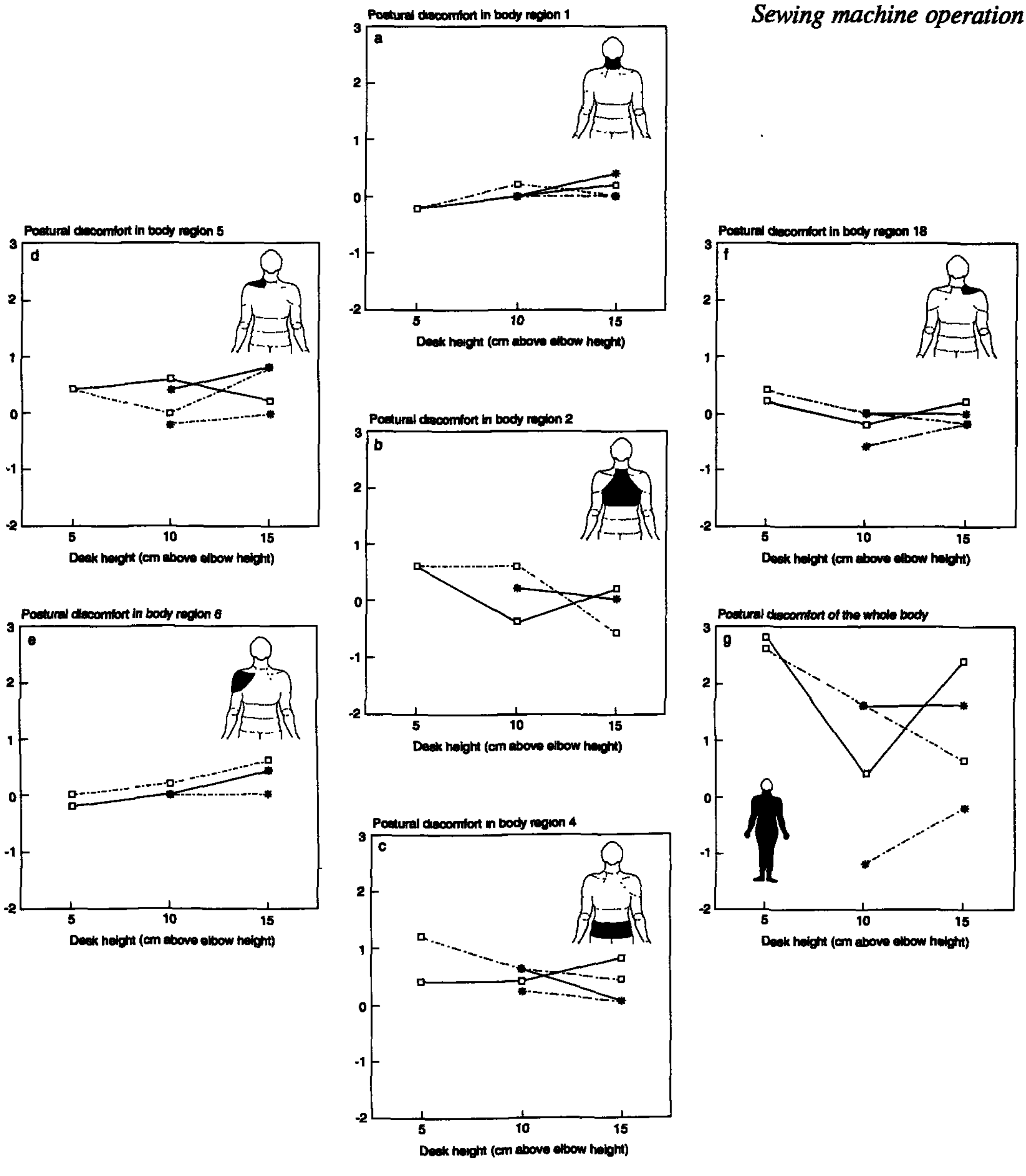


Figure 4.7 Postural discomfort in body regions 1, 2, 4, 5, 6, and 18 (a–f) as well as of the whole body (g) versus experimental conditions (average group scores). Results for individual body regions are shown if at least 2 operators indicated discomfort in the region. Vertical axis: amount of decrease (-) or increase. -□- = desk slope 0° and pedal position -4cm; -∗- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --∗-- = desk slope 10° and pedal position +6cm.

4.3.1.5 Trunk inclination for-/backwards

Desk slope 10° leads to a significantly more upright trunk posture as compared to desk slope 0° (figure 4.4d; desk heights +10cm and +15cm). Pedal position +6cm leads to a more upright trunk posture ($p=.09$) (figure 4.4d), as compared to pedal position -4cm.

At desk height +10cm, based on perceived back posture desk slope 10° and pedal position +6cm is favoured instead of desk slope 0° and pedal position +6cm (figure 4.6b, --*-- vs. -*-, 3 operators in favour and 2 ties, $p=.11$). At desk height +15cm, based on perceived back posture desk slope 10° and pedal position +6cm is favoured instead of desk slope 0° and pedal position -4cm (figure 4.6b, --*-- vs. -□-, 4 operators in favour and 1 tie, $p=.07$). Pedal position +6cm leads to significantly less postural discomfort in body region 4 (low back; figure 4.3), as compared to pedal position -4cm (figure 4.7c).

Except for postural discomfort in body region 4 (low back; figure 4.3), none of the dependent variables with respect to postural discomfort showed any significant effect of workstation adjustment. For the discussion of the results, however, it was considered necessary to give the reader an impression of the localized postural discomfort perceived by the sewing machine operators. Therefore, figure 4.7 shows the results for the postural discomfort of the whole body as well as for those individual body regions that were indicated for discomfort by at least 2 operators.

4.3.1.6 Hip-needle fore/aft distance

At pedal position +6cm the hip is significantly closer to the needle in the fore/aft direction as compared to pedal position -4cm only in the case of desk slope 10° (figure 4.4e).

At desk height +10cm, based on perceived right lower leg posture desk slope 10° and pedal position +6cm is favoured instead of desk slope 0° and pedal position -4cm (--*-- vs. -□-, 3 operators in favour and 2 ties, $p=.11$). At desk height +15cm, based on perceived left lower leg and foot postures desk slope 10° and pedal position -4cm is favoured instead of desk slope 0° and pedal position +6cm (--□-- vs. -*-, 3 operators in favour and 2 ties, $p=.11$).

At desk slope 0° and pedal position +6cm, based on perceived left lower leg and foot postures desk height +10cm is favoured instead of desk height +15cm (3 operators in favour and 2 ties; $p=.11$).

4.3.1.7 Movement characteristics

For the posture variables described above an indication on the variation around the mean position within a sewing cycle may be of interest to the reader. For trunk inclination for-/backwards a standard deviation of about 1.5° was measured, whereas for head and neck movements (inclination for-/backwards and flexion/extension measures) the standard deviation is about 2.5°.

4.3.2 Upper extremities

4.3.2.1 Manipulation distance

At working height +5cm the manipulation distance is significantly greater than at working heights +10cm and +15cm (figure 4.5b).

Working height +15cm leads to a significantly greater horizontal manipulation distance than working height +10cm (table 4.6). Desk slope 10° leads to a significantly greater horizontal manipulation distance as compared to desk slope 0°.

Table 4.6 Horizontal manipulation distance versus experimental conditions (average group scores).

Desk height	Desk slope	Pedal position	Horizontal manipulation distance
+15cm	10°	+6cm	44.5 cm
+15cm	0°	+6cm	43.6 cm
+15cm	10°	-4cm	44.1 cm
+15cm	0°	-4cm	42.4 cm
+10cm	10°	+6cm	42.2 cm
+10cm	0°	+6cm	40.8 cm
+10cm	10°	-4cm	43.2 cm
+10cm	0°	-4cm	41.8 cm
+5cm	10°	-4cm	45.3 cm
+5cm	0°	-4cm	41.2 cm

4.3.2.2 Left upper arm elevation

A higher desk causes a significant increase of left upper arm elevation forwards as well as sidewards (figure 4.8). Changing the desk height from +10cm to +15cm causes a greater effect on left upper arm elevation sidewards for pedal position -4cm than for pedal position +6cm ($p=.055$).

At desk height +15cm, based on perceived right upper arm posture desk slope 10° and pedal position -4cm is favoured instead of desk slope 0° and pedal position -4cm (--□-- vs. -□-, 3 operators in favour and 2 ties, $p=.11$).

For the left upper arm movements around the mean position within a sewing cycle a standard deviation of about 4.0° was measured.

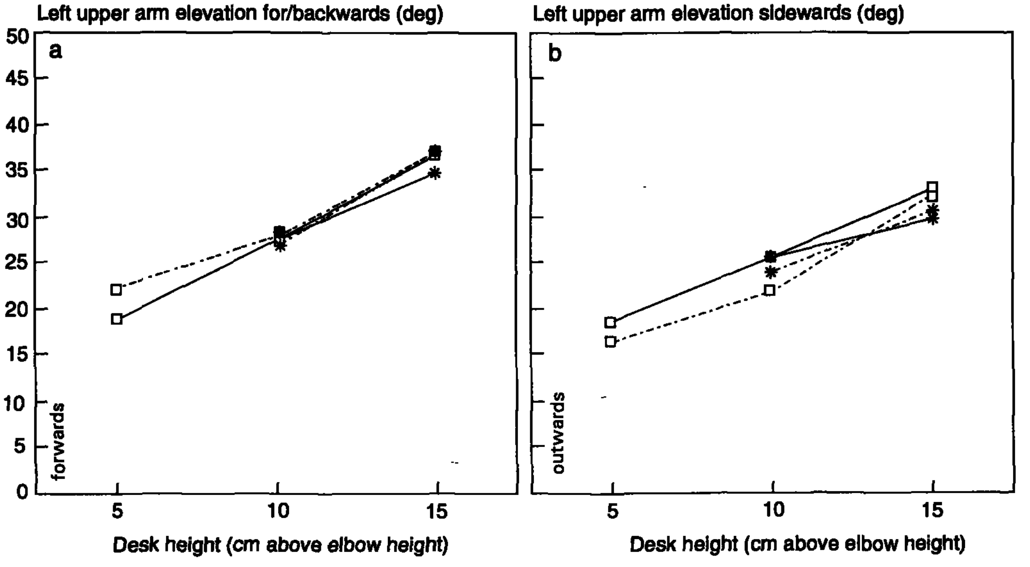


Figure 4.8 Left upper arm elevation for-/backwards (a) and sidewards (b) versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position -4cm; -*- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --*-- = desk slope 10° and pedal position +6cm.

4.3.3 Integral workers' perceptions

4.3.3.1 Estimated endurance time

The estimated endurance time at desk slope 10° and pedal position +6cm (--*--) is longer than at desk slope 10° and pedal position -4cm (--□--, $p=.06$), desk slope 0° and pedal position +6cm (-*-, significant), and desk slope 0° and pedal position -4cm (-□-, significant) (figure 4.9).

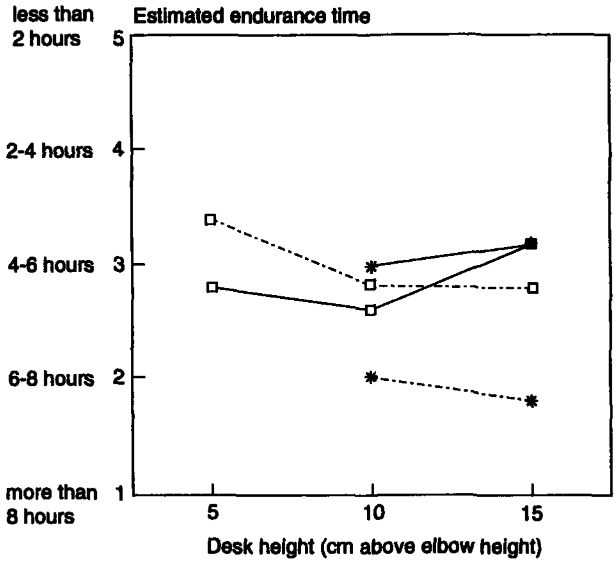


Figure 4.9 Estimated endurance time versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position −4cm; -∗- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position −4cm; --∗-- = desk slope 10° and pedal position +6cm.

4.3.3.2 Judgement on desk height

Desk height +5cm is considered on average 'a little too low' (figure 4.10a), with all individual judgements between 'right' (3 out of 10 judgements) and 'much too low'. Desk height +15cm is considered on average 'a little too high' (figure 4.10a), with all individual judgements between 'right' (5 out of 20 judgements) and 'much too high'. For desk height +10cm individual judgements ranged from 'much too low' to 'a little too high'. No significant differences were found between the desk heights.

4.3.3.3 Judgement on desk slope

Desk slope 0° is considered 'right' (20 out of 25 judgements) or 'a little too flat' (figure 4.10b). Desk slope 10° is considered on average between 'right' and 'a little too steep' (figure 4.10b), with all individual judgements between 'right' (16 out of 25) and 'much too steep'. No significant differences were found between both desk slopes.

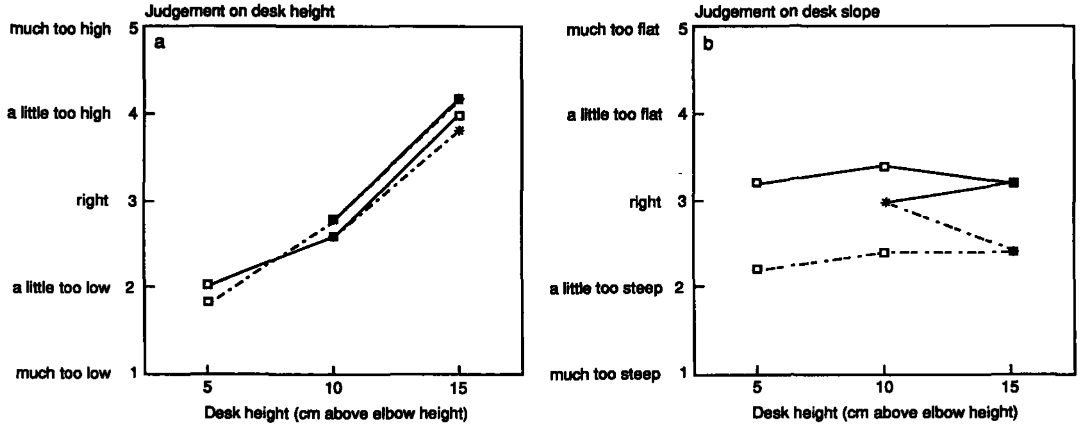


Figure 4.10 Judgement on desk height (a) and desk slope (b) versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position -4cm; -*- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --*-- = desk slope 10° and pedal position +6cm.

4.3.3.4 Judgement on pedal position

Pedal position -4cm is considered 'right' at 27 out of 30 judgements. Pedal position +6cm is considered 'right' at 19 out of 20 judgements. No significant differences were found between both pedal positions.

4.3.3.5 Judgement on the whole workstation adjustment

At desk height +10cm, the judgement on the whole workstation adjustment is better for desk slope 10° and pedal position +6cm than for desk slope 0° and pedal position +6cm, and desk slope 10° and pedal position -4cm (figure 4.11, --*-- vs. -*- and --□--, at both paired comparisons 3 operators in favour and 1 tie, p=.11). At desk height +15cm, the judgement on the whole workstation adjustment is better for desk slope 10° and pedal position +6cm than for desk slope 0° and pedal position +6cm, and desk slope 0° and pedal position -4cm (figure 4.11, --*-- vs. -*- and -□-, at both paired comparisons 3 operators in favour and 1 tie, p=.11).

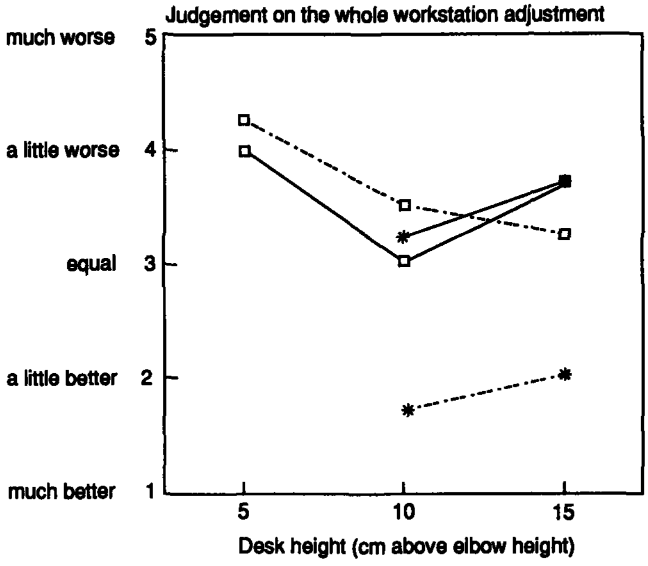


Figure 4.11 Judgement on the whole workstation adjustment (as compared to the own workstation adjustment in industry) versus experimental conditions (average group scores). -□- = desk slope 0° and pedal position -4cm; -*- = desk slope 0° and pedal position +6cm; --□-- = desk slope 10° and pedal position -4cm; --*-- = desk slope 10° and pedal position +6cm.

4.4 Discussion

The first purpose of the paper was to study determinants of working posture as well as relationships between working posture and workers' perceptions. In §§ 4.4.1-4.4.5 the former issue will be discussed among other issues. In § 4.4.6 the latter will be discussed only as far as the neck is concerned. For the upper arm no discriminating effects of elevation forwards and elevation sidewards were found.

4.4.1 Head-neck-trunk posture

Figure 4.4 clearly demonstrates several major effects of workstation adjustment. Firstly, as desk height increases the head and neck get more upright. To a lesser extent this effect is seen for the trunk also. Secondly, a 10° desk slope induces a more upright head, neck, and trunk. Besides these top-down effects, a bottom-up effect also is present. That is, at desk slope 10° and pedal position +6cm operators move closer to the needle. This is reflected by a more upright trunk posture, as well as by a greater neck flexion, as demonstrated by the neck-trunk angle and the head-trunk angle.

Some of the expected postural effects could not be demonstrated at a significance level of .05. A somewhat greater number of test subjects is to be recommended for future research. For example, at desk slope 10° and pedal position +6cm condition, it seems likely that the trunk acts as a mediator when operators move (significantly) closer to the needle, thereby (significantly) flexing their neck. However, this interaction effect of desk slope and pedal position on trunk inclination for-/backwards reached a p-value of .12 only.

4.4.2 Viewing distance and manipulation distance

Figure 4.5 shows that the viewing distance and the manipulation distance co-variate very well, indicating that, irrespective of the workstation adjustment, a relatively fixed configuration of the visual-manual system (a virtual triangle with the needle tip, the eye, and C7-T1 as angular points) is active during sewing.

The viewing distance, the manipulation distance, and the horizontal manipulation distance are affected by the workstation adjustment (figure 4.5 and table 4.6). These systematic changes indicate a stronger determinant of working posture, that is most probably the fixed relationship between gaze inclination and head inclination for-/backwards (§ 4.4.3.2), and/or the fixed configuration of the visual-manual system (refer to the previous paragraph in this section). The former determinant would imply that a higher needle tip creates a less downward gaze inclination and a reduced for-/backward inclination of the head/neck segment. The latter determinant would imply that a reduced for-/backward inclination of the head/neck segment is accompanied by a reduced for-/backward inclination of the trunk segment. The body segment rotations mentioned are in accordance with the experimental results showing that the eyes and C7-T1 move along a certain arc, away from the needle in the fore/aft direction, and upwards with respect to elbow height (figure 4.12). It seems as if the viewing distance is reduced when raising the desk height from +5cm to +10cm because the displacement of the eyes and C7-T1 is not a full compensation for the displacement of the needle tip. However, when raising the desk height from +10cm to +15cm, the viewing distance stays about the same, apparently because the change of head and trunk inclination for-/backwards is greater then when raising the desk height from +5cm to +10cm (figures 4.4b and 4.4d), and the resulting displacement of the eyes and C7-T1 compensates for the displacement of the needle tip.

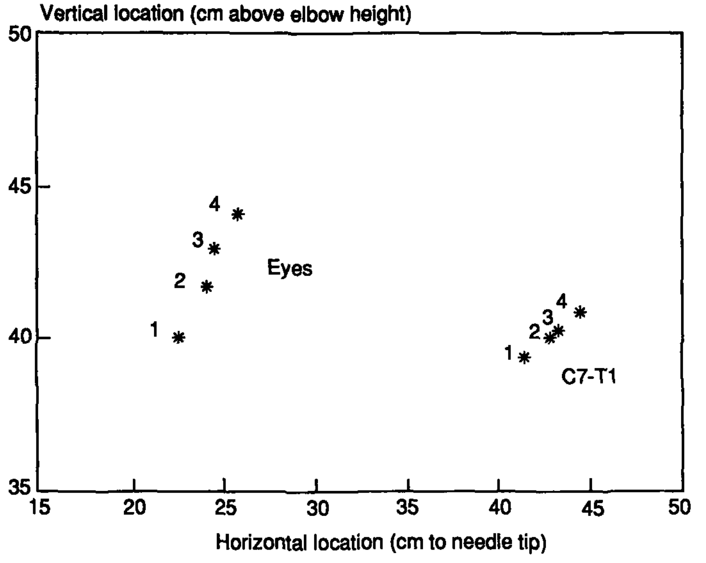


Figure 4.12 Horizontal and vertical locations of the eyes and C7-T1 (average group scores). 1 = desk height +10cm and desk slope 0°; 2 = desk height +10cm and desk slope 10°; 3 = desk height +15cm and desk slope 0°; 4 = desk height +15cm and desk slope 10°. Data shown are average results for both pedal positions.

4.4.3 Gaze

4.4.3.1 Gaze-desk angle

It was hypothesized that operators may want to preserve a favourable gaze angle to the sewing material at the desk. The gaze-desk angle resembles gaze inclination. That is, for desk slope 0° the gaze-desk angle is exactly equal to gaze inclination (figure 4.4a), while for desk slope 10° the gaze-desk angle equals gaze inclination plus 10°. The finding of one particular (favourable) gaze inclination for all experimental conditions or the same minimum gaze inclination for a number of experimental conditions would have given support to the idea that the gaze angle to the sewing material is critical. No such evidence was found. So, it cannot be concluded that within the experimental conditions tested the gaze-desk angle is a determinant of working posture during sewing machine operation.

4.4.3.2 Gaze inclination

Head inclination for-/backwards shows a strong resemblance to gaze inclination (figures 4.4b and 4.4a, respectively). All operators show a linear relationship with moderate or high correlation (table 4.5). This relationship, however, differs among individuals considerably, i.e. the contribution by head inclination for-/backwards to a change of gaze inclination varies from 88% to 127%. Contributions above 100% were found for operators 2 and 5. This unexpected result means that the up-/downward orientation of the eye with respect to the head/orbit is reduced. One explanation may be that, after the initial downward rotation of the eye, an unfavourable eye position with respect to the head/orbit is reached at a certain gaze inclination. This position can be quitted by rotating the eyes upwards with respect to the orbit if the operator has increasingly to look downwards. The most likely cause for the phenomenon observed, however, seems to be that the regression lines were based on too small a range of gaze inclinations (i.e. 11.3° on average for the 5 operators) and/or on too small a number of data pairs (i.e. 10), 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 sewing machine operation in this study, i.e. -41.9° to -59.2°, estimates on the basis of data presented by Brues (1946) show that the contribution of head inclination for-/backwards to gaze inclination is around 50% (average group score). For gaze inclinations from horizontal down to -50°, data by Conrady *et al.* (1987) disclosed a slightly higher contribution, i.e. about 55-60% (average group score). With respect to the Brues data, the actual contribution of head inclination for-/backwards to gaze inclination for operators 2-5 was found to be somewhat higher (table 4.5; at parameter H/G). The actual contribution for operators 2 and 4 match with the range obtained from the data presented by Conrady and colleagues, while the figures for operators 3 and 5 are slightly higher. For operator 1 gaze inclination seems to be created entirely by head inclination for-/backwards; that is, without any up-/downward rotation of the eye with respect to the head/orbit. No convincing explanation for this result was found. In the reference posture the included angle of line M2-M3 (eye-ear) and the vertical, projected in the YZ-plane (figure 4.2 and tables 4.2 and 4.3), was found to be 54.8°, 45.3°, 44.1°, 46.4°, and 54.9° for operators 1-5, respectively. During operation this angle increased to 107.3°, 75.0°, 81.7°, 74.9°, and 89.6° (averages over all 10 sets of experimental conditions) for operators 1-5, respectively. The clear differences between the head posture of operator 1 and the head postures of the other four operators during operation, as suggested by the latter array, could not be confirmed by video observations. The may have to do with the fact that operators 2-5 were involved in the experiments a couple of weeks later than operator 1. Probably, the experimental procedure concerning the markers positions at the head as well as concerning the reference posture shifted somewhat in the meantime.

4.4.4 Slope effects

So far, it has been demonstrated that a desk inclined towards the operator induces a more upright head, neck, and trunk. The data available allow for a discussion on the mechanism behind a slope effect, which has not been described explicitly in the literature so far. In § 4.4.3.1 it could not be concluded that the gaze angle to the sewing material at the desk plays a role in this respect. However, from figure 4.12 it can be seen that both 10° desk slope conditions lead to average locations of the eye(s) and of C7-T1, which are well in line with those resulting from both 0° desk slope conditions. It seems therefore that during sewing machine operation a slope effect is in fact a height effect. This impression is checked by simple calculations as follows. At the workstation used in this study the distance from the desk front edge to the needle tip was 18.5 cm. This means that by using a 10° desk slope the needle tip rises about 3.2 cm, as compared to a flat desk. It may be said then that in fact, apart from desk height +5cm, four other desk heights were tested, i.e. 10 cm, 13.2 cm, 15 cm, and 18.2 cm above elbow height (denoted as conditions 1 to 4 in figure 4.12, respectively). The eyes and C7-T1 locations at desk height 13.2 cm are expected then to be at 39% of the linear distance between the eyes and C7-T1 locations at desk heights 10 cm and 18.2 cm (calculation based on conditions 1-2-4). It turned out that the eyes are located at 39%, and C7-T1 at 40%. Calculations based on conditions 1-2-3, 1-3-4, and 2-3-4 gave percentages of 77% (64%), 53% (61%), and 21% (36%) for the eyes, and percentages of 67% (64%), 59% (61%), and 33% (36%) for C7-T1, respectively (expected percentages in brackets). Deviations of 8-15% from the percentages expected for the eyes most likely are due to some deviating postural behaviour in condition 3. On the basis of C7-T1 locations especially, the calculation results provide support for the notion that a slope effect is a height effect.

Three studies on other visual-manual operations were found that may add to the understanding of a possible generic mechanism behind a slope effect, i.e. whether it is a height effect as in sewing machine operation, or perhaps a changing angle between the line of sight and the surface of the target, that was not considered valid for sewing machine operation (§ 4.4.3). Bendix and Hagberg (1984) measured the postural effects of three desk slopes, i.e. 0° (horizontal), as well as 22° and 45° inclined towards reading subjects. The latter two conditions were realized by placing special desks on top of the horizontal desk, their lowest point being elevated 6 cm and 8 cm, respectively. It was found that the forward inclination of the head and cervical spine was reduced by 8.4° after changing from a 0° desk slope to a 22° desk slope, and by 5.1° after changing from a 22° desk slope to a 45° desk slope (forward inclination of the trunk reduced by 4.3° and 3.4°, respectively). This means that about the same increase of desk slope induces different postural changes. Assuming that here also the slope effect is in fact a height effect, this may be explained by the changes concerning the elevation of the desk top lower edge, i.e. 6 cm from a 0° desk slope to a 22° desk slope, and 2 cm from a 22° desk slope to a 45° desk slope. However, it must be said that the study by Bendix and Hagberg (1984) does not allow for fully unravelling the single effects of height and slope. Douwes *et al.* (1992) studied the effects of an object inclined by 10° towards assembly workers, who were using a vertically-aligned balanced pneumatic screwdriver. Working height, defined as the point of operation on the object, was the same for the object when positioned flat on the desk and the object in the inclined position. Due to this absence of a working height difference, any postural effect would have represented a pure effect of the gaze-object angle. However, no significant effects on head, neck, and/or trunk posture were found. In contrast, it was demonstrated that a change of the working height by as little as 5 cm did in fact induce significant effects on upper body posture. Among other conditions, Kumar and Scaife (1979) tested desk slopes 0°, 2.5°, and 5° towards operators involved in threading computer memories with the aid of a stereoscopic microscope. While the gaze-desk angle stayed at about 90° due to the particular orientation of the microscope tubes, the forward inclination of the head and trunk increased when increasing the desk slope. A drawing of the experimental set-up showed that the rotation axis of the desk was behind the operation area at the desk. Giving the desk a slope towards the operator then lowers this operation area, as well as the height of the eyes at the top of microscope tubes, thereby explaining the forward inclination of the head and trunk. The studies described suggest that most often an apparent slope effect is actually a height effect.

For various visual-manual operations other than sewing, Eastman and Kamon (1976), Bendix and Hagberg (1984; refer above), Magnusson and Örtengren (1987), Bridger (1988), De Wall *et al.* (1991), and Freudenthal *et al.* (1991) also showed that a desk inclined towards the operator induces a more upright posture of the head, neck, and trunk. In addition, the present study demonstrated that for sewing machine operation this desk slope did not have an adverse effect on upper arm elevation (figure 4.8) and shoulder load. The relatively clear picture that emerges from the postural effects of a desk slope is not reflected by workers' perceptions. For writing, for example, Bendix and Hagberg (1984) found that a flat desk was preferred, whereas for reading a preference for a 45° desk slope was expressed. Eastman and Kamon (1976) found that for reading and writing back discomfort was higher at a flat desk than at each of two desk slopes (12° and 24° to the horizontal). According to the subjects tested a flat desk was also more fatiguing than a sloping desk, though this was demonstrated by statistical significance for reading only. On the basis of data presented in a study on meat-cutting by Magnusson and Örtengren (1987), for the majority of butchers no improvement with respect to workers' perceptions (overall comfort-discomfort scale, body map discomfort technique) was found when comparing a 5–8° desk slope to a flat desk (both having the same height of the desk front edge). Douwes and Delleman (1992; also Douwes *et al.*, 1992) revealed that during assembly work an object inclined 10° towards the operator was judged 'not good' by 6 out of 8 operators involved, due to the extra force needed to tilt the vertically-aligned balanced pneumatic screwdriver used and a relatively unfavourable right wrist posture. The studies described give reason to suppose that the positive postural effects of a desk inclined towards the operator are not supported by the majority of operators themselves when a hand tool is involved (pencil, knife, screwdriver). The present study even shows that operators may favour or disfavour an inclined desk depending on the position of a pedal (§ 4.4.5). In conclusion, it is recommended that the effects of a desk slope in any particular operation should be tested before introducing it at full scale in practice. If it turns out that only a minority of test subjects favour a desk slope, one may still introduce this facility at the workstation as an option for adjustment, that is, if additional financial costs for all workstations are considered reasonable in relation to the benefits received from the expected use by a few of the operators.

4.4.5 Desk slope 10° and pedal position +6cm

The results show that the postural effects of desk slope 10° depend on the pedal position in the fore/aft direction. Although the pedal position +6cm allows for approaching the needle more closely, operators use this opportunity only when desk slope 10° is present (figure 4.4e). This creates a more upright trunk posture as well as a greater neck flexion. The question now is why the operators behave this way.

A first hypothetical answer is based on the assumption that sewing machine operators during their professional career find and maintain an individual most favourable length of the trapezius muscle (descending part). The trapezius muscle length is affected by the for-/backward inclination of the head/neck (upper attachment region, spinal processes), as well as by the posture of the shoulder girdle (lower attachment region, clavicula and scapular spine). The shoulder girdle is re-positioned continuously during elevation of the upper arm (Pronk, 1991; Van der Helm, 1991), thereby causing length changes of the trapezius muscle (Van der Helm, 1991). By introducing a 10° desk slope the head/neck becomes more upright (figures 4.4b and 4.4c), but the elevation of the (left) upper arm stays the same (figure 4.8). This means that the trapezius muscle leaves the individual most favourable length. A return to this habitual muscle length is realized by increasing neck flexion by means of a more upright trunk posture. This possible mechanism is supported by the fact that a change of neck flexion by a backward inclination of the trunk leads to reduced EMG-activity of the trapezius muscles (descending part) (Schüldt *et al.*, 1986a;b). From figures 4.4g and 4.4h, however, it can be seen that the neck flexion for a combination of desk slope 10° and pedal position +6cm (--*--) is greater than for the operators' industrial workstation adjustment (-□-, desk slope 0° and pedal position -4cm). An explanation for this over-shoot may be that for the correction of a trapezius muscle length change, induced by a certain amount of head/neck inclination change (for-/backwards), a greater amount of trunk inclination change (for-/backwards) is necessary. The unequal amount of inclination change for these body segments does not correct the neck flexion to its initial status. The *trapezius habitual muscle length correction hypothesis* described above does not match, however, the (non-significant) tendencies towards a better perceived neck posture and less postural discomfort in the trapezius muscle regions (figures 4.8d and 4.8f, body regions 5 and 18, respectively) for a combination of desk slope 10° and pedal position +6cm (--*--), as compared with the operators' industrial workstation adjustment (-□-, desk slope 0° and pedal position -4cm).

The above remark leads to a second hypothetical answer to the question why operators, when a pedal is positioned further under the workstation (+6cm), only approach the needle more closely in the case of desk slope 10°. It is reasoned that a most favourable trapezius muscle length and neck flexion were found and maintained within the narrow constraints imposed by the operator's own industrial workstation adjustment. It may, however, very well be that an overall optimum (i.e. most favourable) neck flexion is greater than this habitual neck flexion. The *trigger hypothesis* then states that the introduction of a 10° desk slope acts as a trigger, an eye-opener, to the operator. While correcting the deviation from the habitual status operators become aware of the fact that more favourable postures exist.

A third hypothetical answer to the main question on operators' postural behaviour raised before is based on the (non-significant) tendencies towards better workers' perceptions for both neck and trunk postures at desk slope 10° and pedal position +6cm (--*--; figures 4.6a, 4.6b, 4.7c, 4.7d, and 4.7f), as compared to the other three combinations of desk slope and pedal position tested. For the neck posture the workers' perceptions are supported by the neck flexion found (head-trunk angle and neck-trunk angle; figures 4.4g and 4.4h, respectively). For the trunk posture the workers' perceptions are supported by the results on trunk inclination for-/backwards, i.e. a more upright trunk (figure 4.4d). Figure 4.4d shows that also desk slope 10° and pedal position -4cm (--□--) resulted in a more upright trunk posture, as compared to the operators' own industrial workstation adjustment (desk slope 0°, pedal position -4cm). The fact that this trunk posture is not accompanied by better workers' perceptions indicates that, for this to be the case, some other criterion is to be met, i.e. a certain neck flexion. The fact that trunk posture and neck posture together seem to be responsible for better workers' perceptions leads to the *spinal bow optimum tension hypothesis*. The spinal bow includes the flexible system between the head and the pelvis. At the upper end this bow is fixed to the visual target (needle tip) through a sort of extension by the strictly followed relationship between gaze inclination and head inclination for-/backwards (§ 4.4.3). At the lower end the opportunity exists to increase or decrease bow tension by moving the hips more or less close to the needle. Apparently, at desk slope 10° and pedal position +6cm an optimum (i.e. relatively favourable) tension of the spinal bow was found, by a combination of a certain amount of trunk inclination forwards and a certain neck flexion. This presumed phenomenon was observed also by Lepoutre *et al.* (1986) in their study on typing. By reducing the backrest – keyboard distance (fore/aft direction), the lumbar curvature at vertebra L3 decreases and the dorsal curvature at vertebra T1 increases, meaning less trunk inclination forwards and a greater neck flexion. This spinal posture was well appreciated by the subjects.

4.4.6 What determines neck load?

Within the present study, head/neck inclination for-/backwards as well as neck flexion/extension were determined, where neck flexion/extension was described by the head-neck angle, by the neck-trunk angle, and by the head-trunk angle. The results on the latter two measures roughly reveal the same pattern (figures 4.4g and 4.4h). Consequently, no major postural effects were found in the upper cervical spine, at the junction to the head segment, as shown by the head-neck angle (figure 4.4f). In addition, no substantial differences were found between head inclination for-/backwards and neck inclination for-/backwards (figures 4.4b and 4.4c, respectively).

The results on perceived neck posture (figure 4.6a) are reflected by the neck flexion/extension found (figures 4.4g and 4.4h), and not by the head/neck inclination for-/backwards (figures 4.4b and 4.4c). Apparently, during sewing machine operation neck flexion/extension plays a dominant role with respect to the workers' perceptions on neck posture, as compared to head/neck inclination for-/backwards. The major difference between head/neck inclination for-/backwards and neck flexion/extension is found at desk slope 10° and pedal position +6cm. The neck flexion at this set of experimental conditions is the greatest found for a specific desk height. Judging from the (non-significant) tendencies towards a better perceived neck posture and less postural discomfort in the trapezius muscle regions (figures 4.7d and 4.7f, body regions 5 and 18, respectively), it seems that sewing machine operators favour a greater neck flexion. The statement by Lepoutre *et al.* (1986) that typists favour a relatively high seat height (e.g. reduced fatigue and pain in the neck), *despite* an increased curvature at vertebra T1 (equivalent to a greater neck flexion) is remarkable in this respect. In view of the data presented above, however, it may very well be that the better workers' perceptions in fact are *due to* the greater neck flexion.

In view of the above reasoning one should always be aware that the workers' perceptions for the neck may as well be determined by factors that were not studied here. The posture of the shoulder girdle, for example, is such a factor, i.e. 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 posture of the upper arm (Pronk, 1991; Van der Helm, 1991), the latter asked for a closer look. It was found that at a specific desk height (+10cm, +15cm) the upper arm elevation was the same for all four combinations of desk slope and pedal position (figure 4.8). So, at least the upper arm elevation does not seem to play a role with respect the remarkable workers' perceptions for the neck at desk slope 10° and pedal position +6cm discussed in the previous paragraph. Furthermore, the possible role the position of the upper arm with respect to the trunk was studied. The results reflect the effect of desk height on upper arm elevation (figure 4.8) as well as the effects of desk slope and pedal position on trunk inclination for-/backwards (figure 4.4d). These three effects also do not match the effects found on workers' perceptions for the neck.

Earlier in this section (§ 4.4.6) it was stated that better workers' perceptions may be due to a greater neck flexion. It is not reasonable, however, to assume that a continuous increase of neck flexion will improve the perceptions of the neck posture. The active muscle components as well as passive structures in the neck will be stretched, ultimately resulting in a reduced active force capacity and a (near) rupture length, respectively. Therefore, the existence of an optimum (i.e. most favourable) neck flexion (range) may be expected. In the literature some support for this notion was found. Maximum neck extensor moment measured by Harms-Ringdahl and Schüldt (1988) was highest at a slightly flexed neck posture, though not being significantly different from both a neutral posture (subject sitting upright and looking straight forward) and a much flexed posture (near maximum neck flexion). Schüldt *et al.* (1986a;b) showed that, at a constant neck inclination for-/backwards (with respect to the vertical), EMG-activity of various neck muscles was reduced by an increase of neck flexion (created by a backward inclination of the thoraco-lumbar spine). Though not proven, it is likely that the lower EMG-activity at the greater neck flexion represents more favourable neck posture from a biomechanical viewpoint (e.g. concerning muscle moment arms and length-tension characteristics).

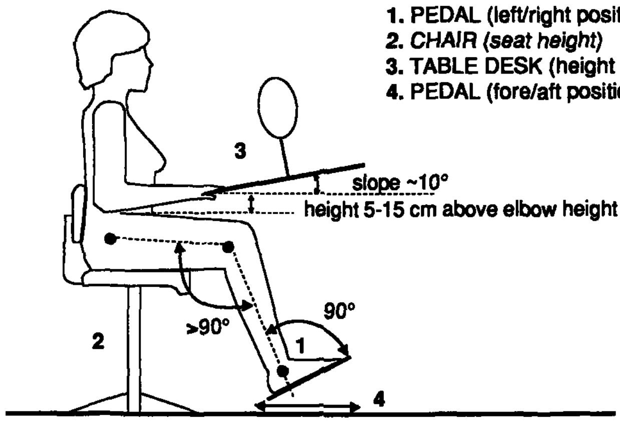
4.5 Formulation of guidelines

The second purpose of the paper was to formulate ergonomic guidelines for adjustment (and redesign) of sewing machine workstations. In order to formulate guidelines, results on working posture and workers' perceptions are to be discussed with regard to their mutual relationships in the process of evaluation of experimental conditions. § 4.5.1 focuses on the results for some particular sets of experimental conditions. In the following two sections the guidelines are formulated for desk height (§ 4.5.2) and for desk slope and pedal position (§ 4.5.3). The guidelines are visualized in figure 4.13. In § 4.5.4 the role of the worker's own workstation adjustment in industry at the evaluation of the experimental workstation adjustments (i.e. workers' perceptions) is discussed.

Guidelines for adjustment of a sewing machine workstation

Sequence of adjustment:

1. PEDAL (left/right position and inclination)
2. *CHAIR (seat height)*
3. TABLE DESK (height and slope)
4. PEDAL (fore/aft position)



1. The PEDAL shall be positioned right in front of the operating foot, while its inclination shall be adjusted in such a way that the angle between the lower leg and the foot is about 90°.

2. The CHAIR shall be revolving, have soft upholstery, adjustable seat height, no arm-rests, no wheels, and adequate support for the low back. The seat height shall be adjusted in such a way that the angle between the upper leg and the lower leg is more than 90° .

3. The TABLE DESK shall be given a height between 5 and 15 cm above elbow height (see the reference posture on the drawing), as well as a slope (indication: 10°).

4. The PEDAL shall be positioned as far under the table as considered comfortable (indication: pedal axis behind the needle).

Figure 4.13 Guidelines for adjustment of a sewing machine workstation.

4.5.1 Lower and upper extremities

On the basis of the perceived posture of lower or upper extremities some sets of experimental conditions were favoured instead of others by three operators, while the remaining operators indicated the same perception with respect to both conditions (p=.11). These results will be discussed in the following.

4.5.1.1 Lower extremities

At desk height +10cm, desk slope 10° and pedal position +6cm (--*--) is favoured instead of desk slope 0° and pedal position -4cm (-□-) for the left lower leg and foot. At desk height +15cm, desk slope 10° and pedal position -4cm (--□--) is favoured instead of desk slope 0° and pedal position +6cm (-*-) for the right lower leg. Furthermore, at desk slope 0° and pedal position +6cm (-*-) desk height +10cm is favoured instead of desk height +15cm for the left lower leg and foot posture. Lower extremity posture was studied in order to find support for these workers' perceptions. Lower extremity posture is determined on the one hand by the seat height versus the pedal height, and on the other hand by the horizontal distance between the hip and the pedal. Because seat height and pedal height were kept the same for each operator individually, the hip-pedal horizontal distance determined lower extremity posture during the experiments. The latter distance is directly related to the hip-needle fore/aft distance. From figure 4.4e it can be seen that the hip-needle fore/aft distance was not affected by desk height. This leaves unexplained why the effect on the left lower leg and foot is not found at desk height +15cm, and also why the effect on the right lower leg is not found at desk height +10cm. Furthermore, it leaves unexplained why desk height +10cm is favoured instead of desk height +15cm, while the hip-pedal horizontal distance is the same for both desk heights. The above considerations tend to the conclusion that the workers' perceptions on lower extremity posture are not systematically related to the workstation adjustments tested. This notion is strengthened by the fact that no postural discomfort was mentioned for almost all of the body regions in the lower extremities. Most likely this absence of postural discomfort during the experiments is due to the fact that, prior to the first experimental session, each operator selected a seat height at which pedal operation was comfortable. After this, desk heights were adjusted relative to elbow height (bottom-up adjustment). As a consequence, in the experiments the absolute desk heights for a specific experimental desk height varied considerably among the operators. In industry, however, usually desk heights at all individual workstations are the same, because of the presence of one adjacent table for the transport of material from one workstation to the next. Operators adjust desk height relative to elbow height by raising or lowering seat height (top-down adjustment). This, in most cases, will lead to non-optimum (i.e. relatively unfavourable) lower extremity posture, explaining the complaints reported in the literature.

4.5.1.2 Upper extremities

At desk height +15cm, the combination of desk slope 10° and pedal position -4cm (--□--) is favoured instead of desk slope 0° and pedal position -4cm (-□-) for the right upper arm posture. Upper extremity posture was studied in order to find support for this workers' perception. Upper arm posture is determined by the manipulation distance and by the height of the desk front edge. It was found that the manipulation distance stayed more or less the same for all combinations of desk slope and pedal position tested at desk heights +10cm and +15cm (figure 4.5b). According to the definition of desk height the front edge height of the desk was the same for desk slope 10° and pedal position -4cm (--□--) and desk slope 0° and pedal position -4cm (-□-). These considerations tend to the conclusion that the workers' perception of the right upper arm posture is not systematically related to the workstation adjustments tested. This notion is strengthened by the fact that virtually no postural discomfort was mentioned in body region 19, i.e. the right shoulder.

4.5.2 Guideline on desk height

The workers' perceptions on estimated endurance time and postural discomfort of the whole body do not show a group preference for a single desk height (figures 4.7g and 4.9). With respect to localized physical perceptions also no significant effect of desk height was found (e.g. figures 4.6 and 4.7a–f). At first sight this is remarkable because desk height had a significant effect on the elevation of the left upper arm as well as on the for-/backward inclination of the head and neck (an effect on trunk inclination for-/backwards could not be demonstrated in a statistically significant way, though to a lesser extent than for the head and neck, it seems present). Probably the relatively small left upper arm elevation measured at the various desk heights (roughly between 15° and 35°) is not a significant determinant of shoulder (girdle) load. Bjelle *et al.* (1981) found upper arm elevation (i.e. forward flexion and/or 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. Furthermore, the amount of elbow/forearm support on the desk may also affect the load on the shoulder and shoulder girdle to a certain extent. Elbow/forearm support may also have eliminated or reduced the differences in localized physical perceptions that were expected from the differences in upper arm elevation between desk heights tested. The head and neck inclinations for-/backwards found at the various desk heights also do not seem to affect the localized physical perceptions. It may be that the differences of head/neck inclinations for-/backwards do not lead to significant differences with respect to gravitational load on the neck structures. As described before (§ 4.4.6), operators seem more sensitive to changes of neck flexion. Also here, elbow/forearm support on the desk may affect body load, i.e. on the low back, to a certain extent. The above results and considerations lead to the conclusion that no guideline for a single higher desk height can be given. The judgements on desk heights do not justify excluding any of the desk heights tested for recommendation, i.e. no one desk height was judged significantly worse or better than another. However, the majority of judgements on a desk height 5 cm above elbow height were 'much too low' or 'a little too low' (70%, 'right'=30%). This agrees with the recommendation by Dul *et al.* (1988), that the desk height should not be lower than 5 cm above elbow height during sewing machine operation. A desk height 15 cm above elbow height was found 'a little too high' or 'much too high' in the majority of the judgements (75%, 'right'=25%). These results lead to the guideline that a desk adjusted between 5 and 15 cm above elbow height will minimize the postural load for the majority of sewing machine operators. An operator who supports the arms on the desk may prefer a higher desk within this range due to a conceivable positive effect on the head-neck-trunk posture and the absence of the conceivable adverse effect of an elevated upper arm posture on the shoulder load, and vice versa. For redesign purposes it means that the desk height has to be adjustable at least between the elbow height of a lower percentile (e.g. 5th) of the user population (in a comfortable working posture) plus 5 cm, and the elbow height of a higher percentile (e.g. 95th) plus 15 cm.

4.5.3 Guideline on desk slope and pedal position

Operators show a distinct preference for desk slope 10° combined with pedal position +6cm, as compared to the other three combinations of desk slope and pedal position tested, i.e. the estimated endurance time (figure 4.9, --*--) was considerably longer. This was confirmed by the results with respect to postural discomfort of the whole body and to judgement on the whole workstation adjustment, which were best for this specific combination of workstation adjustments (figures 4.7g and 4.11, --*--; differences from the other three combinations not statistically significant). The greater neck flexion and/or the more upright trunk posture support the workers' localized physical as well as integral perceptions (§ 4.4.6). Due to the fact that only two adjustments for each independent variable were tested (0 and 10° for desk slope, -4cm and +6cm for pedal position), only an (interaction) effect in general could be demonstrated in the present study. Therefore, no exact values on (combined) adjustments of desk slope and pedal position can be given. The above results and considerations lead to the guideline, stating that the desk should be given a slope (indication: 10°) and the pedal should be positioned as far under the workstation as considered comfortable (indication: pedal axis behind the needle). A pedal position further under the workstation requires enough free leg (knee) space, therefore, a somewhat higher desk is necessary because of possible obstructions as various structures are suspended below the desk, e.g. the motor. Consequently guidelines for redesign emerge, stating that the desk has to be adjustable in slope (at least 10°), the pedal should be easy (free) to position, and ample leg space should be provided.

4.5.4 Effects of workers' own workstation adjustment in industry

The question may be raised as to whether a judgement on desk height, desk slope, and/or pedal position was affected by the workers' own workstation adjustment in industry.

4.5.4.1 Desk height

Before the experiments the industrial desk heights of four of the five operators involved were measured. A judgement on their own industrial desk height could be deduced from the judgements on the experimental desk heights tested. These indirect judgements on their own industrial desk height were then 'a little too low' (score of 2), 'right' (score of 3), in between 'right' and 'a little too high' (score of 3.5), and 'a little too high' (score of 4), on a scale ranging from 'much too low' (score of 1) to 'much too high' (score of 5).

Furthermore, a 'right' desk height (i.e. a score of 3) was determined for each operator by her own judgements on various sets of experimental conditions. An individual relation between the judgement scores on desk height and the desk heights themselves was calculated by linear regression. In the case of a 10° desk slope 3.2 cm was added to the desk height (§ 4.4.4). For the four operators their 'right' desk heights were 3.5-3 cm lower, 1.5-0 cm lower, 0-1 cm higher, and 5.5 cm higher than their own industrial desk heights. On the basis of both calculation procedures it can neither be concluded that the effects of the workers' own industrial desk heights were present, nor that these effects were absent.

4.5.4.2 Desk slope and pedal position

In industry the operators involved in the experiments work at a desk slope 0° and an average pedal position -4cm. As described before, in the experiments the operators showed a distinct preference for desk slope 10° combined with pedal position +6cm. Therefore, it can be concluded that effects of the workers' own industrial adjustment of desk slope and pedal position were not present.

4.6 Conclusions

Concerning the hypotheses and experimental conditions tested for sewing machine operation, the following conclusions were drawn.

1 The gaze inclination is a determinant of head inclination for-/backwards.
2 The gaze-desk angle is *not* a determinant of working posture.
3 A desk slope induces a more upright head and trunk posture, without an additional elevation of the upper arms due to obstruction by the desk.
4 A slope effect is a (covert) height effect in fact.
5 The viewing distance, the manipulation distance, and the horizontal manipulation distance are *not* determinants of working posture.
6 Neck flexion/extension is the dominant determinant of neck load, as compared to head/neck inclination for-/backwards.
7 The working posture and the workers' perceptions at a 10° desk slope depend on the fore/aft pedal position.
8 The desk should be adjusted between 5 and 15 cm above elbow height.
9 The desk should be given a slope (indication: 10°) and the pedal should be positioned as far under the workstation as considered comfortable (indication: pedal axis behind the needle).

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Chapter 5

Touch-typing VDU operation
Workstation adjustment, working posture, and workers' perceptions

At a VDU workstation professional touch-typing operators worked at eight different combined adjustments of visual target height and chair backrest inclination. Working posture, workers' perceptions, and work performance were measured. From the results several conclusions were drawn, i.e. (1) in order to minimize the load on the musculoskeletal system for touch-typing VDU operators, the gaze inclination to a visual target (screen, document) should be 6-9° (range 0-15°) below the horizontal, (2) the gaze inclination recommended is independent of sitting posture (upright or leaning backwards), and (3) work performance is not affected by the gaze inclination to a visual target adjusted, nor by the sitting posture preferred. Data from the present experiment as well as from the 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. During VDU operation the working posture was constrained by a strictly followed individual relationship between gaze inclination and head inclination for-/backwards. Most likely, upper extremity posture is determined by the intention to adopt specific optimum (i.e. relatively favourable) postures of the shoulder joint and the wrist joint, whereas the elbow joint is of less importance in this respect. Neck flexion/extension (i.e. head inclination for-/backwards versus trunk inclination for-/backwards) was found to be a determinant of neck load, that is to be considered in future research, besides the traditionally measured for-/backward inclination of the head and/or neck segment.

5.1 Introduction

Apart from hand-arm-shoulder complaints VDU operators show a large number of complaints of the neck and the back (e.g., Arndt, 1983; Bammer, 1990; Bergqvist *et al.*, 1990). The neck complaints are most probably aggravated or caused by a non-optimum (i.e. relatively unfavourable) neck posture, the back complaints by inadequate trunk support, which is substantially mediated by the amount of backward inclination of the trunk. In order to optimize neck posture and trunk support/posture and reduce the number of complaints, quantitative ergonomic guidelines for the adjustment of VDU workstations are needed.

This study on touch-typing VDU operation 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 the workstation, i.e. visual target height and chair backrest inclination, 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 and Bishop, 1976). The *first* purpose of the paper is to study determinants of working posture (§ 5.1.1), as well as relationships between working posture and workers' perceptions (§ 5.1.3) for the sake of comparison with other visual-manual operations and generalization. The *second* purpose is to formulate ergonomic guidelines for adjustment (and redesign) of VDU workstations (§ 5.1.2). 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.

5.1.1 Determinants of working posture

Two hypothetical determinants of working posture during VDU operation, i.e. visual target position and chair backrest inclination (table 5.1), will be described successively along with existing guidelines. A determinant is defined as a constraint as regards posture selection by the operator involved. Recognized potential determinants, such as keyboard position, leg space, chair position and seat height will not be discussed.

Table 5.1 Hypothetical determinants of working posture.

Visual target position
- left/right of trunk (horizontal gaze direction)
- height above/below eyes (vertical gaze direction)
- gaze-screen angle
- viewing distance

} → head/neck posture

Chair backrest inclination → trunk inclination for-/backwards inclination
↘ upper arm elevation for-/backwards
↘ elbow extension ↔ forearm

An arrow stands for 'affects'.

It is hypothesized that at VDU operation the posture of the head is determined by the gaze direction through a strict relationship, as was found for other operations and tasks (e.g., Brues, 1946; Gresty, 1974; Barnes, 1979; Conrady *et al.*, 1987; Straumann *et al.*, 1991; Volle and

Guitton, 1993; Radau *et al.*, 1994; Rossetti *et al.*, 1994; chapter 4). Gaze is described by a horizontal (left/right) and/or a vertical gaze direction (up/down, gaze inclination). As far as the horizontal gaze direction is concerned there is no discussion of the guideline that visual targets (e.g. screen, document, keyboard) should be right in front of the trunk. The optimum (i.e. most favourable) gaze inclination for VDU operations, however, has been debated in the literature for several years. Gaze inclination is determined by the visual target height (with respect to eye height) and the viewing distance to the target. Guidelines on gaze inclination roughly range from 15° above to 45° below the horizontal (e.g., Kroemer and Hill, 1986a;b; De Wall *et al.*, 1992). In other words, the guidelines vary by as much as 60°. This wide range will be studied here for to find out whether it may be narrowed by distinguishing between more and less favourable gaze inclinations.

In general, it may be that during visual-manual operations a particular head posture is adopted to preserve a favourable angle between the line of sight (gaze direction) and the target surface. For the gaze-screen angle, a guideline already exists: 'Keep the plane of screen perpendicular to the gaze direction'. Furthermore, for VDU operation this adjustment does not appear to be critical, i.e. considerable deviations from the guideline do not seem to affect posture. For both reasons, it was decided that this hypothetical determinant of head posture should not be a matter of study here.

The role of viewing distance as a determinant of workstation adjustment and working posture became more clear in recent years. Firstly, subjects prefer a distance between the eyes and the visual target(s) roughly between 50 cm and 90 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., Brown and Schaum, 1980; Grandjean *et al.*, 1982;1983; Jaschinski-Kruza, 1987;1988;1990;1991; Akbari and Konz, 1991). Secondly, the viewing distance is limited by the size of the information (e.g. characters) used. At viewing distances of 50 cm and 90 cm the choice of a character height greater than about 2.5 mm and 4.5 mm, respectively, is recommended (Chang and Konz, 1993). Though, it should be mentioned that Grandjean *et al.* (1983) found preferred viewing distances up to about 90 cm at a character height of 3.4 mm only. Within the present study it was decided to take account of the above facts by giving the subjects as much freedom as possible to adopt a viewing distance of their own preference.

The reasons for adopting a certain inclination of the trunk (upright/backwards) and selecting an accessory backrest inclination of the chair during VDU operation are not completely understood. The fact is that an upright trunk posture is generally advised, whereas a backwardly inclined trunk is found mostly in practice (Grandjean *et al.*, 1983; Ong *et al.*, 1988). Probably the latter posture is adopted because of the lower musculoskeletal load at the trunk and the neck

(Andersson and Örtengren, 1974; Andersson *et al.*, 1974; Schüldt, 1986a;b). Here the inclination of the backrest will be studied, to find out whether a guideline on gaze inclination (refer above) should distinguish between an upright trunk posture and a backwardly inclined trunk, as well as to find out whether a separate guideline on backrest inclination should be formulated.

Grandjean *et al.* (1983) indicated that a backward inclination of the trunk may have an effect on upper arm elevation forwards, but not on elevation sidewards (for definitions, refer to § 5.1.3). Their data show that, irrespective of trunk inclination, the trunk and upper arms stay in a fixed geometric configuration, i.e. the elbows somewhat in front of the trunk, close to the stomach. As a consequence, the upper arms become more elevated forwards if the trunk gets more inclined backwards. One reason for this may be that an operator prevents the elbows from lying at the side of the trunk, possibly limiting upper arm mobility, or even getting behind the trunk, approaching an extreme shoulder joint position. Another reason may be that operators try to retain a favourable reach position of the hands with respect to the upper trunk (manipulation distance). Theoretically, this postural behaviour may be guided by an optimization of the upper extremity joint positions (i.e. an optimization of the manipulation distance), or, due to the weight of the upper extremities, 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), though, the latter does not seem very realistic because of the likely forearm/wrist support at the desk top.

If the upper arms are elevated forwards through a backward inclination of the trunk, the hands are raised and lose contact with the keyboard. An operator has two options to correct this situation, i.e. (1) raise the keyboard, or (2) extend the elbow somewhat more. With respect to both options, simply changing the elbow angle may be considered less cumbersome for an operator than raising the keyboard. Judging from the data presented by Grandjean *et al.* (1983) it seems as if operators strive to get the forearm in line with the keyboard top, i.e. to create a neutral wrist posture by adopting of a forearm inclination that is equal to the inclination of the keyboard top. It was indeed confirmed that elbow extension was involved. No conclusions could be drawn on keyboard height change.

With respect to guidelines on VDU workstation adjustment a distinction is hardly ever made between touch-typing, i.e. no visual control of the hands on the keyboard, and sight-typing, being its opposite. From an ergonomic viewpoint this is quite strange because both ways of operation differ essentially. With touch-typing head posture and upper extremity posture can be optimized independently. Sight-typing, however, requires a certain compromise between optimum (i.e. most favourable) postures of both body segment systems. It may be expected that a higher keyboard position will improve head posture, but also will create more elevated, possibly worse upper arm postures, and vice versa. In this study the focus will be on touch-typing.

5.1.2 Formulation of guidelines

With the standardized research approach mentioned before, professional workers 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. 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 and 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 (that is, can be explained by) objective information. In principle, the remaining (best) experimental conditions constitute the guideline.

Task performance is measured in order to check whether better workers' perceptions (and working posture) for a set of experimental conditions as compared to another set possibly came into being at the cost of task performance. If a set of experimental conditions is recommended and its accompanying task performance measured is worse than for the majority of the other sets of experimental conditions, the worse task performance result will be mentioned in the guideline formulated.

5.1.3 Working posture versus workers' perceptions

The posture of the head and/or neck segment in the sagittal plane is mostly evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, i.e. head/neck inclination for-/backwards (e.g., Chaffin, 1973; Hünting *et al.*, 1980;1981; Kilbom *et* *al.*, 1986; Lee *et al.*, 1986; Snijders *et al.*, 1991; Lindberg *et al.*, 1993). 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, i.e. 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 and Hagberg, 1984; Lepoutre *et al.*, 1986; Schüldt *et al.*, 1986a;b; Harms-Ringdahl and Schüldt, 1988; Kumar, 1994; chapter 4). 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, i.e. 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, i.e. upper arm elevation (e.g., Chaffin, 1973; Bjelle *et al.*, 1979;1981; Dul, 1988; Van der Grinten and 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 above). In addition, the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively), may play a role with respect to shoulder (girdle) load (Kilbom *et al.*, 1986; Mital and Faard, 1990; Jensen, 1991; Aarås, 1994). 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, i.e. trunk inclination for-/backwards (e.g., Jørgensen, 1970; Wickstrom *et al.*, 1988; Van der Grinten and Smitt, 1992; Aarås, 1994). The load on the low back increases with forward inclination. The load, however, decreases with backward inclination in the case of adequate trunk support (Andersson and Örtengren, 1974; Andersson *et al.*, 1974). Remarkably, these systematic effects of trunk inclination were found not only in the lumbar region, but also up into the cervico-thoracic region of the head-neck-trunk system. Considering also that head/neck inclination for-/backwards in the sagittal plane affects thoracic spine curvature (Nakaseko *et al.*, 1993) and relates to complaints of the back and loin (Grandjean *et al.*, 1982; Lee *et al.*, 1986), there is reason to study workers' perceptions with respect to the neck and the back in close connection.

5.2 Methods

In the laboratory eight sets of experimental conditions were tested. Test subjects executed a word-processing task for each set of conditions. Working posture, workers' perceptions, and task performance were measured.

5.2.1 Subjects

Eight experienced female VDU operators participated in the experiment (experience ranging from 1.5 to 7 years). On average, they were 29.4 years old (range 23–37) and 173.2 cm tall (range 166–182). The operators had neither received treatment nor has been on sick-leave recently due to complaints of the musculoskeletal system or of the eyes. Visual acuity of all operators was 1.0 or more for each eye separately as well as for both eyes together, tested at a viewing distance of 66 cm. One operator wore contact lenses and two wore spectacles for correction of nearsightedness. None wore bifocal spectacles.

5.2.2 Experimental task

The operators executed the word-processing task by touch-typing. The text to be typed was presented on screen, one sentence at a time (character height of capitals 4.5 mm). Each sentence to be typed (on average 3 screen lines) and the same sentence as typed by the operator appeared above and below the middle of the screen, respectively (figure 5.1). As in touch-typing no visual control of the hands on the keyboard is needed, the middle of the screen on average is the visual target. Operators were instructed to type as much as possible, but to work at the same pace and to use the same method of error correction for all sets of experimental conditions tested. Operators were not obliged to correct the errors made.

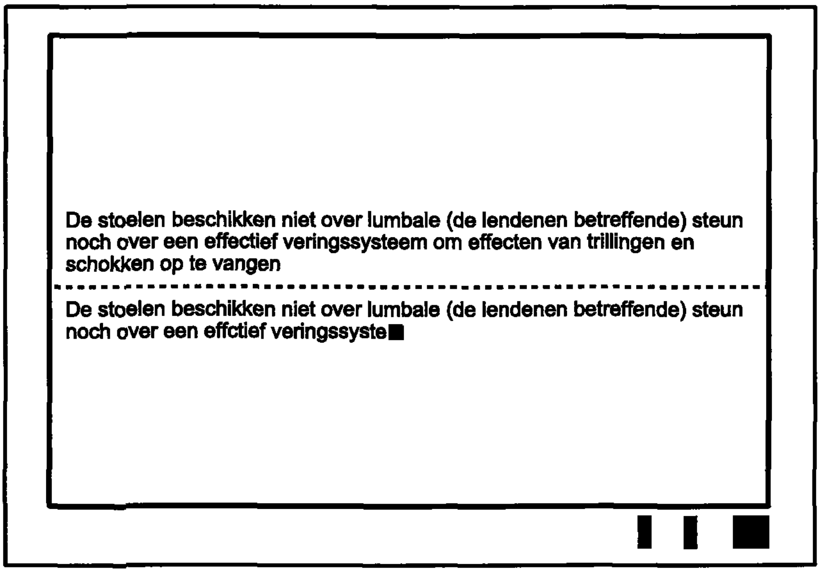


Figure 5.1 Text presentation on screen.

5.2.3 Independent variables

The eight sets of experimental conditions consisted of different combinations of visual target height and chair backrest inclination. The visual target heights tested, covering the whole range of existing guidelines on gaze inclination, were related to the individual eye height (figure 5.2):

- 5 cm above (+5cm)
- 10 cm below (-10cm)
- 25 cm below (-25cm)
- 40 cm below (-40cm).

Eye height was defined as the distance from the floor to the pupil of the eye with the operator leaning against the backrest and looking along the horizontal (figure 5.2).
The chair backrest inclinations tested were related to the vertical (figure 5.2):

- upright (0°)
- 15° inclined backwards (-15°).

The first was chosen in order to create an upright trunk posture which is generally advised, while the latter is in accordance with the trunk posture seen on average in practice (Grandjean *et al.*, 1983; Ong *et al.*, 1988).

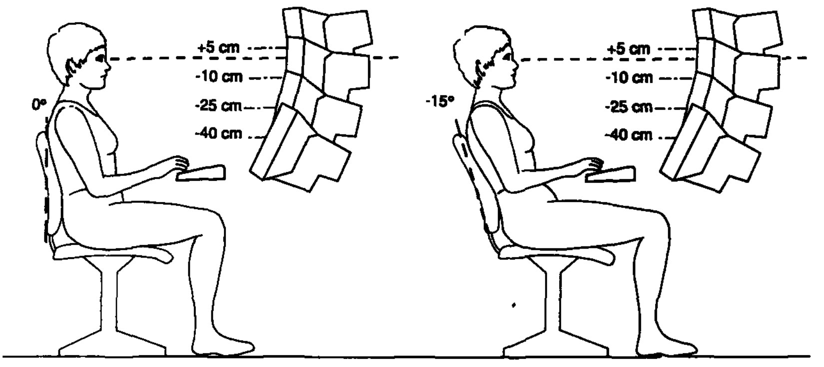


Figure 5.2 The 8 sets of experimental conditions. Eye height is shown by the horizontal broken line.

5.2.4 Experimental procedure

Each operator worked in eight experimental sessions of 25 minutes followed by breaks of 10 minutes. In each session one of the eight sets of experimental conditions was presented. The whole experiment lasted 1 day. In each session one of eight (equally difficult) texts was presented. The order of presentation for the sets of experimental conditions as well as for the texts was balanced over subjects and sessions.

The duration of an experimental session was chosen roughly in accordance with the average of continuous work periods seen during a normal working day (data acquired from the test subjects). It is assumed that the experimental results are valid for regular daily task execution, as workers' perceptions in terms of postural discomfort are linearly related to the duration of postures (refer to § 5.2.5, sub B). In other words, it is expected that the subjective differences to be found between particular workstation adjustments remain as they are if the duration of task execution is increased.

Prior to the first session each operator selected a comfortable seat height, guided by written instructions. For this, visual cues from keyboard and screen positions were absent. The individual seat height chosen was constant during the experiments, but the operator was free to choose the fore/aft distance from the chair/seat to the keyboard as well as from the seat to the screen. Furthermore, while typing a test text, for each chair backrest inclination tested each operator selected a comfortable keyboard height, and a comfortable viewing distance (visual target at eye height). Keyboard height selection was guided by written instructions ('Adjust table height such that the desk top is at about elbow height. This may be checked by having the upper arms hang down, and the forearms horizontal, while leaning against the backrest. During operation the hand should be in line with the forearm.'). The keyboard height selected (equal to table height plus 3 cm) was kept constant for all four visual target heights tested at each backrest inclination. The viewing distance was kept as close as possible to the comfortable viewing distance selected for all four visual target heights tested at each backrest inclination, in order to prevent operators from having to move the eyes to the screen for reasons of readability. For this, depending on the visual target height to be tested, in between experimental sessions the screen was re-positioned in the fore/aft direction guided by simple goniometric calculations, assuming a fixed eye position. Whenever the backrest inclination was changed in between sessions, the keyboard height was adjusted, as well as the viewing distance by re-positioning the screen in the fore/aft direction, both according to the individual preferences that were determined prior to the first session. Finally, eye height was measured for each backrest inclination tested in order to be able to adjust experimental visual target heights precisely.

During the experiments lighting at the workstation in the laboratory was adjusted according to generally accepted guidelines on luminance level and ratio, as well as on avoiding reflection and glare (Çakir *et al.*, 1980). Below the table desk enough leg space was available. Keyboard position on the desk was left free.

5.2.5 Dependent variables and measurement techniques

Working posture and *vision characteristics* were measured by an opto-electronic VICON-system. Retro-reflective markers were put on the skin overlying selected body segments and joints, as well as on the workstation (table 5.2 and figure 5.3). The three-dimensional positions of the markers were determined while the operators were in a reference posture (sitting 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 for each set of experimental conditions.

On the basis of the marker positions various dependent variables with respect to vision, head-neck-trunk, and upper extremities were calculated (table 5.3). In accordance with the hypothetical effects of visual target height and chair backrest inclination, most of these dependent variables describe the sagittal plane posture of the head, trunk, and upper extremities. For data analysis average scores on 2 measurements done between 15 and 20 minutes after the beginning of each experimental session were used.

Table 5.2 Markers; names and locations (refer also to figure 5.3).

Marker	Name	Location
M1	visual target	at the side of the screen, on the middle screen line
M2	eye	near the lateral corner
M3	ear	just ventrally of the lobe
M4	neck	intervertebral disc C7-T1
M5	shoulder	acromio-clavicular joint
M6	elbow	humero-radial joint
M7	wrist	distal radio-ulnar joint, at the dorsal side
M8	hip	upper edge of the greater trochanter
M9	keyboard	at the side, on the middle key row

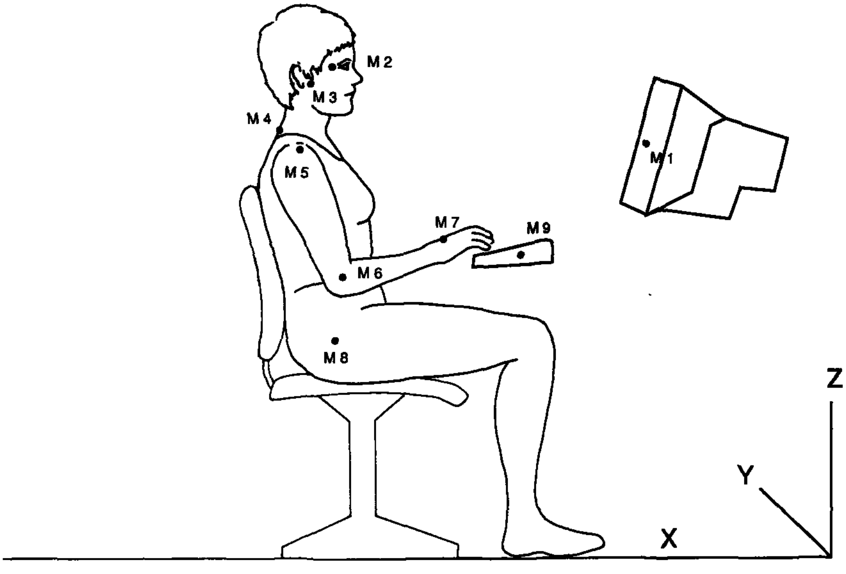


Figure 5.3 The marker positions for measurement of working posture and vision characteristics (refer also to table 5.2). The orthogonal axes shown represent the coordinate system used. The Y-axis is aligned parallel to the table desk front edge. The Z-axis is vertical. The YZ-plane corresponds to the frontal plane of the operator's body. The XZ-plane corresponds to the sagittal plane of the operator's body.

Table 5.3 Working posture and vision; names and definitions of dependent variables (refer also to table 5.2 and figure 5.3).

Name	Definition
Viewing distance	distance between M1 and M2, projected in the XZ-plane
Gaze inclination	angle between the horizontal and the line M1-M2, projected in the XZ-plane (a negative value means the operator looks downward)
Head inclination for-/backwards	angle between the line M2-M3 during operation and the line M2-M3 in the reference posture, projected in the XZ-plane (a negative value means the head is inclined for-/downwards)
Trunk inclination for-/backwards	angle between the line M4-M8 during operation and the line M4-M8 in the reference posture, projected in the XZ-plane (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 M4 and M9, projected in the XZ-plane
Horizontal manipulation distance	distance between M4 and M9 along the X-axis of the coordinate system
Upper arm elevation for-/backwards	angle between the line M5-M6 during operation and the line M5-M6 in the reference posture, projected in the XZ-plane (a positive value means the upper arm is elevated forwards)
Upper arm elevation sidewards	angle between the line M5-M6 during operation and the line M5-M6 in the reference posture, projected in the YZ-plane (a positive value means the upper arm is elevated outwards)
Elbow flexion	angle between the lines M5-M6 and M6-M7 during operation minus this angle in the reference posture
Forearm inclination	angle between the line M6-M7 and the horizontal, projected in the XZ-plane (a positive value, i.e. M7 has a higher Z-coordinate than M6, means that the forearm is inclined upwards; it should be recognized that the line M6-M7 may not exactly match the long axis of the forearm)

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, that may be matched directly with working posture variables. The modules 'Estimated endurance time' and 'Judgement on workstation adjustment' focus on integral responses. The modules (A-D) and the dependent variables are described below.

A *Perceived posture*

The operator was asked to rate her perception of the posture of the head, neck, back, left shoulder, right shoulder, left upper arm, right upper arm, left forearm, right forearm, left wrist, and right wrist. Directly after the session a written response was given on a seven-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 11 body parts mentioned were used as dependent variables.

B *Localized postural discomfort*

The operator was asked to rate her postural discomfort in 40 regions shown on a diagram of the rear view of a human body (figure 5.4; modified after Corlett and Bishop, 1976) as well as discomfort of the eyes, using a category-ratio scale by Borg (1982) ranging from 0 (no discomfort) to 10 (extreme discomfort, close to maximum) (Van der Grinten and Smitt, 1992). A written response was given at the beginning and at the end of the session. For each body region and for the eyes the score at the beginning was subtracted from the score at the end. The resulting scores for each region and the eyes were used as dependent variables. Furthermore, the resulting scores for various regions were grouped into larger functional units (table 5.4), guided by the information presented in the introduction (various health complaint locations; furthermore, refer to § 5.1.3). Finally, an overall dependent variable was constructed, i.e. postural discomfort of the whole body, the sum of the resulting scores for all 40 body regions. 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 subjects reasonably linear relationships were found between gravitational load and discomfort in a body region (e.g., Boussenna *et al.*, 1982; Van der Grinten and Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g., Manenica, 1986; Meijst *et al.*, 1995).

C *Estimated endurance time*

The operator was asked to estimate, on the basis of her perceptions, how much longer she could continue operation at the experimental workstation adjustment without difficulty. Directly after the session a written response was given on a five-point scale (1 = ½ working day (4 hours) to 1 working day (8 hours), 2 = 2 hours to ½ working day (4 hours), 3 = 1 to 2 hours, 4 = 25 minutes to 1 hour, 5 = less than 25 minutes). The estimated endurance time was used as a dependent variable.

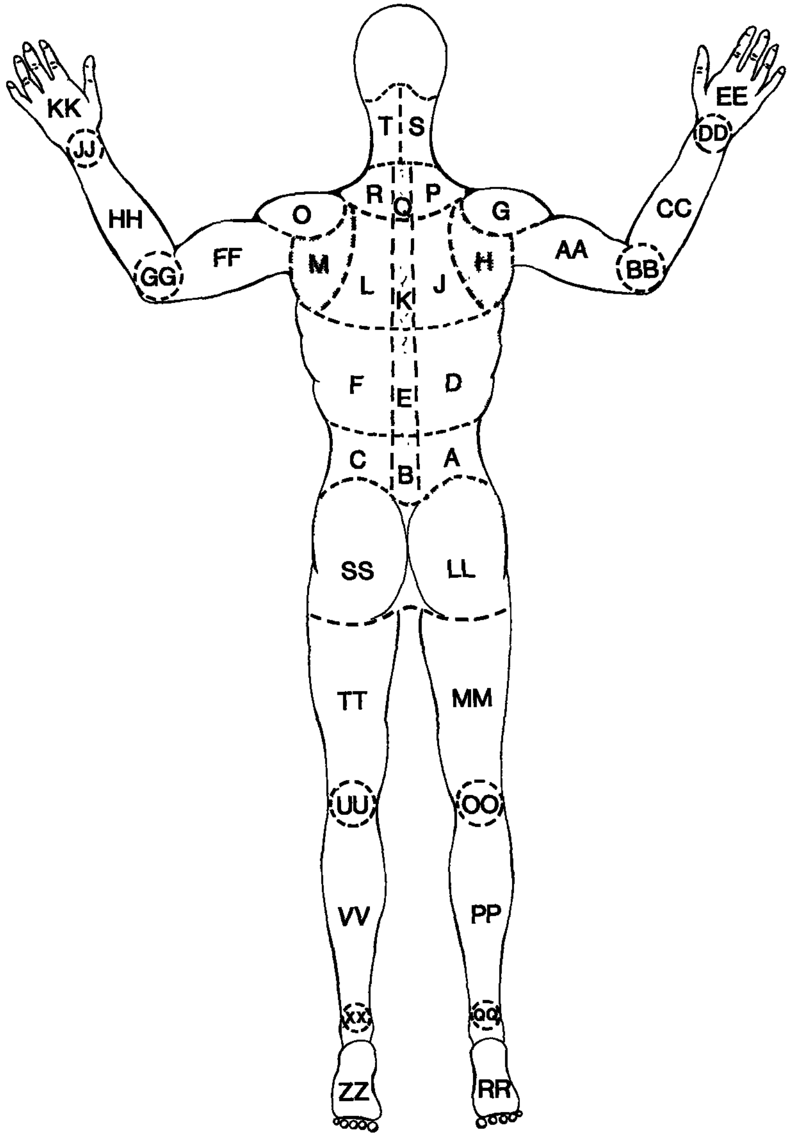


Figure 5.4 Diagram of the rear view of a human body, that was used in the questionnaire module on localized postural discomfort. Forty regions are distinguished.

Table 5.4 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/shoulders	T, S, R, Q, P, O, G
Left shoulder/arm	KK, JJ, HH, GG, FF, O, M
Right shoulder/arm	EE, DD, CC, BB, AA, G, H
Whole body	All 40 body regions

D *Judgement on workstation adjustment*

Firstly, the operator was asked to judge the screen height. Directly after the session a written response was given on a five-point scale (1 = much too low, 2 = a little too low, 3 = right, 4 = a little too high, and 5 = much too high). Secondly, the operator was asked to judge the chair backrest inclination. Directly after the session a written response was given on a five-point scale (1 = much too much inclined backwards, 2 = a little too much inclined backwards, 3 = right, 4 = a little too much upright, and 5 = much too much upright). Finally, the operator was asked to judge the whole workstation adjustment. Directly after the session a written response was given on a seven-point scale (1 = very favourable, 3 = favourable, 5 = unfavourable, 7 = very unfavourable. Scores of 2, 4, and 6 were available for intermediate responses). The judgements on screen height, chair backrest inclination, and the whole workstation adjustment were used as dependent variables. For part of the statistical analyses (§ 5.2.6, paired comparisons of sets of experimental conditions) the actual scores on screen height and chair backrest inclination given were converted, i.e. 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).

Task performance was measured by the number of words typed and the number of (uncorrected) errors made. Any discrepancy between the text to be typed and the text as typed by the operator (e.g. a word, punctuation mark, capital/small letter or space typed wrongly, not at all, or extra) was counted as an error. The number of words and the number of (uncorrected) errors were used as dependent variables.

5.2.6 Data analysis

On the basis of the literature described in § 5.2.5 (at 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 analysed by parametric statistical tests. Data on dependent variables with respect to perceived posture, estimated endurance time, and judgement on workstation adjustment were analysed by non-parametric (distribution-free) statistical tests, due to the ordinal character of the scales used.

The main and interaction effects of visual target height and chair backrest inclination 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 (4 * 2 design). Differences between sets of experimental conditions were tested by a post-hoc Tukey test (paired comparisons).

The effects of visual target height on the variables relating to perceived posture, estimated endurance time, and judgement on workstation adjustment were tested at each of the two chair backrest inclinations by a Friedman Test. Differences between sets of experimental conditions were tested by a Wilcoxon Matched-pairs Signed-ranks Test (paired comparisons). The effects of chair backrest inclination on the variables mentioned before were tested at each of the four visual target heights by a Wilcoxon Matched-pairs Signed-ranks Test (paired comparisons). The paired comparisons at the variables 'judgement on screen height' and 'judgement on chair backrest inclination' were done on the basis of converted scores (§ 5.2.5, sub D).

The main and interaction effects of visual target height and chair backrest inclination on the two task performance variables were tested multivariate by a MANOVA for Repeated Measures (4 * 2 design). Differences between sets of experimental conditions were tested by a Hotelling T^2-test (paired comparisons).

The selected level of significance in all tests was $p=.05$ (two-tailed). The description of the results (refer below) will be focussed on significant (combined) effects of visual target height and chair backrest inclination. 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 $\geq.8660$ (i.e. $R^2\geq.75$), as moderate if $\geq.7071$ and $<.8660$ (i.e. $.50\leq R^2<.75$), and as low if $<.7071$ (i.e. $R^2<.50$).

5.3 Results

§ 5.3.1 contains results for working posture and related workers' localized physical perceptions on vision and head-neck-trunk. In § 5.3.2 working posture and related workers' localized physical perceptions on the upper extremities will be described. In §§ 5.3.3 and 5.3.4 workers' integral perceptions and task performance are presented, respectively.

5.3.1 Vision and head-neck-trunk

5.3.1.1 Viewing distance

The viewing distance was significantly affected by the visual target height, as well as by the chair backrest inclination (table 5.5). On average, for each 15 cm lowering of the visual target height the viewing distance was reduced by 1.5 cm. Viewing distances differed by an average 3.6 cm for both backrest inclinations.

Table 5.5 Vision characteristics as a function of visual target height and chair backrest inclination (average group scores on gaze inclination and viewing distance).

Chair backrest inclination	Visual target height			
	-40cm	-25cm	-10cm	+5cm
0°	-32.9°/64.2 cm	-17.7°/66.2 cm	-5.7°/68.2 cm	5.8°/69.7 cm
-15°	-31.0°/69.3 cm	-18.4°/69.5 cm	-6.3°/71.4 cm	5.1°/72.6 cm

5.3.1.2 Gaze inclination

Gaze inclination was significantly affected also by the visual target height (table 5.5). On average, for each 15 cm lowering of the visual target height the gaze inclination was directed 12-13° more downwards. At visual target height -40cm a small significant difference was found between both backrest inclinations. Within the range of experimental conditions tested all operators show a linear relationship between gaze inclination and head inclination for-/backwards with high correlation (table 5.6). For each operator, table 5.6 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 8 sets of experimental conditions).

Table 5.6 Head inclination for-/backwards versus gaze inclination for individual operators. Head inclination for-/backwards = A * gaze inclination + B (where n = 8 sets of experimental conditions); #: number of operator; r: Pearson correlation coefficient. H/G: head inclination for-/backwards (average of 8 sets of experimental conditions)/gaze inclination (average of 8 sets of experimental conditions). H/G (corrected): same definition as for H/G, where head inclinations measured were corrected by subtracting the value at B, because, by definition, at a gaze inclination 0° head inclination for-/backwards should be 0° (refer to § 5.2.5). Range of gaze inclinations measured: 7.7° to -39.2°.

#	A	B	r	H/G	H/G corrected
1	.63	-9.71	.99	1.45	.63
2	.37	-.32	.94	.40	.37
3	.83	-3.38	.99	1.10	.83
4	.50	5.13	.99	.14	.50
5	.53	-9.77	.97	1.51	.53
6	.53	.17	.97	.52	.53
7	.70	2.10	.99	.51	.70
8	.40	-4.65	.97	.74	.40

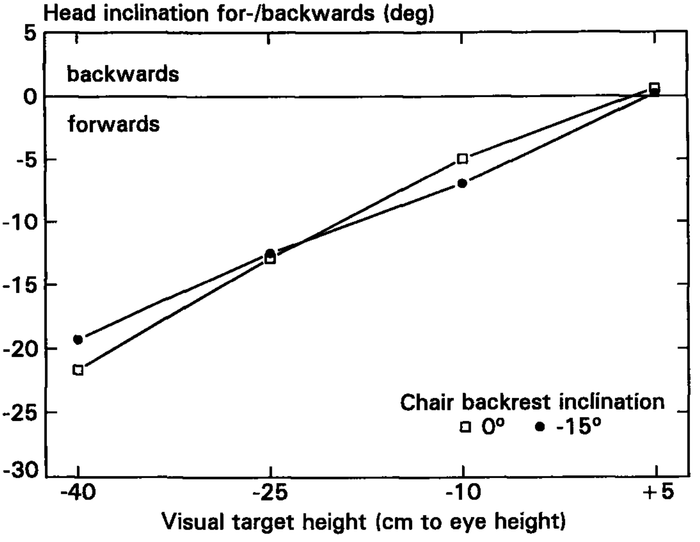


Figure 5.5 Head inclination for-/backwards versus experimental conditions (average group scores).

5.3.1.3 Head inclination for-/backwards

Head inclination for-/backwards is significantly affected by the visual target height (figure 5.5). On average, a 15 cm lower visual target caused the head to incline forwards by 6.5–7.5°. At visual target height -40cm a small significant difference on head inclination for-/backwards was found between both backrest inclinations (figure 5.5).

5.3.1.4 Trunk inclination for-/backwards

Trunk inclination for-/backwards is significantly affected by the chair backrest inclination. At the upright and the backrest inclined 15° backwards average trunk inclinations measured were -5.7° and -12.5°, respectively.

5.3.1.5 Neck flexion/extension

The significant effects of visual target height and chair backrest inclination on head inclination for-/backwards and trunk inclination for-/backwards, respectively, are reflected by the significant results on neck flexion/extension (figure 5.6).

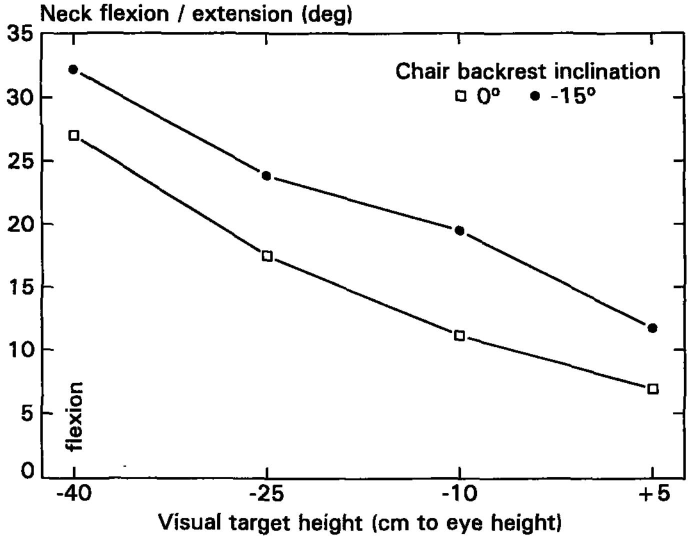


Figure 5.6 Neck flexion/extension versus experimental conditions (average group scores).

5.3.1.6 Workers' perceptions

Effects on workers' physical perceptions with respect to the head-neck-trunk system and the whole body are summarized in tables 5.7 and 5.8. Figure 5.7 shows the perceived postures of the neck and the back. Figure 5.8 shows the postural discomfort in the neck, back, and neck/back.

Table 5.7 Workers' perceptions; worse results for visual target heights -40cm, -25cm, and +5cm than for visual target height -10cm on localized physical perceptions with respect to the head-neck-trunk system, as well as on integral perceptions ($p \leq .10$). p.p. = perceived posture, p.d. = postural discomfort. Example: at chair backrest inclination -15° the judgement on the whole workstation adjustment for visual target height -40cm is significantly worse than for visual target height -10cm.

Chair backrest inclination	Visual target height	Significant effects	Effects approaching significance
-15°	-40cm	p.p. neck p.d. neck p.d. whole body judg. screen height judg. wh. workst. adj.	p.d. neck/back (p=.06) p.d. neck/upper back (p=.06)
-15°	-25cm	---	p.p. neck (p=.08) judg. screen height (p=.07) judg. wh. workst. adj. (p=.06)
-15°	+5cm	judg. screen height	---
0°	-40cm	judg. screen height	p.d. neck/back (p=.06)
0°	-25cm	p.p. back	---
0°	+5cm	judg. screen height	---

Table 5.8 Workers' perceptions; differences between both chair backrest inclinations on localized physical perceptions with respect to the head-neck-trunk system, as well as on integral perceptions ($p \leq .10$). No significant effects were found. Example: at visual target height -40cm the estimated endurance time is shorter for chair backrest inclination -15° than for chair backrest inclination 0°.

Visual target height	Effects approaching significance
-40cm	shorter estimated endurance time at backrest inclination -15° (p=.07) worse perceived head posture at backrest inclination -15° (p=.08)
+5cm	worse judgement on screen height at backrest inclination 0° (p=.07) worse perceived neck posture at backrest inclination 0° (p=.06)

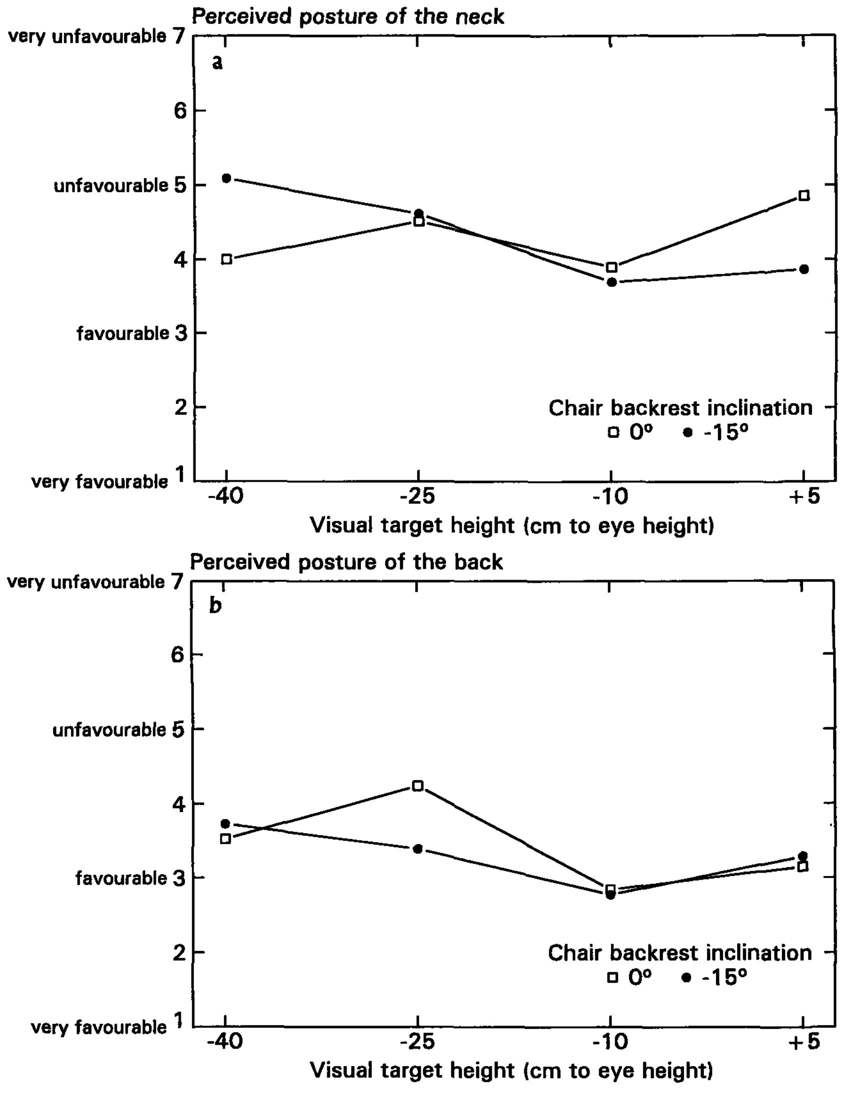


Figure 5.7 Perceived posture of the neck (a) and back (b) versus experimental conditions (average group scores).

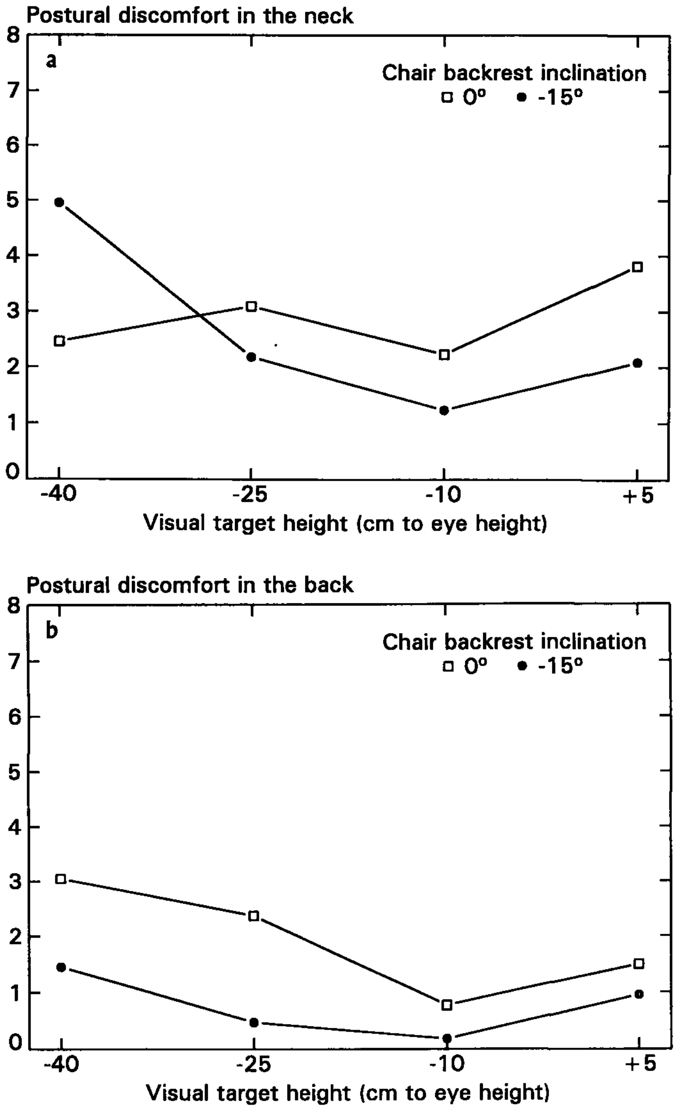


Figure 5.8 Postural discomfort in the neck (a), the back (b), and the neck/back (c; refer to the next page) versus experimental conditions (average group scores).

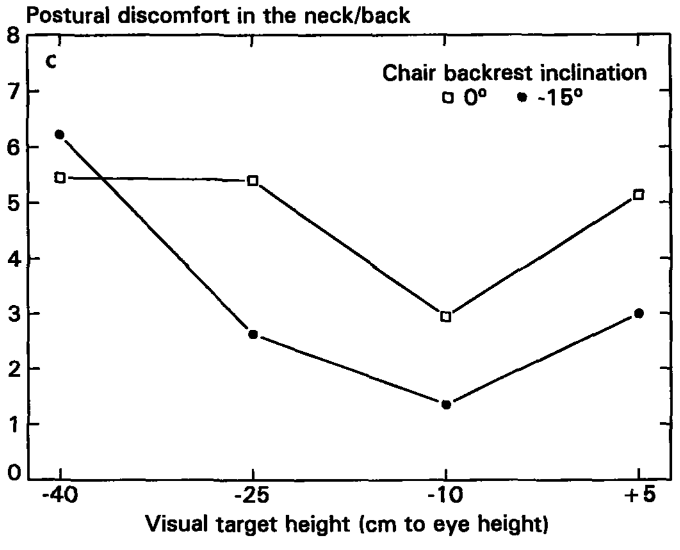


Figure 5.8 Postural discomfort in the neck (a; refer to the previous page), the back (b; refer to the previous page), and the neck/back (c) versus experimental conditions (average group scores).

5.3.2 Upper extremities

5.3.2.1 Keyboard height

The keyboard height selected is significantly affected by the chair backrest inclination. On average, at chair backrest inclination 0° keyboard height is 70.1 cm, whereas at chair backrest inclination −15° keyboard height is 68.8 cm.

5.3.2.2 Manipulation distance

Manipulation distance and horizontal manipulation distance are significantly affected by the chair backrest inclination. On average, at the upright and the backrest inclined 15° backwards the manipulation distance is 64.0 cm and 66.0 cm, respectively. On average, at the upright and the backrest inclined 15° backwards the horizontal manipulation distance is 53.2 cm and 56.4 cm, respectively.

5.3.2.3 *Upper arm elevation*

Upper arm elevation for-/backwards is significantly affected by the chair backrest inclination (figure 5.9a). On average, at the backrest inclined 15° backwards the upper arms were elevated forwards 5.0° more than at the upright backrest. No (combined) effects of visual target height and chair backrest inclination were found with respect to upper arm elevation sidewards (all p-values >.10). On average the upper arms were elevated sidewards 5.8°.

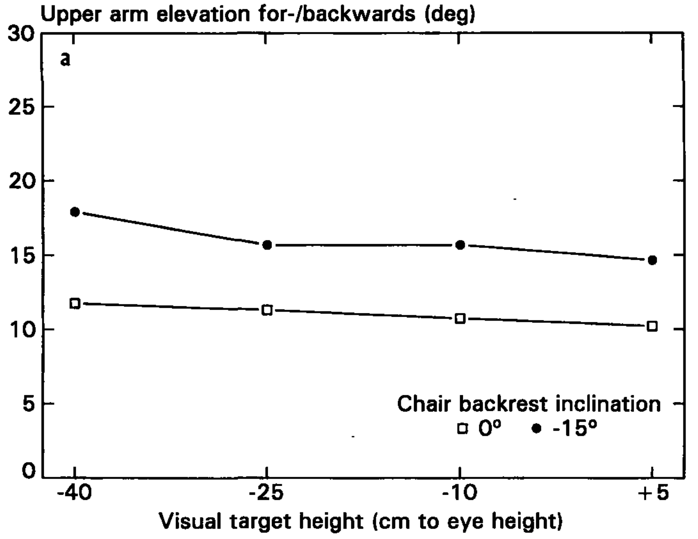


Figure 5.9 Upper arm elevation for-/backwards (a), elbow flexion (b; refer to the next page), and forearm inclination (c; refer to the next page) versus experimental conditions (average group scores).

5.3.2.4 *Elbow flexion/forearm inclination*

Elbow flexion is significantly affected by the chair backrest inclination (figure 5.9b). On average, at the backrest inclined 15° backwards the elbows are 3.6° more extended than at the upright backrest.

No (combined) effects of visual target height and chair backrest inclination were found with respect to forearm inclination (all p-values >.10). On average, the forearms were inclined upwards by 9.2° (figure 5.9c).

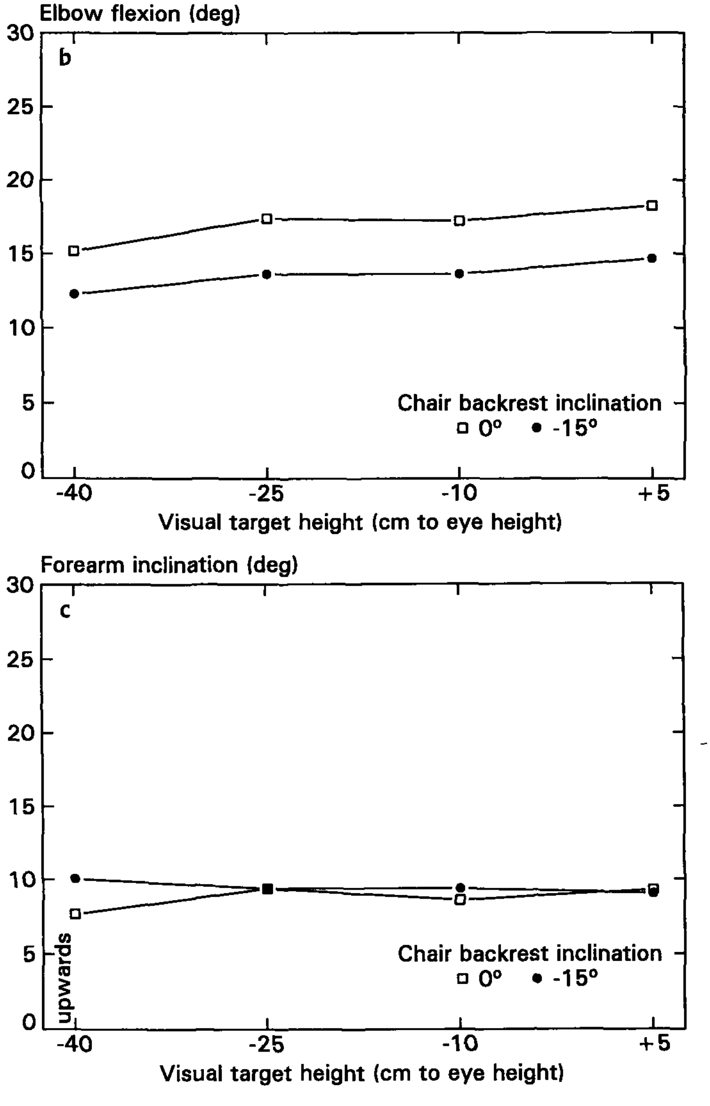


Figure 5.9 Upper arm elevation for-/backwards (a; refer to the previous page), elbow flexion (b), and forearm inclination (c) versus experimental conditions (average group scores).

5.3.2.5 Workers' perceptions

Effects on workers' localized physical perceptions with respect to the upper extremities are summarized in tables 5.9 and 5.10.

Table 5.9 Workers' perceptions; worse results for visual target heights -25cm, -10cm, and +5cm than for visual target height -40cm on localized physical perceptions with respect to the upper extremities ($p \leq .10$). p.d. = postural discomfort. Example: at chair backrest inclination -15° the postural discomfort in the left shoulder/arm for visual target height +5cm is significantly worse than for visual target height -40cm.

Chair backrest inclination	Visual target height	Significant effects	Effects approaching significance
-15°	-10cm	---	p.d. left shoulder/arm (p=.06)
-15°	+5cm	p.d. left shoulder/arm	---

Table 5.10 Workers' perceptions; differences between both chair backrest inclinations on localized physical perceptions with respect to the upper extremities ($p \leq .10$). Example: at visual target height -10cm the perceived posture of the right wrist for chair backrest inclination -15° is significantly worse than for chair backrest inclination 0°.

Visual target height	Significant effects	Effects approaching significance
-40cm	---	worse perceived posture of the left shoulder at backrest inclination -15° (p=.07)
-10cm	worse perceived posture of the right wrist at backrest inclination -15°	worse perceived posture of the left wrist at backrest inclination -15° (p=.07) worse perceived posture of the left shoulder at backrest inclination -15° (p=.07) worse perceived posture of the right forearm at backrest inclination -15° (p=.07)

5.3.3 Integral workers' perceptions

Figure 5.10 shows the average estimated endurance time. Figure 5.11 shows the judgements on screen height, chair backrest inclination, and the whole workstation adjustment. Effects of visual target height and chair backrest inclination on workers' integral perceptions are summarized in tables 5.7 and 5.8.

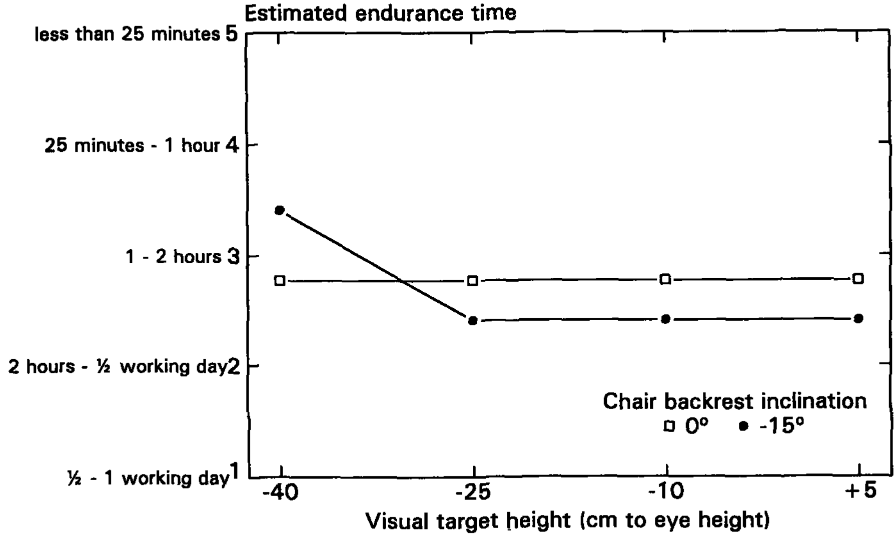


Figure 5.10 Estimated endurance time versus experimental conditions (average group scores).

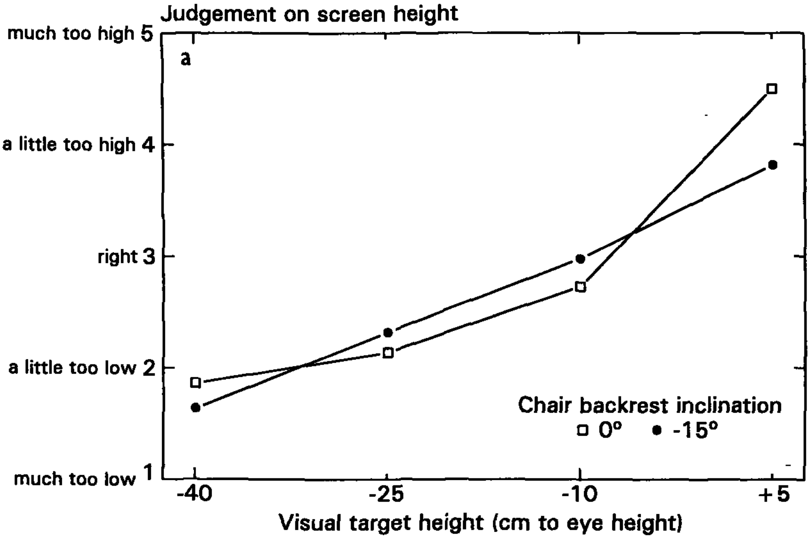
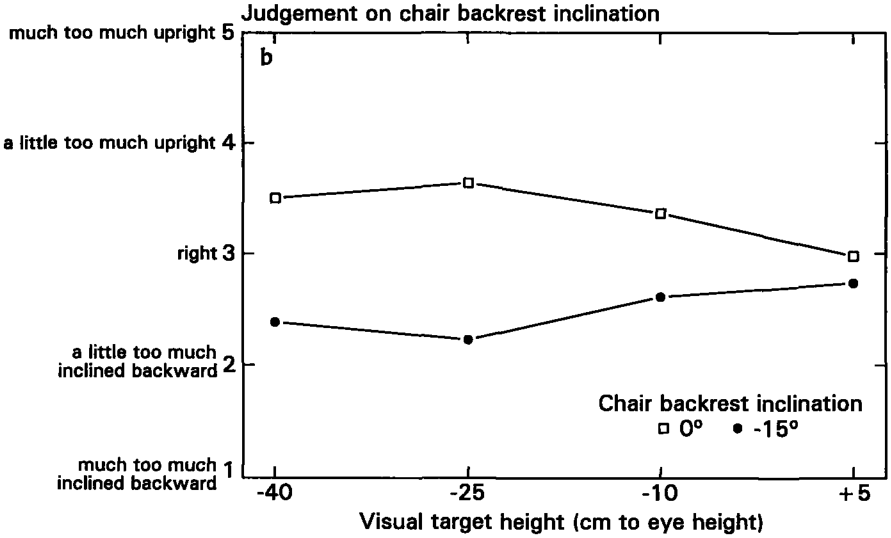


Figure 5.11 Judgements on screen height (a), chair backrest inclination (b; refer to the next page), and the whole workstation adjustment (c; refer to the next page) versus experimental conditions (average group scores).



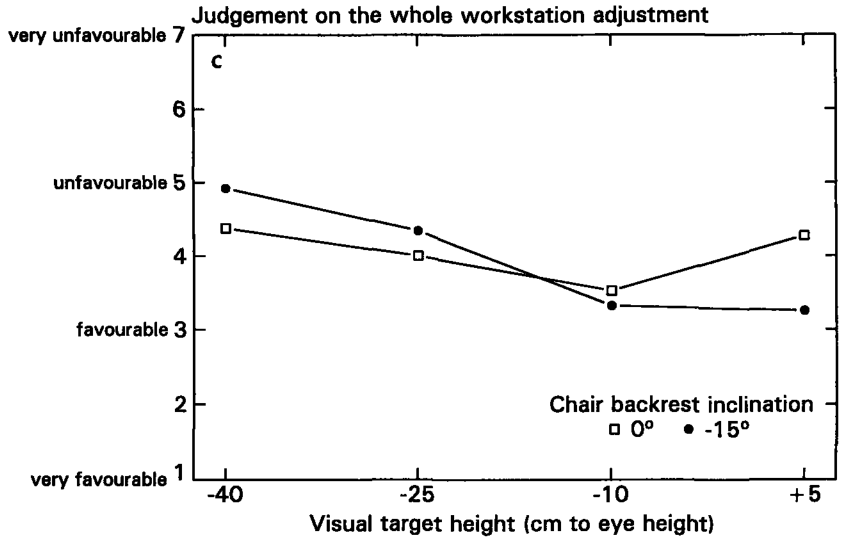


Figure 5.11 Judgements on screen height (a; refer to the previous page), chair backrest inclination (b), and the whole workstation adjustment (c) versus experimental conditions (average group scores).

5.3.4 Task performance

No (combined) effects of visual target height and/or chair backrest inclination were found with respect to task performance (all p-values $>.10$). On average, 959 words were typed and 22 (uncorrected) errors were made at an experimental session.

5.4 Discussion

5.4.1 Head-neck-trunk posture

By definition, at a gaze inclination 0° head inclination for-/backwards should be 0° (§ 5.2.5). However, at this gaze inclination average head inclination for-/backwards was found to be about −2.5° (table 5.6; parameter B). Therefore, the lines presented in figures 5.5 and 5.6 have to be shifted by 2.5° upward and downward, respectively.

At the upright backrest and the backrest inclined backwards average trunk inclinations measured were −5.7° and −12.5°, respectively. This means that these actual inclinations differ from their expected inclinations 0° and −15°. Video observations indicated that the average 5.7° backward inclination of the trunk at the upright backrest may be explained, at least partly, by some of the operators sitting without direct contact of the low back with the backrest (slouched posture). Video observations also indicated that at the backrest inclined 15° backwards the lower back is closely aligned with the backrest. However, the upper back usually is more upright during operation, without direct contact with the backrest. Therefore, the 15° backrest inclination is only partly reflected by the trunk inclination backwards measured. The observed inclination of the upper back segment seems to be a direct consequence of the for-/backward inclination of the head/neck segment, as described earlier by Nakaseko *et al.* (1993). Finally, differences between actual and expected trunk inclinations for-/backwards that are common to both conditions of chair backrest inclination may have been created in the experiment. For example, while the backrest was being used, it may have given way a little (some degrees of backward inclination).

On the basis of the above discussion with respect to the absolute figures on head inclination for-/backwards and trunk inclination for-/backwards, it is likely that the lines in figure 5.6 on neck flexion/extension have to be shifted up or down somewhat. If neck flexion/extension is considered a measure of the total flexion/extension between the head and the hip, a downward shift of the lines in figure 5.6 by 2.5° constitutes an adequate correction.

5.4.2 Viewing distance

Within the experimental conditions tested viewing distance did not turn out to be a determinant of working posture, because a systematic variation with both independent variables was found. The longer viewing distance at a higher visual target is a result of the eyes getting further away from the target as the head gets more upright. The longer viewing distance at a backward inclined backrest simply reflects the slightly different preferences expressed by the operators prior to the first session.

5.4.3 Gaze

In all sets of experimental conditions tested, the screen surface was kept perpendicular to the gaze direction. So, no conclusion can be drawn as to whether the gaze angle onto a visual target constitutes a postural constraint or not at VDU operation. However, the highly linear relationship between on the one hand gaze inclination and on the other head inclination for-/backwards constitutes a postural constraint (table 5.6). At the range of gaze inclinations for touch-typing VDU operation measured in this study, i.e. 7.7° to -39.2°, estimates based on data presented by Brues (1946) show that the contribution of head inclination for-/backwards to gaze inclination is 42% to 48%, respectively (average group scores). Data by Conrady *et al.* (1987) and Straumann *et al.* (1991) disclosed a slightly higher contribution, i.e. about 55-60% (average group scores). For the VDU operators in the present study the actual contribution by head inclination for-/backwards to gaze inclination varies from 37% to 83%, the remainder being contributed by up-/downward orientation of the eye with respect to the head/orbit (table 5.6; parameter H/G (corrected)). For 6 operators the actual contribution is somewhat higher than the contributions derived from the Brues data, and vice versa for the other two. For 5 operators the actual contribution is slightly lower than the contributions derived from the studies by Conrady and colleagues and Straumann and colleagues, and vice versa for the other three.

5.4.4 Upper extremity posture

As hypothesized in the introduction, VDU operators indeed elevated their upper arms more forwards when the trunk was more inclined backwards. At the upright backrest on average the upper arms showed an elevation forwards of 11.0°, while the trunk was inclined backwards at 5.7°. With the backrest inclined backwards on average the upper arms showed an elevation forwards of 16.0°, while the trunk was inclined backwards at 12.5°. From these figures it seems that the trunk and upper arms stay in a fixed geometric configuration, no matter what trunk inclination for-/backwards is chosen (cf. Grandjean *et al.*, 1983). Our results, however, do not give support to the hypothesis that this postural behaviour is determined by the intention to retain a typical favourable manipulation distance or horizontal manipulation distance. Both turned out to be significantly longer with the trunk inclined backwards than with an upright trunk. Therefore, it is more likely that the operators want to keep the elbows somewhat in front of the trunk, in order to preserve upper arm mobility.

An increased elevation forwards of the upper arms with the trunk inclined backwards would lead to the situation that the hands are no longer in touch with the keyboard. Only one of two options to preserve contact between the hands and keyboard, mentioned in the introduction, was actually used, i.e. the elbows were on average 3.6° more extended (figure 5.9b). Keyboard height was not raised as expected, but lowered by an average 1.3 cm. It is very likely that operators use both mechanisms to keep the forearm at a typical invariant inclination, i.e. in this study 9.2° on average. This forearm inclination shows a strong resemblance to the inclination of the top of the keyboard used, suggesting that operators strive for a neutral wrist posture. So, in summary, given the fixed relationship between the trunk and the upper arms as well as the fixed forearm inclination, a backward inclination of the trunk leads to (1) an increase of elbow extension, and (2) a lower elbow height, that is compensated for by lowering keyboard height.

The above results on upper extremity posture tend to the conclusion that operators strive for specific optimum (i.e. relatively favourable) positions of the shoulder joint (angle between upper arm and trunk) and the wrist joint (angle between forearm and keyboard/hands), whereas the elbow joint is of less importance in this respect.

5.4.5 What determines neck load?

In the present study, workers' perceptions revealed an optimum (i.e. most favourable) visual target height of 10 cm below eye height. The perceptions for the visual target heights −40cm and −25cm were worse than for the optimum target height (table 5.7). It is very likely that the more forward inclined head at the latter two target heights (figure 5.5) is to be counteracted by a higher force of the muscles at the neck and upper back. In addition, at these head inclinations the muscles may be stretched beyond their optimum (i.e. most favourable) length, reducing their active force capacity. Both a higher force level and a reduced force capacity lead to an earlier onset of muscle fatigue.

At the optimum visual target height the chair backrest inclinations showed no significant differences with regard to workers' perceptions (table 5.8). However, at visual target heights −40cm and +5cm remarkable differences between both backrest inclinations were found ($.05 < p \leq .10$). At visual target height −40cm the perceptions for the backward inclined backrest were worse than for the upright backrest. An explanation was found in the postural data. At the backward inclined backrest the head was significantly less inclined forwards by an average 2.6° (figure 5.5). Furthermore, a considerably greater neck flexion was found at the backward inclined backrest than at the upright backrest (figure 5.6). Both results suggest that the combination of a backrest inclined 15° backwards and an average gaze inclination −31° to the horizontal (table 5.5) creates a relatively unfavourable extreme neck flexion (cf. Harms-Ringdahl and Ekholm, 1986). At visual target height +5cm the workers' perceptions for the upright backrest were worse than for the backward inclined backrest (table 5.8). Gravity effects can be excluded as a causal factor due to the same head inclination for-/backwards found at both backrest inclinations. Apart from the fact that a backward inclined backrest may be more favourable because it supports body weight somewhat more, here too the neck flexion is the most likely cause for the differing perceptions of workers. A considerably smaller neck flexion (towards extension) was found at the upright backrest than at the backward inclined backrest (figure 5.6). This may shorten the muscles in the neck and upper back beyond their optimum lengths, reducing active force capacity. The same explanation most probably holds for the workers' perceptions for visual target height +5cm which were worse than for the optimum visual target height −10cm (table 5.7). The above considerations stress the role of neck flexion/extension as a determinant of musculoskeletal load on the neck structures, besides the for-/backward inclination of the head and/or neck segment.

In view of the above 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, i.e. 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 posture of the upper arm (Pronk, 1991; Van der Helm, 1991), the latter asked for a closer look. For visual target height −40cm as well as for visual target height +5cm, it was found that (1) the position of the upper arm with respect to the trunk was about the same for both backrest inclinations (§ 5.4.4), and (2) the upper arm elevation forwards was significantly greater with the backrest inclined 15° backwards than with the upright backrest. Both results show that at least the upper arm posture does not play a role with regard to the opposite preferences for the backrest inclination at visual target heights −40cm and +5cm, discussed in the previous paragraph.

The present study suggests that a slightly/moderately flexed neck is optimum, i.e. most favourable (figures 5.6, 5.7a, and 5.8a). This notion is supported by various other studies. Harms-Ringdahl and Schüldt (1988) found that maximum neck extensor moment was highest with a slightly flexed neck posture, though not being significantly different from both the neutral posture (subject sitting upright with vertical trunk and neck, and looking straight ahead) and the much flexed posture (near maximum cervical spine flexion). Schüldt *et al.* (1986a;b) showed that, at a constant neck inclination for-/backwards (with respect to the vertical), EMG-activity of various neck muscles was reduced by an increase of neck flexion (created by a backward inclination of the thoraco-lumbar spine). Though not proven, it is likely that the lower EMG-activity at the greater neck flexion represents a more favourable neck posture from a biomechanical viewpoint (e.g. concerning muscle moment arms and length-tension characteristics). Finally, from the data presented by Lepoutre *et al.* (1986) it can be concluded that a greater spinal curvature at vertebra T1 (equivalent to a greater neck flexion) is associated with reduced fatigue and pain in the neck. The same phenomenon was described in chapter 4.

In the introduction it was supposed that workers' perceptions with respect to head and/or neck posture may affect workers' perceptions with respect to trunk posture, and vice versa. Judging from the resemblance between figures 5.7a and 5.7b as well as between figures 5.8a and 5.8b, the present study supports this notion.

5.5 Formulation of guidelines

The second purpose of the paper was to formulate ergonomic guidelines for adjustment (and redesign) of VDU workstations. In order to formulate guidelines results on working posture and workers' perceptions are to be discussed regarding their mutual relationships in the process of evaluation of experimental conditions. § 5.5.1 focuses on the results for some particular sets of experimental conditions. In the following section the role of task performance is discussed (§ 5.5.2). In § 5.5.3 the guidelines for workstation adjustment are formulated.

5.5.1 Upper extremities

Upper extremity posture was found to be different for both chair backrest inclinations, but the same for all four visual target heights at each backrest inclination (§ 5.3.2). It is reasonable then to expect a difference between both backrest inclinations with respect to workers' localized physical perceptions either at all four visual target heights or at none of the four visual target heights. Table 5.10, however, shows that differences ($p=.07$) were only found at visual target heights -40cm and -10cm. Furthermore, since it is reasonable to expect that keyboard operation for word-processing creates a symmetric upper extremity posture, the left-right differences found with respect to workers' localized physical perceptions (table 5.10) are left unexplained. On the basis of both observations, it is concluded that subjective information (worker's perceptions) and objective information (working posture) on the upper extremities do not support each other, and are therefore not to be considered while formulating the guidelines for workstation adjustment (§ 5.5.3).

At a chair backrest inclination of −15°, upper extremity posture was the same for all four visual target heights (§ 5.3.2). It is reasonable then to expect the same localized physical perceptions. However, localized postural discomfort at visual target height −40cm was found to be greater than at visual target heights −10cm and +5cm (table 5.9; $p=.06$ and $p \leq .05$, respectively). Furthermore, discomfort was only found in the left upper extremity, which cannot be explained by a left-right difference with respect to upper extremity posture. On the basis of both observations, again subjective information (worker's perceptions) and objective information (working posture) on the upper extremities do not support each other, and are therefore not to be considered while formulating the guidelines for workstation adjustment (§ 5.5.3).

5.5.2 Task performance

Task performance was affected neither by the visual target height nor by the chair backrest inclination. Therefore, guidelines for workstation adjustment will be formulated without mentioning positive or negative side-effects with respect to task performance.

5.5.3 Visual target height and chair backrest inclination

Workers' perceptions revealed an optimum (i.e. most favourable) visual target height of 10 cm below eye height (gaze inclination: 6° below the horizontal) for backrest inclination 0° as well as for backrest inclination −15° (§§ 5.3.1, 5.3.3, and 5.4.5). At this visual target height the backrest inclinations did not show significant differences with regard to workers' perceptions (table 5.8). Therefore, the optimum visual target height is considered valid for all backrest inclinations between 0° and −15°, i.e. those backrest inclinations that are seen most often in practice. A general guideline in favour of a backward inclined backrest during VDU operation (cf. Andersson *et al.*, 1974; Andersson and Örtengren, 1974) cannot be formulated on the basis of the present study. Two plausible reasons are given. Firstly, it may be that the beneficial effects of a backward inclined trunk, supported by a backrest, appear at longer exposure durations than used in the present experiment. Secondly, in contrast to the studies by Andersson and colleagues, in the present experiment head inclination for-/backwards was involved due to the visual task on the screen. As supposed in the introduction, the effects of head inclination for-/backwards in fact do interfere with the effects of a backward inclined and supported trunk (§ 5.4.5; final paragraph).

Workers' perceptions for visual target heights −40cm, −25cm, and +5cm were worse than for visual target height −10cm (table 5.7). In general, it can be concluded that subjective information concerning localized physical perceptions with respect to neck and back is reasonably well supported by objective information concerning the postures of the head, neck and trunk (§ 5.4.5). However, the partial statistical significance of the localized physical perceptions with respect to the neck and back (table 5.7), stresses the importance of a literature review before formulating a guideline on visual target height.

Four studies were found, that allow for comparison with the present experiment. Bhatnager *et al.* (1985) asked subjects to inspect printed circuit boards. Three gaze inclinations to the centre of the boards were tested, i.e. +38°, +10°, and -23° to the horizontal. Responses were given by pressing either the reject or accept button, i.e. without visual control on the hands. Body part discomfort was lowest at gaze inclination -23°, whereas postural changes, i.e. an indicator of postural fatigue, were least frequent at gaze inclination +10°. It can be concluded that the optimum (i.e. most favourable) gaze inclination most likely is between these angles.

De Wall *et al.* (1992) asked subjects to execute CAD tasks at three different screen heights relatively close to eye height. Operations were carried out by looking at the screen 90% of the time, i.e. hardly any visual control on the hands is present. From the results it can be concluded that gaze inclinations less than 15° below the horizontal were preferred. On the basis of theoretical biomechanical considerations (a balanced posture of the head; its centre of gravity above its axis of rotation), it was expected that a gaze inclination above the horizontal would be optimum, i.e. most favourable. However, this was not confirmed by operators' preferences. Apparently, at gaze inclinations above the horizontal less favourable conditions arise (e.g. shortening of the neck and upper back muscles beyond their optimum, i.e. most favourable, lengths).

Grandjean *et al.* (1983) did a large field study on optimum (i.e. most favourable) workstation adjustment for VDU operations. Operators adjusted their workstation according to their preferences. The majority of operators were involved in conversational (i.e. interactive) VDU operations for seat-space control at an airline company. For this, according to Läubli (1987), all information is presented on screen (no source documents are being used). Therefore, it can be assumed that the screen is their main visual target during a working day. On average, the operators involved in the field study positioned the middle of the screen at a gaze inclination -9° to the horizontal (95% of the angles measured between -15° and 0°).

Hansson and Attebrant (1986; also Attebrant, 1995) tested three relatively low document heights during a word-processing task. The test subjects were sitting with the trunk upright on average. They were free to look at the manuscript and the keyboard at will. The majority of the subjects were satisfactory at type writing and a minority of them (about 20%) showed excellent type writing skills. Those that were good at type writing were almost continuously looking at the manuscript and those who were not that good were looking at the manuscript less. The middle document height was preferred by the majority of subjects. On the basis of the gaze inclinations calculated, the middle and highest document height can be compared with the visual target heights -40cm and -25cm to eye height tested in the present study, respectively. The results on workers' perceptions at the present study indicate that there may be a sort of secondary local optimum at relatively low visual target heights (refer to figures 5.7 and 5.8 at chair backrest inclination 0°, for comparison with the upright trunk posture in the study by Hansson and Attebrant, 1986). Probably at these heights the force generated by the (lengthening of) neck ligaments and passive muscle components reduces the amount of active muscle force needed. Higher targets relatively increase the active muscle force needed, whereas lower targets extremely stretch passive neck structures. Both effects are considered relatively unfavourable.

The study by Bhatnager *et al.* (1985) indicated that the optimum (i.e. most favourable) gaze inclination is between -23° and +10° to the horizontal. In the present study it was found that gaze inclinations between -18° and +5° to the horizontal (table 5.7) induce significantly better perceptions of workers than outside this range. The studies by De Wall *et al.* (1992) and Grandjean *et al.* (1983) narrow the optimum gaze inclination range to -15° to the horizontal and the horizontal itself. The study by Grandjean *et al.* (1983) and the present study indicate that the optimum gaze inclination is approximately in the middle of this interval, i.e. 6° to 9° below the horizontal. These results lead to the guideline that at VDU operation without visual control on the hands gaze inclination should be 6° to 9° (range 0° to 15°) below the horizontal, if the chair backrest is adjusted between the upright and inclined 15° backwards (figure 5.12). At preferable viewing distances the recommended gaze inclination range leads to visual target heights ranging from eye height to 20 cm below eye height.

After the guideline on visual target height was formulated, it was tested in practice by Berndsen and Delleman (1993). Eleven touch-typing VDU operators (bank employees) worked for one week at each of three visual target heights, i.e. -25cm, -10cm, and +5cm to eye height. Based on workers' perceptions (e.g. localized postural discomfort, perceived posture) the -10cm adjustment turned out to be optimum, i.e. most favourable. Recently, the guideline formulated was confirmed in a field study on office workers by Jaschinski *et al.* (1998), showing that gaze inclinations between horizontal (0°) and 16° below the horizontal are preferred. Furthermore, it turned out that there are subjects preferring viewing distances beyond 90 cm (refer to § 5.1.1), but not more than 100 cm.

In line with a general remark by Bergqvist *et al.* (1990) ("certain VDU work types may be a marker for jobs of generally more adverse conditions"), the authors of the present study are of the opinion that the optimum, i.e. most favourable, neck flexion derived also holds good for other work situations where visual control on the hands is reduced to a minimum (e.g. car driving, surgery by VDU monitor), whereas the hazardous neck flexion/extension positions derived should be kept in mind especially when evaluating or (re)designing work situations with visual control on the hands.

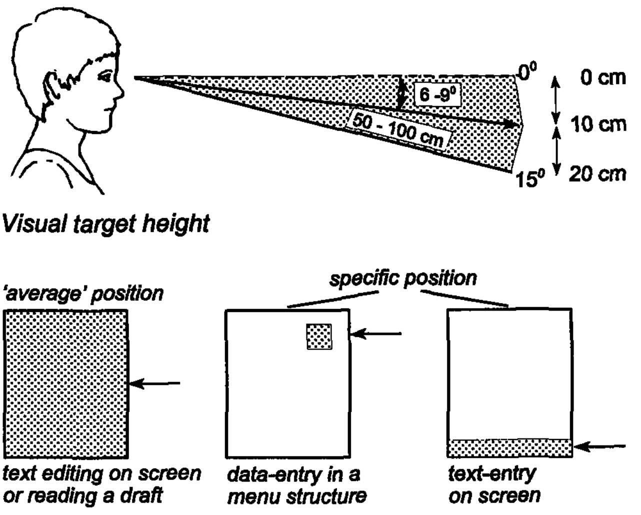


Figure 5.12 Guideline on adjustment of visual target height for touch-typing VDU operation.

5.6 Conclusions

Concerning the hypotheses and experimental conditions tested for touch-typing VDU operation the following conclusions are drawn:

1. the gaze inclination is a determinant of head inclination for-/backwards;
2. the viewing distance, the manipulation distance, and the horizontal manipulation distance are *not* determinants of working posture;
3. most likely, the upper extremity posture is determined by the intention to adopt specific optimum, i.e. relatively favourable, positions of the shoulder joint and the wrist joint, whereas the elbow joint is of less importance in this respect;
4. neck flexion/extension is a determinant of neck load;
5. the gaze inclination should be 6°-9° (range 0°-15°) below the horizontal.

Acknowledgements

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Chapter 6

Maintenance operations
Workstation adjustment, working posture, and workers' perceptions

In the study maintenance workers were involved in pneumatic wrenching, oxy-gas cutting, and grinding at five 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 the 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. All posture parameters mentioned are to be considered in future research.

6.1 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, i.e. 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 and Bishop, 1976). The *first* purpose of the paper is to study determinants of working posture (§ 6.1.1), as well as relationships between working posture and workers' perceptions (§ 6.1.3) for the sake of comparison with other visual-manual operations and generalization. The *second* purpose is to formulate ergonomic guidelines for adjustment (and redesign) of maintenance workstations (§ 6.1.2). 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 *et al.*, 1991). The latter publication contains information that was omitted here, for reasons of conciseness.

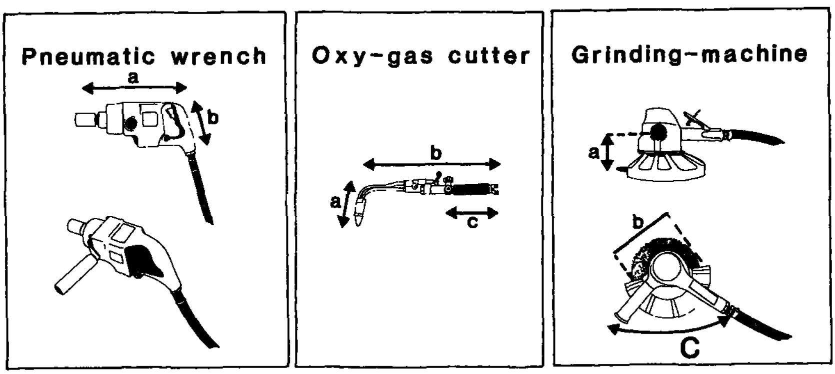

Figure 6.1 The pneumatic wrench, oxy-gas cutter, and grinding-machine, that were used in the experiments. Dimensions are presented in table 6.3.

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 6.1), and assuming the right-handedness of the worker. A pneumatic wrench is a tool to tighten or loosen nuts, requiring a considerable 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, i.e. 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 workbench for example, a little over the edge, so that sparks fall on the floor. Oxy-gas cutting is usually a precision operation, i.e. 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 and/or upper leg 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, i.e. 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.

6.1.1 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, i.e. 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?

Table 6.1 contains hypothetical determinants of working posture for pneumatic wrenching, oxy-gas cutting, and grinding. 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 *et al.*, 1987; Straumann *et al.*, 1991; chapters 4 and 5). In addition, for oxy-gas cutting it is hypothesized that a subject 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, subjects prefer a *viewing distance* of between 50 cm 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. Brown and Schaum, 1980; Grandjean *et al.*, 1982;1983; Jaschinski-Kruza, 1987;1988;1990;1991; Jaschinski *et al.*, 1998; Akbari and Konz, 1991).

Table 6.1 Hypothetical determinants of working posture.

- 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)

Secondly, it is hypothesized that a subject 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.

6.1.2 Formulation of guidelines

With the standardized research approach mentioned before, professional subjects 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 and 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 (that is, can be explained by) objective information. In principle, the remaining (best) experimental conditions constitute the guideline.

6.1.3 Working posture versus workers' perceptions

The posture of the head and/or neck segment in the sagittal plane is mostly evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, i.e. head/neck inclination for-/backwards (e.g. Chaffin, 1973; Hünting *et al.*, 1980;1981; Kilbom *et al.*, 1986; Lee *et al.*, 1986; Snijders *et al.*, 1991; Lindberg *et al.*, 1993). 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, i.e. 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 and Hagberg, 1984; Lepoutre *et al.*, 1986; Schüldt *et al.*, 1986a;1986b; Harms-Ringdahl and Schüldt, 1988; Kumar, 1994; chapters 4 and 5). 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, i.e. 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, i.e. upper arm elevation (e.g. Chaffin, 1973; Bjelle *et al.*, 1979;1981; Dul, 1988; Van der Grinten and 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 above). In addition, the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively), may play a role with respect to shoulder (girdle) load (Kilbom *et al.*, 1986; Mital and Faard, 1990; Jensen, 1991; Aarås, 1994). 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, i.e. trunk inclination for-/backwards (e.g. Jørgensen, 1970; Wickstrom *et al.*, 1988; Van der Grinten and Smitt, 1992; Aarås, 1994). 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 and Örtengren, 1974; Andersson *et al.*, 1974). Considering also that head/neck inclination for-/backwards affects thoracic spine curvature (Nakaseko *et al.*, 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, i.e. especially regarding joint positions, and related workers' perceptions.

6.2 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 subjects executed each operation at five different working heights. Working posture and workers' perceptions were measured.

6.2.1 Subjects

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 eight males from the Steel Construction and Welding sub-department co-operated. Seven of them were the same for both experiments. For each of these subjects both experiments were executed on separate days. Subjects were asked to participate according to availability. Table 6.2 presents several characteristics of the three experimental subject groups. All subjects were right-handed.

Table 6.2 Characteristics of the experimental subject groups for operations pneumatic wrenching, oxy-gas cutting, and grinding (group averages and ranges).

Operation	Age (years)		Stature (cm)		Weight (kg)	
	average	range	average	range	average	range
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

6.2.2 Experimental task

For pneumatic wrenching the experimental operation consisted of tightening ten 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 subject. 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 subject. For grinding the experimental operation consisted of grinding the top surface of a horizontal steel plate. Table 6.3 shows the dimensions, net weight, and weights in the right and left hand during operation for the tools used (figure 6.1).

Table 6.3 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=31cm b=10cm	6.0 (+1.0**)	4.5	2.5
Oxy-gas cutter	a=11.5cm b=39.5cm c=10cm	1.0 (+1.0**)	1.5	0.5
Grinding machine	a=9cm b=23cm C=100°	4.5 (+0.75**)	3.75*** (3.25****)	1.5*** (1.0****)

* Visualized in figure 6.1.
** 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.

6.2.3 Independent variable

The independent variable of this study was working height, i.e. relative to elbow height. Elbow height was defined as the distance from the floor to the elbow (underside) with the subject standing upright, the upper arms hanging down, and the forearms horizontal (figure 6.2). For each operation five levels for working height were selected on the basis of the posture effects seen during a small pilot-study (figure 6.2). For pneumatic wrenching working height was defined as the centre of the bolt and nut. Working height levels -20, -10, 0, +10, and +20cm 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 +20cm 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 -5cm relative to elbow height were selected.

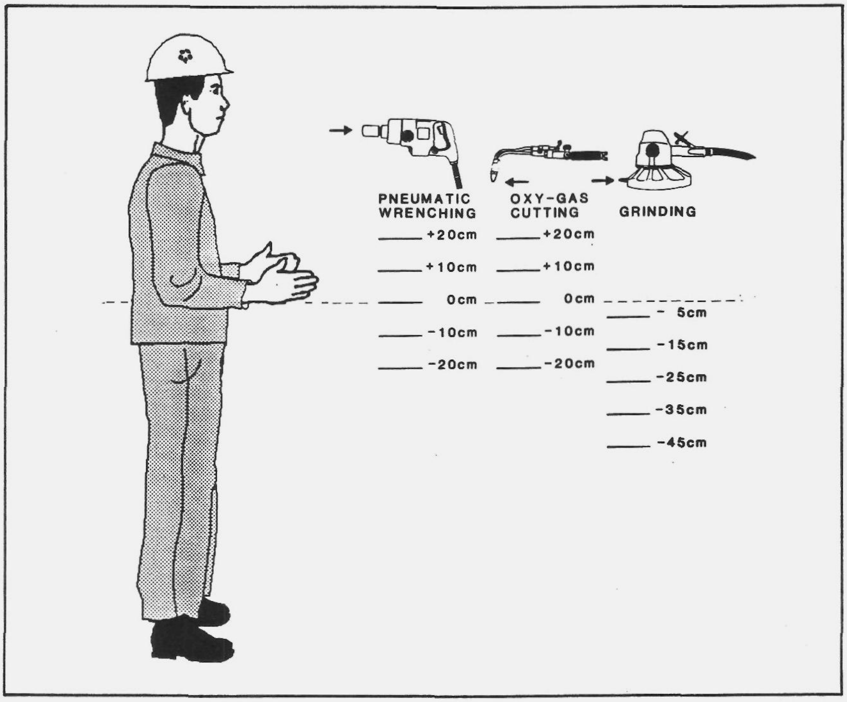

Figure 6.2 The five experimental working heights for pneumatic wrenching, oxy-gas cutting, and grinding. Elbow height is shown by the horizontal broken line.

6.2.4 Experimental procedure

The subjects carried out the experimental operations at the central maintenance building. Working height was adjustable by a scissor lift table. Each subject participated in five experimental sessions, each consisting of five minutes of operation. In each session one of the five working heights was presented. A session was followed by a break of at least ten minutes. The order of presentation of the working heights was balanced as well as possible over subjects and sessions. In total a subject was involved in testing all five experimental working heights for 1½ to 2 hours. The duration of a session was chosen roughly in accordance with the periods of operation during a normal working day.

6.2.5 Dependent variables and measuring techniques

Working posture and *vision characteristics* were measured by an opto-electronic VICON-system. 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 6.3 and table 6.4). The three-dimensional positions of the markers were determined while the subjects 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).

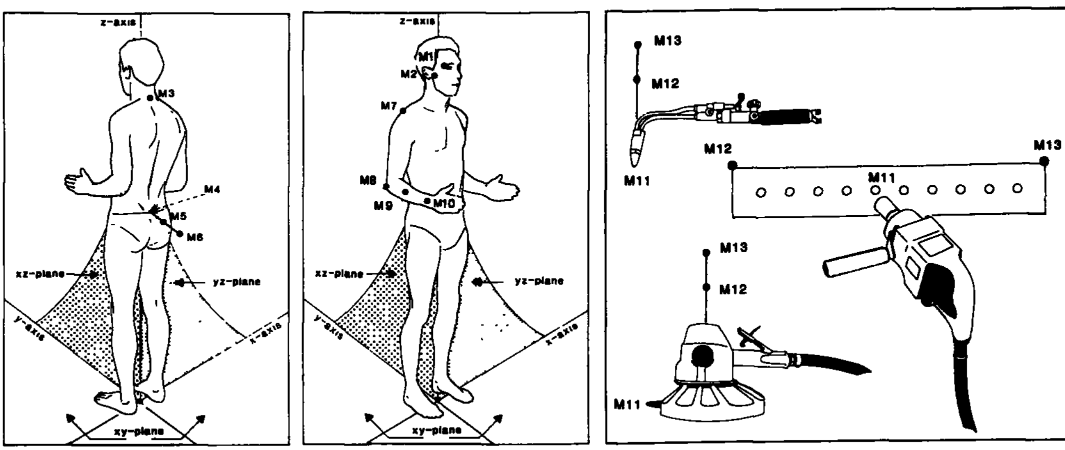

Figure 6.3 The marker positions for measurement of working posture and vision characteristics (refer also to table 6.4).

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 6.5). 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.

Table 6.4 Markers; names and locations (refer also to figure 6.3).

Marker	Name	Location
M1	eye	near the lateral corner
M2	ear	just ventrally of 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

Table 6.5 Working posture and vision; names and definitions of dependent variables (refer also to table 6.4 and figure 6.3).

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 subject looks downwards)
Head inclination for-/backwards	angle between the line M1-M2 and the vertical during operation minus the angle between the line M1-M2 and the vertical in the reference posture (a negative value means the head is inclined for-/downwards)
Trunk inclination for-/backwards	angle between the line M3-M4 and the vertical during operation minus the 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

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, that 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 below.

A Perceived posture

The subject was asked to rate his perception of the posture of the neck, the back, and the right upper extremity, i.e. shoulder, upper arm, forearm, and wrist. Directly after the session a written response was given on a seven-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 subject was asked to rate his postural discomfort in 40 regions shown on a diagram of the rear view of a human body (figure 6.4; modified after Corlett and Bishop, 1976), using a scale by Borg (1982) ranging from 0 (no discomfort) to 10 (extreme discomfort, close to maximum) (Van der Grinten and Smitt, 1992). The diagram and the rating scale were positioned in front of the subject. 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 6.6), guided by the information presented in the introduction (the workers involved show low back complaints; furthermore, refer to § 6.1.3). Finally, an overall dependent variable was constructed, i.e. postural discomfort of the whole body, the sum of the resulting scores for all 40 body regions (table 6.6). 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 subjects reasonably linear relationships were found between gravitational load and discomfort in a body region (e.g. Boussenna *et al.*, 1982; Van der Grinten and Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g. Manenica, 1986; Meijst *et al.*, 1995).

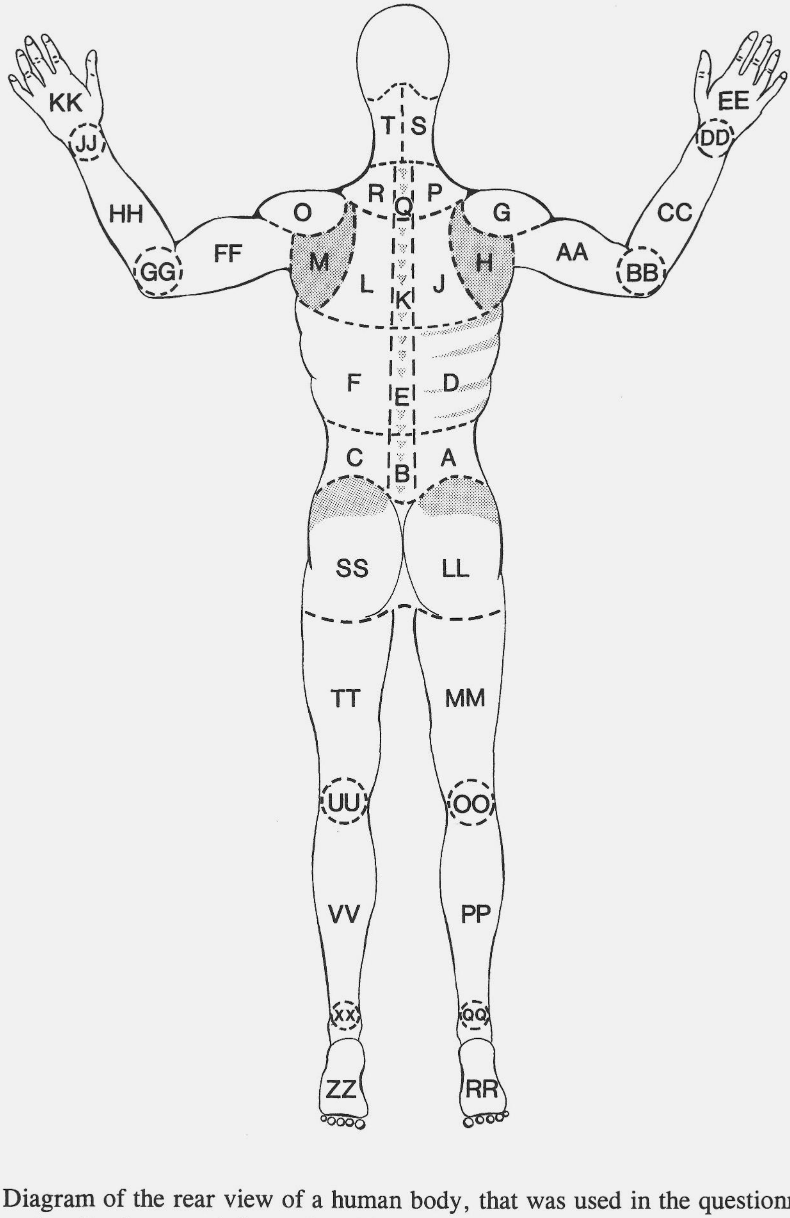

Figure 6.4 Diagram of the rear view of a human body, that was used in the questionnaire module on localized postural discomfort. Forty regions are distinguished.

Table 6.6 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 subject 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 nine-point scale (1 = more than 1 working day (8 hours), 2 = ½ working day (4 hours) to 1 working day (8 hours), 3 = 2 hours to ½ working day (4 hours), 4 = 1 to 2 hours , 5 = 30 minutes to 1 hour, 6 = 20 to 30 minutes, 7 = 10 to 20 minutes, 8 = 5 to 10 minutes, 9 = less than 5 minutes). The estimated endurance time was used as a dependent variable.

D *Judgement on working height*

The subject was asked to judge the working height. Directly after the session a written response was given on a five-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 (§ 6.2.6, paired comparisons of working heights) the actual scores on working height given were converted, i.e. 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).

6.2.6 Data analysis

On the basis of the literature described in § 6.2.5 (at 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 analysed by parametric statistical tests. Data on dependent variables with respect to perceived posture, estimated endurance time, and judgement on working height were analysed 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 (§ 6.2.5, sub 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, i.e. the optimum working height. The selected level of significance in all tests was $p=.05$ (two-tailed). The description of the results (refer below) will be focussed 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 $\geq.8660$ (i.e. $R^2\geq.75$), as moderate if $\geq.7071$ and $<.8660$ (i.e. $.50\leq R^2<.75$), and as low if $<.7071$ (i.e. $R^2<.50$).

6.3 Results

The results for pneumatic wrenching, oxy-gas cutting, and grinding are presented in separate sections (§§ 6.3.1–6.3.3). Each section has three subsections. The first subsection contains results for working posture and related workers' localized physical perceptions on vision and head-neck-trunk. In the second subsection working posture and related workers' localized physical perceptions on the right upper extremity will be described. In the third subsection workers' integral perceptions are presented.

6.3.1 Pneumatic wrenching

6.3.1.1 Vision and head-neck-trunk

The *viewing distance* was significantly affected by the working height (table 6.7). 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 subjects show a linear relationship between *gaze inclination* and head inclination for-/backwards with high correlation (table 6.8). For each subject, table 6.8 also shows the average head inclination for-/backwards as a percentage of the average gaze inclination (averages calculated on 5 working heights).

Table 6.7 Viewing distance (VD, cm), manipulation distance (MD, cm), and horizontal manipulation distance (HMD, cm) as a function of working height (average group scores).

	Working height				
pneumatic wrenching	-20cm	-10cm	0cm	+10cm	+20cm
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	-20cm	-10cm	0cm	+10cm	+20cm
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	-45cm	-35cm	-25cm	-15cm	-5cm
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 6.8 Head inclination for-/backwards versus gaze inclination for individual subjects. Head inclination for-/backwards = A * gaze inclination + B (where n = 5 working heights); #: number of subject; 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°.

#	A	B	r	H/G
pneumatic wrenching				
1	.58	-8.39	.96	.73
2	.91	24.77	.99	.55
3	1.18	37.16	.94	.56
4	.72	8.47	.99	.59
5	1.10	32.71	.99	.52
6	1.03	20.80	.94	.67
7	.71	10.53	.99	.53
oxy-gas cutting				
8	.95	-13.19	.93	1.24
9	1.14	-1.93	.99	1.19
10	.97	-6.33	.65	1.13
11	.86	-5.20	.94	.98
12	.98	-8.80	.99	1.17
13	.38	-32.82	.70	1.13
14	.83	-17.43	.92	1.17
15	.93	-10.68	.99	1.17
grinding				
8	.70	2.28	.93	.67
10	.99	32.93	.93	.54
11	.77	7.34	.73	.67
12	.73	11.79	.97	.56
13	.54	-6.21	.81	.63
14	.73	6.48	.56	.65
15	1.19	43.13	.90	.63
16	1.14	12.70	.75	.97

Head inclination for-/backwards, *trunk inclination for-/backwards*, as well as *neck flexion/extension* are significantly affected by the working height (figure 6.5). 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 6.5a/b). However, at working heights below 0cm neck flexion is relatively constant, i.e. head and trunk do incline forwards at about the same rate.

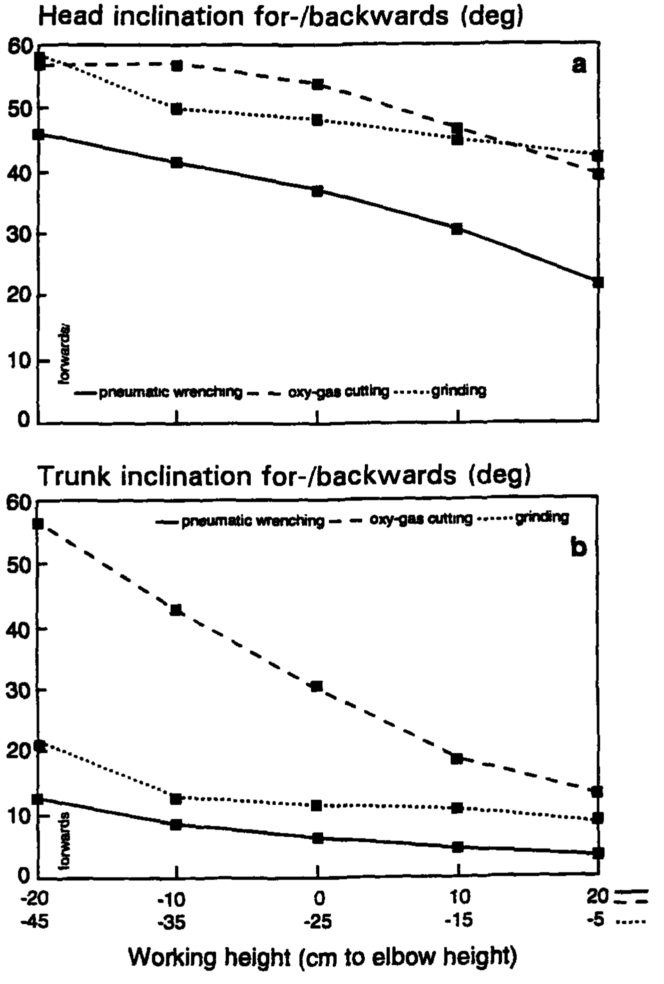

Figure 6.5 Head-neck-trunk posture variables versus experimental working heights (average group scores). a. head inclination for-/backwards; b. trunk inclination for-/backwards; c. neck flexion/extension (refer to the next page).

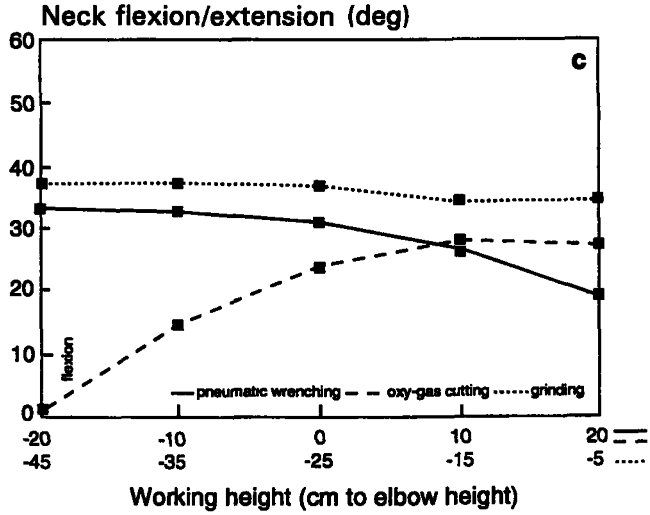

Figure 6.5 Head-neck-trunk posture variables versus experimental working heights (average group scores). a. head inclination for-/backwards (refer to the previous page); b. trunk inclination for-/backwards (refer to the previous page); c. neck flexion/extension.

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in table 6.9 (refer also to figures 6.6a and 6.7a).

Table 6.9 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, i.e. the optimum working height (mentioned in brackets). 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 -20cm is significantly worse than for its optimum working height (+10cm).

Working height	Significant effects	Effects approaching significance (level in brackets)
pneumatic wrenching		
-20cm	p.p. neck (+10cm)	---
+20cm	---	judg. on work. hght (p=.07; 0cm) p.p. upper arm (p=.04*; -10cm) (p=.03*; -20cm)

Working height	Significant effects	Effects approaching significance (level in brackets)
oxy-gas cutting		
-20cm	judg. on work. hght. (0cm) est. end. time (0cm) p.p. back (+10cm) p.p. upper arm (0cm) p.d. low back (+10cm)	p.p. shoulder (p=.07; 0cm)
+10cm	---	p.p. upper arm (p=.07; 0cm)
+20cm	p.d. whole body (0cm) p.d. neck/shoulder (-20cm) p.d. shoulder/arm (0cm) p.p. shoulder (0cm) p.p. upper arm (0cm) p.p. forearm (0cm)	p.p. wrist (p=.02**; 0cm)
grinding		
-45cm	judg. on work. hght. (-35cm) p.d. neck/back (-25cm)	---
-25cm	p.p. wrist (-35cm)	p.p. forearm (p=.07; -35cm)
-15cm	p.p. wrist (-35cm)	p.p. upper arm (p=.07***; -35cm)
-5cm	p.d. shoulder/arm (-45cm) p.p. wrist (-35cm) p.d. whole body (-35cm)	p.p. upper arm (p=.04***; -35cm) p.p. forearm (p=.052; -35cm)

Main effect of working height: * p=.08; ** p=.052; *** p=.10.

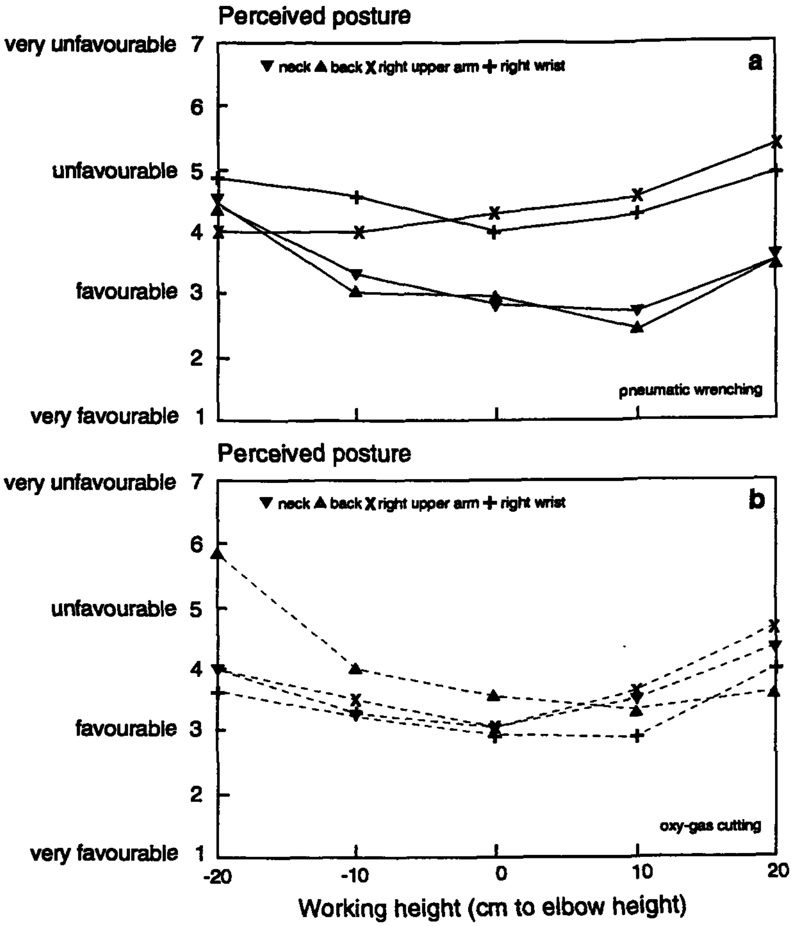

Figure 6.6 Perceived postures of the neck, back, upper arm, and wrist versus experimental working heights for pneumatic wrenching (a), oxy-gas cutting (b), and grinding (c; refer to the next page) (average group scores).

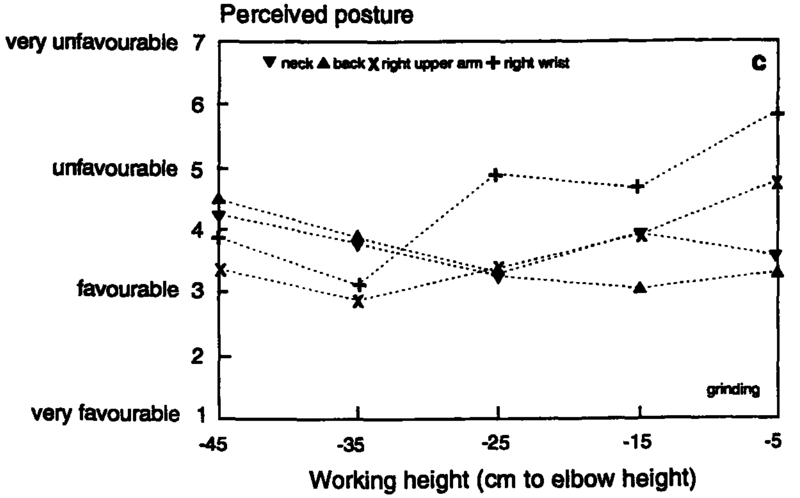

Figure 6.6 Perceived postures of the neck, back, upper arm, and wrist versus experimental working heights for pneumatic wrenching (a; refer to the previous page), oxy-gas cutting (b; refer to the previous page), and grinding (c) (average group scores).

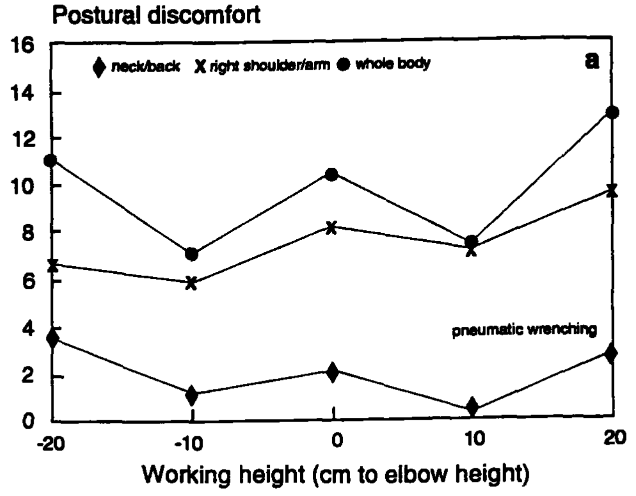

Figure 6.7 Postural discomfort in the neck/back, in the right shoulder/arm, and of the whole body versus experimental working heights for pneumatic wrenching (a), oxy-gas cutting (b; refer to the next page), and grinding (c; refer to the next page) (average group scores).

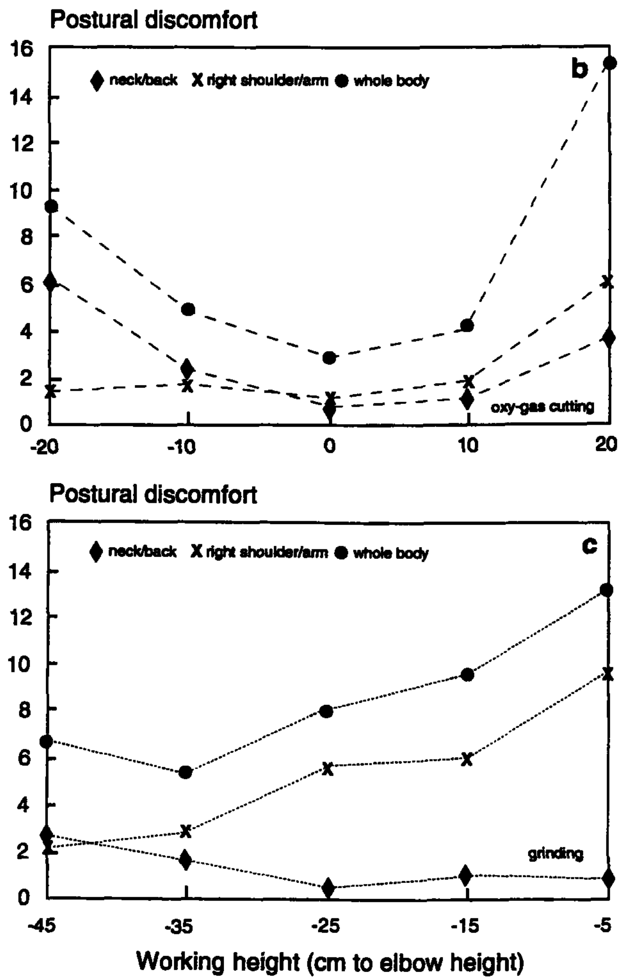

Figure 6.7 Postural discomfort in the neck/back, in the right shoulder/arm, and of the whole body versus experimental working heights for pneumatic wrenching (a; refer to the previous page), oxy-gas cutting (b), and grinding (c) (average group scores).

6.3.1.2 Right upper extremity

The *manipulation distance* and the *horizontal manipulation distance* are significantly affected by the working height (table 6.7). 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 −20cm was smaller than for working heights 0cm (p=.06), +10cm (significant), and +20cm (significant). The horizontal manipulation distance for working height −10cm was significantly smaller than for working height +20cm.

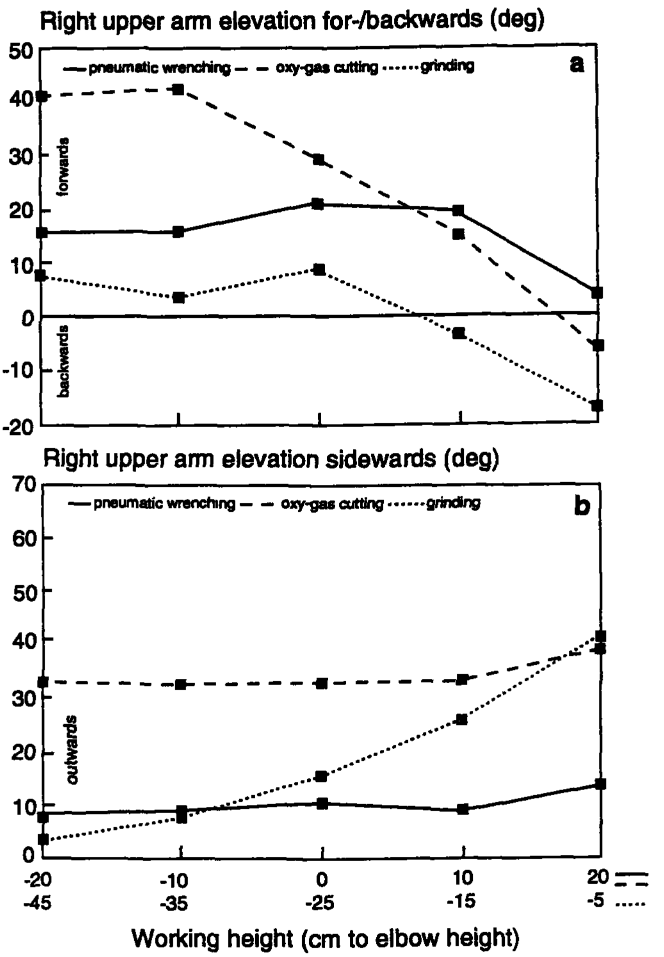

Figure 6.8 Right upper arm elevation for-/backwards (a) and sidewards (b) versus experimental working heights (average group scores).

Upper arm elevation for-/backwards is significantly affected by the working height (figure 6.8a). For working height +20cm the upper arm was less elevated forwards than for working height +10cm (significant), 0cm (significant), -10cm (p=.0504), and -20cm (p=.06). *Upper arm elevation sidewards* is not affected by the working height (figure 6.8b). On average, the upper arm was elevated sidewards 10.1°.

Elbow flexion is significantly affected by the working height (figure 6.9). 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 6.10). 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.

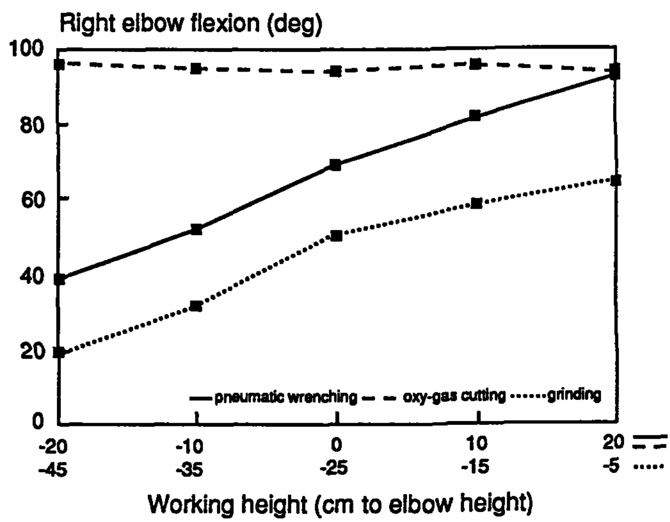

Figure 6.9 Right elbow flexion versus experimental working heights (average group scores).

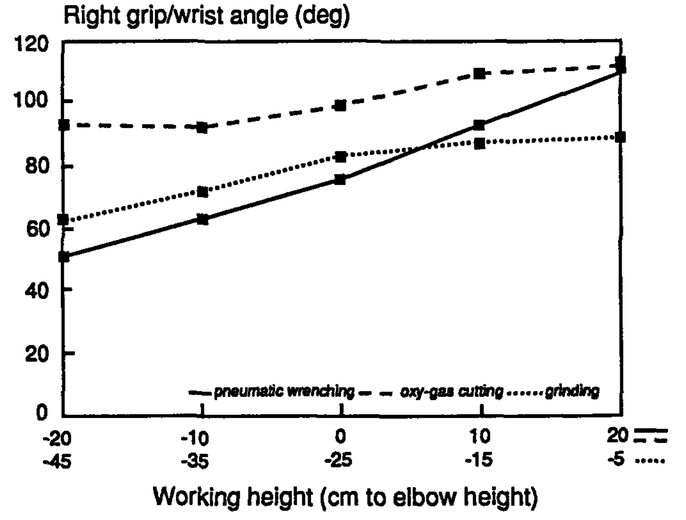

Figure 6.10 Right grip/wrist angle versus experimental working heights (average group scores).

Effects on *workers' localized physical perceptions* with respect to the right upper extremity are summarized in table 6.9 (refer also to figures 6.6a and 6.7a).

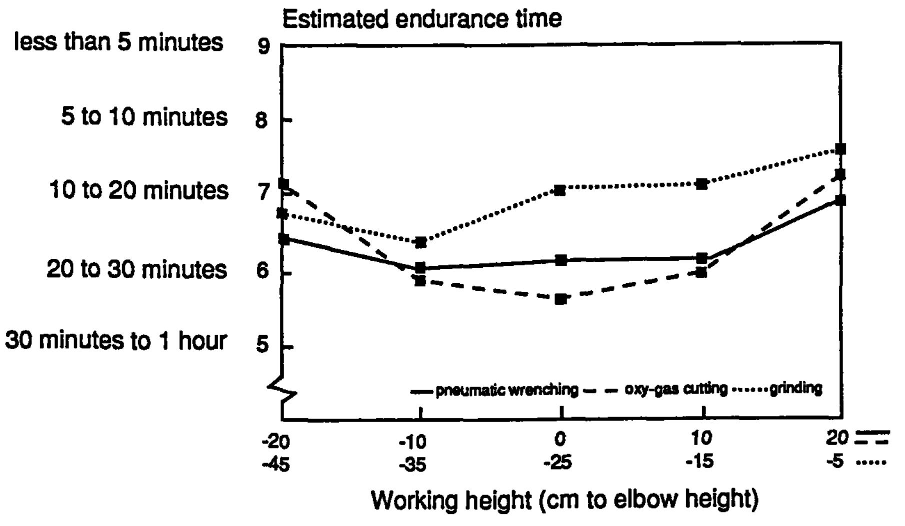

Figure 6.11 Estimated endurance time versus experimental working heights (average group scores).

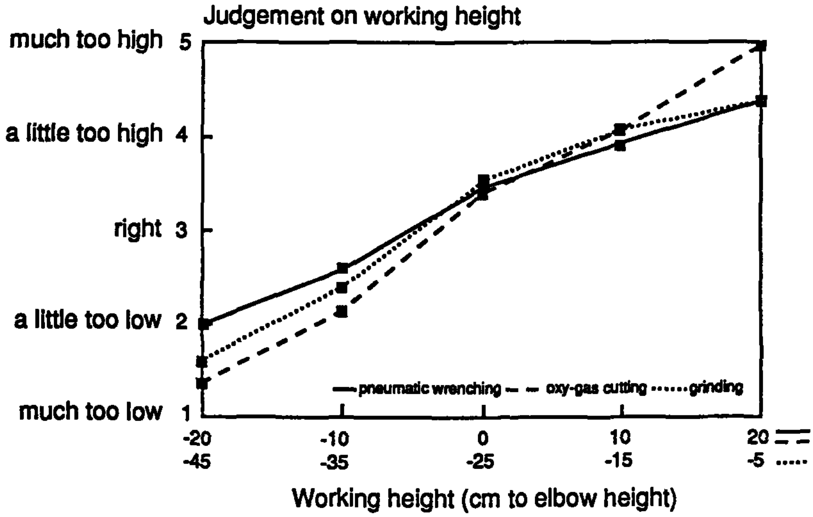

Figure 6.12 Judgement on working height versus experimental working heights (average group scores).

6.3.1.3 Workers' integral perceptions

Effects on *workers' integral perceptions* are summarized in table 6.9 (refer also to figures 6.11 and 6.12).

6.3.2 Oxy-gas cutting

6.3.2.1 Vision and head-neck-trunk

The *viewing distance* was significantly affected by the working height (table 6.7). The distance for working height −20cm was significantly shorter than for working heights +20cm and +10cm. For the range of working heights tested the majority of the subjects show a linear relationship between *gaze inclination* and head inclination for-/backwards with high correlation (table 6.8). For each subject, table 6.8 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*, as well as *neck flexion* are significantly affected by the working height (figure 6.5). It turned out, however, that at working heights below 0cm the head inclination forwards is relatively constant (figure 6.5a). Furthermore, above working height 0cm neck flexion is relatively constant (figure 6.5c), i.e. head and trunk incline for-/backwards at about the same rate (figure 6.5a/b).

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in table 6.9 (refer also to figures 6.6b and 6.7b).

6.3.2.2 *Right upper extremity*

The *manipulation distance* is not affected by the working height (table 6.7). On average, the manipulation distance was 38.9 cm. The *horizontal manipulation distance* is significantly affected by the working height (table 6.7). The horizontal manipulation distance for working heights +20cm and +10cm were significantly greater than for working heights -10cm and -20cm.

Upper arm elevation for-/backwards is significantly affected by the working height (figure 6.8a). For working height +20cm the upper arm was significantly less elevated forwards than for all other working heights. For working height +10cm the upper arm was significantly less elevated forwards than for working heights -10cm and -20cm. *Upper arm elevation sidewards* is not affected by the working height (figure 6.8b). On average, the upper arm was elevated sidewards 34.1°.

Elbow flexion is not affected by the working height (figure 6.9). On average, the elbow was 93.4° flexed.

The *grip/wrist angle* is significantly affected by the working height (figure 6.10). However, at working heights below 0cm as well as above +10cm 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 6.9 (refer also to figures 6.6b and 6.7b).

6.3.2.3 *Workers' integral perceptions*

Effects on *workers' integral perceptions* are summarized in table 6.9 (refer also to figures 6.11 and 6.12).

6.3.3 Grinding

6.3.3.1 *Vision and head-neck-trunk*

The *viewing distance* was significantly affected by the working height (table 6.7). On average, the distance increased by 7.6 cm for each 10cm the working height was lowered, until working height -35cm was reached. For the range of working heights tested the majority of the subjects show a linear relationship between *gaze inclination* and head inclination for-/backwards with moderate or high correlation (table 6.8). For each subject, table 6.8 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 6.5a/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 -35cm 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 6.5c), because the head and the trunk do incline for-/backwards at about the same rate.

Effects on *workers' localized physical perceptions* with respect to the head, neck, and trunk are summarized in table 6.9 (refer also to figures 6.6c and 6.7c).

6.3.3.2 *Right upper extremity*

The *manipulation distance* and the *horizontal manipulation distance* are significantly affected by the working height (table 6.7). All pairwise comparisons of working heights on manipulation distance disclosed significant differences, except for working height -45cm versus working height -35cm, and working height -15cm versus working height -5cm ($p > .10$ 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 6.8a). For working height -5cm the upper arm was significantly less elevated forwards than for working heights -45cm, -35cm, and -25cm. *Upper arm elevation sidewards* is significantly affected by the working height (figure 6.8b). Elevation sidewards for working height -5cm differed significantly from the elevation sidewards for all other working heights. Elevation sidewards for working height -15cm differed from the elevation sidewards for working heights -25cm ($p = .06$), -35cm (significant), and -45cm (significant). Elevation sidewards for working height -25cm differed significantly from the elevation sidewards for working height -45cm.

Elbow flexion is significantly affected by the working height (figure 6.9). All pairwise comparisons of working heights disclosed significant differences, except for working height -5cm versus working height -15cm, and working height -15cm versus working height -25cm ($p > .10$ for both comparisons).

The *grip/wrist angle* is significantly affected by the working height (figure 6.10). However, at working heights above -25cm 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 6.9 (refer also to figures 6.6c and 6.7c).

6.3.3.3 Workers' integral perceptions

Effects on *workers' integral perceptions* are summarized in table 6.9 (refer also to figures 6.11 and 6.12).

6.4 Discussion

6.4.1 Head-neck-trunk posture

Nakaseko *et al.* (1993) 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 (refer also to chapter 5). Figures 6.5a and 6.5b and video recordings indicated that for pneumatic wrenching and for grinding (working height -35cm and upwards) the trunk inclination for-/backwards measured originates from the for-/backward inclination of its thoracic region. On the basis of the above 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, while 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 = trunk inclination for-/backwards. The close relationship between head inclination for-/backwards and trunk inclination for-/backwards is reflected by the workers' perceptions, i.e. the perceptions of the neck and back posture are tightly connected (figures 6.6a and 6.6c).

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 6.5b). That is, in particular for working heights -20cm, -10cm, and 0cm, where the left upper arm almost vertical, i.e. an elevation of about 10° (Dul *et al.*, 1991). At the lowest experimental working height, i.e. -20cm, 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 § 6.4.2), led to a very small neck flexion (close to extension), which is known to be a relatively unfavourable posture of the neck (refer to chapter 5). 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 6.5c), 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 seven subjects were the same (table 6.8; i.e. subjects 8 and 10–15). At maximum the group averages for these seven subjects were 29.1° for oxy-gas cutting (working height +20cm), and 36.0° for grinding (working height -45cm). One reason for the difference seems to be that during oxy-gas cutting at higher working heights (i.e. 10 cm 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.

6.4.2 Vision

6.4.2.1 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 subjects show a linear relationship with moderate or high correlation (table 6.8). For each operation, however, this relationship differs among individuals considerably (table 6.8; 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 subject groups involved in pneumatic wrenching, oxy-gas cutting, and grinding, respectively) and/or based on too small a number of data pairs (i.e. 5), 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, i.e. -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, i.e. about 55–60% (average group score). The actual contribution of head inclination for-/backwards to gaze inclination for subjects 2, 3, 5, and 7 match with the range obtained from the data presented by Brues, while the figures for the other three subjects are slightly to somewhat higher (table 6.8; parameter H/G). The actual contribution of head inclination for-/backwards to gaze inclination for subjects 2, 3, and 4 matches with the range obtained from the data by Conrady and colleagues, while the actual contribution is slightly lower for subjects 5 and 7, and somewhat higher for subjects 1 and 6.

At the range of gaze inclinations measured for grinding, i.e. -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 subjects 10 and 12 match with the range obtained from the data presented by Brues, while the figures for the subjects 8, 10, and 13-15 are slightly to somewhat higher (table 6.8; parameter H/G). Video observations suggested that the relatively high contribution of head inclination for-/backwards at subject 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, i.e. -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 eight subjects show a considerably higher contribution (table 6.8; parameter H/G). For seven 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 subjects adjusted their dark glasses (figure 6.13) while standing with the head and trunk upright, as about the reference posture. Subjects 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 6.13). That is, because the glasses were designed for work at a smelting-furnace, demanding an upwardly directed gaze. According to the subjects, 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 subjects 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 6.8; 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 near by.

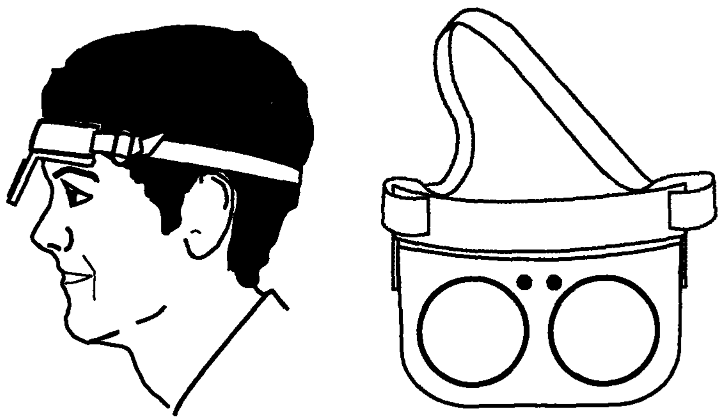

Figure 6.13 The dark glasses worn during oxy-gas cutting.

6.4.2.2 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 6.7). 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 and/or the trunk get more upright (figure 6.5a/b). The notion that the viewing distance is a result of the head inclination for-/backwards (refer also to § 6.4.2.1) and/or of the trunk inclination for-/backwards is supported by data on sewing machine operation (chapter 4), touch-typing VDU operation (chapter 5), 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 6.7).

6.4.3 Right upper extremity posture

6.4.3.1 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 6.7). 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 6.3) 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 6.7; refer also to figure 6.9 for the constant elbow flexion). So, it can be concluded that the manipulation distance is a determinant of working posture.

6.4.3.2 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 6.10). This leaves unexplained why the upper arm is less elevated forwards for working height +20cm than for all other working heights (figure 6.8a). 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 6.8a and 6.8b), 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 +20cm (figure 6.10). At the same time, the upper arm elevation forwards is reduced (figure 6.8a), supporting the hypothesis described before. Remarkably, the postural effects at working height +20cm show a strong resemblance to pneumatic wrenching, i.e. a maximum or nearly maximum grip/wrist angle (figure 6.10), almost zero upper arm elevation for-/backwards (figure 6.8a), and a slightly increased upper arm elevation sidewards (figure 6.8b).

For grinding the right grip/wrist angle seems to have reached a maximum at working heights -25cm and higher (figure 6.10). At the same time, in particular upper arm elevation forwards is reduced (figure 6.8a), supporting the hypothesis described before.

Comparing figures 6.8a and 6.8b, 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 +20cm was found to be worse than for the optimum working height -10cm (table 6.9; effect approaching significance). The small upper arm elevation measured, which was also about the same for all heights (Dul *et al.*, 1991; figure 6.8), 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, i.e. the upper arm approaches a shoulder retroflexion position, because upper arm elevation for-/backwards gets close to zero (figure 6.8b), while the trunk is about upright (figure 6.5b).

For oxy-gas cutting the perceived posture of the upper arm for working heights +10cm and +20cm was found to be worse than for the optimum working height 0cm (table 6.9; 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 6.8). 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, i.e. for working height +20cm in particular the upper arm is close to a shoulder retroflexion position, because upper arm elevation backwards (figure 6.8a) and trunk inclination forwards (figure 6.5b) are about equal. Furthermore, for oxy-gas cutting it was found that the perceived posture of the upper arm for working height -20cm significantly worse than for the optimum working height 0cm (table 6.9). No such result was found for working height -10cm. Because the upper arm elevation was the same for working heights -20cm and -10cm (figure 6.8), elevation itself is not a likely explanation for the workers' perceptions relating to working height -20cm. The fact that the rather great angle between the upper arm and the trunk at working height -10cm (that is mainly shoulder flexion, defined as the sum of upper arm elevation forwards and trunk inclination forwards) gets even greater at working height -20cm (cf. figures 6.8 and 6.5b), points at this parameter for being a reasonable explanation.

For grinding the perceived posture of the upper arm for working heights -15cm and -5cm was found to be worse than for the optimum working height -35cm (table 6.9; both effects approaching significance). Basically, these results can be explained by the greater upper arm elevation (Dul *et al.*, 1991; figure 6.8) as well as by the position of the upper arm with respect to the trunk, i.e. the upper arm approaches or has reached a shoulder retroflexion position, because the upper arm is elevated backwards (figure 6.8a), 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/or 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.

6.4.4 What determines neck load?

Two potential determinants of neck load were studied, i.e. 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 subjects who gave a score ≤ 3 is greater than the number of subjects who gave a score ≥ 5) and unfavourable working heights (i.e. the number of subjects who gave a score ≥ 5 is greater than the number of subjects who gave a score ≤ 3). On the basis of this classification for pneumatic wrenching working height -20cm (figure 6.6a) is unfavourable (refer also to table 6.9), while all other heights are favourable; for oxy-gas cutting (figure 6.6b) working height +20cm is unfavourable, working heights +10cm, 0cm, and -10cm are favourable, and working height -20cm is ambiguous (three subjects gave score of 3, two gave score of 4, and three gave score of 5); for grinding (figure 6.6c) working height -45cm is unfavourable, while all other heights are favourable.

At the favourable working heights mentioned above the head is inclined forwards, i.e. average inclinations roughly between 20° and 60° (figure 6.5a). This range does not match the most favourable head inclinations suggested in the literature, i.e. less than 15° inclined forwards (Chaffin, 1973) or even inclined backwards (De Wall *et al.*, 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 set-up (5 minutes of operation) a working height only tends to be unfavourable at a rather great amount of head inclination forwards (refer to figures 6.5a and 6.6, 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 6.5a), would always have to be relatively favourable. However, then the fact that for oxy-gas cutting working height +20cm is most unfavourable (one subject gave score of 3, two subjects score of 4, and five subjects 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 (-20cm for pneumatic wrenching, +20cm for oxy-gas cutting, and -45cm for grinding) a relatively unfavourable, extremely flexed, neck posture seems to be reached (figure 6.5c). Neck flexion/extension also does seem to explain the ambiguous result for working height −20cm 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 (refer to chapter 5). From the above 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 above 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, i.e. 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 −20cm as well as for grinding at the relatively unfavourable working height −45cm 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 6.8). Also, no clearly unfavourable workers' perceptions for the shoulder/upper arm region were found (figures 6.6a and 6.6c). 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 +20cm the relatively unfavourable perceptions for the upper arm posture (§ 6.4.3.2) may have had an effect on perceptions for the neck.

6.5 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.

6.5.1 Pneumatic wrenching

Only very few significant effects of working height (or effects approaching significance) were found (table 6.9). Nevertheless, the results on estimated endurance time indicate a working height range between -10cm to +10cm for recommendation (figure 6.11). The judgements on working heights -10cm and 0cm were closest to the qualification 'right', i.e. tending to qualifications 'a little too low' and 'a little too high', respectively (figure 6.12). Results on postural discomfort of the whole body disfavour working height 0cm (figure 6.7a), in addition to disfavouring working heights -20cm and +20cm. For working height -20cm the neck posture was found to be significantly more unfavourable than for its particular optimum working height (table 6.9). This localized physical perception is supported by the results on working posture (§ 6.4.4). For working height +20cm the right upper arm posture was found to be more unfavourable than for its particular optimum working height (table 6.9; effect approaching significance). This localized physical perception is supported by the results on working posture (§ 6.4.3.2). 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 +20cm for recommendation. Nevertheless, it is considered best not to recommend this height, because judgements of all subjects 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 cm below to 10 cm above elbow height, a working height of 5 to 10 cm below elbow height is to be preferred.

6.5.2 Oxy-gas cutting

The results on estimated endurance time and postural discomfort of the whole body indicate a working height between -10cm and +10cm for recommendation (figures 6.11 and 6.7b, respectively). The judgement on working height 0cm was closest to the qualification 'right'. The judgements on working heights -10cm and +10cm were given qualifications 'a little too low' and 'a little too high' respectively. For working heights -20cm and +20cm quite a number of variables disclosed that localized physical perceptions were significantly worse than for their particular optimum working height (table 6.9). These perceptions are supported by the results on working posture of the related body segments and joints (figures 6.5, 6.8, and 6.10; refer also to §§ 6.4.3.2 and 6.4.4). 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 -10cm and +10cm should not be excluded for recommendation. Here, it was considered best to do so, but also to emphasize a preference for working height 0cm, because for working height -10cm the judgements of a majority of subjects (5 out of 8) were either 'much too low' or 'a little too low', whereas for working height +10cm judgements of a majority of subjects (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.

6.5.3 Grinding

The results on estimated endurance time and postural discomfort of the whole body show that -35cm is the optimum, i.e. most favourable, working height (figures 6.11 and 6.7c, respectively). The judgements on working heights -35cm and -25cm were closest to the qualification 'right', i.e. tending to qualifications 'a little too low' and 'a little too high', respectively (figure 6.12). Working heights -25cm and upwards led to significantly worse workers' perceptions for the right upper extremity than lower working heights (table 6.9). These localized physical perceptions are supported by the results on working posture (figures 6.8 and 6.10; refer also to § 6.4.3.2). Working height -45cm led to significantly worse workers' perceptions for the neck and back than working heights -25cm and higher (table 6.9). These localized physical perceptions are supported by the results on working posture (figure 6.5; refer also to § 6.4.4). The results discussed above lead to the conclusion that a working height 35 cm below elbow height, i.e. approximately knuckle height for the subjects involved, is recommended.

6.6 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*) and/or the position of the operation switch (*grinding*);
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 cm below and 10 cm above elbow height is recommended, while 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, while a working height range between 10 cm below and 10 cm above elbow height is recommended;
12 for *grinding* a working height 35 cm below elbow height, i.e. approximately knuckle height, is recommended.

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Chapter 7

Press operation
Workstation adjustment, working posture, and workers' perceptions

At a press workstation industrial workers processed light-weight objects at six different combined adjustments of reach distance and working height. Working posture, workers' perceptions, and task performance were measured. Two guidelines were formulated in order to minimize the load on the musculoskeletal system, i.e. (1) the maximum reach distance is not exceeded if the object (held the same way as during actual task execution) can be placed in the stamp on the press as well as be removed without bending the trunk forward, and (2) the working height, i.e. the height of the hands when placing the object in the stamp and when removing it, should be adjusted between 5 and 10 cm above elbow height. Data from the present experiment as well as from the 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. During press operation the working posture was determined by a maximum reach position of the hands with respect to the upper trunk, most probably guided by the intention to stay away from relatively unfavourable upper extremity joint positions. Furthermore, it turned out that visual interference is a postural constraint. The position of the upper arm with respect to the trunk, that is shoulder flexion in particular, seems to be a dominant determinant of shoulder and shoulder girdle load, as compared to upper arm elevation. Both parameters are to be considered in future research.

7.1 Introduction

In the metal industry presses are used for forming objects (e.g. plates), as well as for cutting off superfluous material. The shape arrived at depends on the stamp used. Usually an operator has to reach forward considerably in order to place an object into the stamp, as well as to take it out after the press action. Furthermore, very often awkward working postures exist due to an inadequate working height. In order to optimize working posture and minimize the number of musculoskeletal complaints, quantitative ergonomic guidelines on maximum reach distance and optimum, i.e. most favourable, working height are needed. Current guidelines in ergonomic handbooks (e.g. Burandt, 1978; Clark and Corlett, 1984; Eastman Kodak Company, 1984;

Grandjean, 1988) are of a very general nature. Regarding reach distance the sources studied show the spatial positions that can be reached with an upright trunk and without excessive forward movement of the shoulder girdle (i.e. a comfortable full arm reach). Sometimes for frequent reaching it is recommended that these anthropometry-based zones or envelopes are reduced to somewhere between about half and full arm reach. For precision work mostly 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.

This study on press operation 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 the workstation, i.e. reach distance and 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 and Bishop, 1976). The *first* purpose of the paper is to study determinants of working posture (§ 7.1.1), as well as relationships between working posture and workers' perceptions (§ 7.1.3) for the sake of comparison with other visual-manual operations and generalization. The *second* purpose is to formulate ergonomic guidelines for adjustment (and redesign) of press workstations (§ 7.1.2). Matters of work organization (e.g. shift length, work-rest schedule), as well as other aspects of workstation adjustment (e.g. positions of boxes containing the objects before and after the press action) are recognized as major determinants of musculoskeletal complaints, but will not be a subject of study in this paper.

Table 7.1 Hypothetical determinants of working posture.

- Gaze inclination
- Viewing distance
- Visual interference
- - Manipulation distance
  - Horizontal manipulation distance
- Grip

7.1.1 Determinants of working posture

Table 7.1 contains hypothetical determinants of working posture, where a determinant is defined as a constraint as regards posture selection by the operator involved. Firstly, it is hypothesized that at press operation 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 at other operations and tasks (Brues, 1946; Conrady *et al.*, 1987; Straumann *et al.*, 1991; chapters 4-6).

Secondly, it is hypothesized that a worker will try to retain a favourable reach position of the hand(s) with respect to the upper trunk (*manipulation distance*). Due to the weight of the upper extremities and the object, this postural behaviour may be guided 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), or by an optimization of the upper extremity joint positions (i.e. an optimization of the manipulation distance).

In addition, several other hypothetical determinants may be active depending on particular characteristics of work situation. For instance, in the case of high visual demands, a worker may try to retain a favourable *viewing distance* from the object. Also the working posture may be determined by *visual interference* (e.g. by the upper part of the stamp) or by the *grip* of the object required.

7.1.2 Formulation of guidelines

At the standardized research approach mentioned before, professional workers execute an operation at various adjustments of their workstation. Several variables relating 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. 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 and 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 (that is, can be explained by) objective information. In principle, the remaining (best) experimental *conditions constitute the guideline.*

Task performance is measured in order to check whether better workers' perceptions (and working posture) for particular experimental conditions as compared to any others possibly came into being at the cost of task performance. If experimental conditions are recommended and the accompanying task performance measured is worse than for the majority of the other experimental conditions, the worse task performance result will be mentioned in the guideline formulated.

7.1.3 Working posture versus workers' perceptions

The posture of the head and/or neck segment in the sagittal plane is mostly evaluated in terms of musculoskeletal load by the amount of deviation from the upright posture or the vertical, i.e. head/neck inclination for-/backwards (e.g. Chaffin, 1973; Hünting *et al.*, 1980;1981; Kilbom *et al.*, 1986; Lee *et al.*, 1986; Snijders *et al.*, 1991; Lindberg *et al.*, 1993). 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, i.e. 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 and Hagberg, 1984; Lepoutre *et al.*, 1986; Schüldt *et al.*, 1986a;1986b; Harms-Ringdahl and Schüldt, 1988; Kumar, 1994; chapters 4-6). 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, i.e. 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, i.e. upper arm elevation (e.g. Chaffin, 1973; Bjelle *et al.*, 1979;1981; Dul, 1988; Van der Grinten and 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 above). In addition, the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively), may play a role with respect to shoulder (girdle) load (Kilbom *et* *al.*, 1986; Mital and Faard, 1990; Jensen, 1991; Aarås, 1994). 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, i.e. trunk inclination for-/backwards (e.g. Jørgensen, 1970; Wickstrom *et al.*, 1988; Van der Grinten and Smitt, 1992; Aarås, 1994). 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 *et al.*, 1974; Andersson and Örtengren, 1974). Considering also that head/neck inclination for-/backwards affects thoracic spine curvature (Nakaseko *et al.*, 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.

7.2 Methods

On site, at a company producing coffee-machines, six sets of experimental conditions were tested. Test subjects worked for a certain amount of time under each set of conditions. Working posture, workers' perceptions, and task performance were measured.

7.2.1 Subjects

Eight males (average age 27.5 years, range 22–35; average stature 177.8 cm, range 168–189) participated in the experiment. They were familiar with press operation. None of them had received treatment or had been on sick-leave recently due to complaints of the musculoskeletal system.

7.2.2 Experimental task

The test subjects were asked to place metal plates (220 * 310 * 0.6 mm) flat into the stamp on the press, one at a time (the long side of the plate parallel to the front edge of the stamp and its centre at the fore/aft/left/right centre of the stamp and the press). Subjects visually guide this movement. That is, by looking at the front edge of the plate when it is about to get into the right position at the stamp. The press action made small edgings at all sides of the plates. Plates were taken from a table to the left of the subject and put on a table to the right after the press action. The table surfaces (sized slightly bigger than the plates) were positioned at about the height of the plate when lying in the stamp. The press was put into action by a hand switch, positioned to the right of the subject. Left/right and fore/aft positioning of the tables and the hand switch as well as the height of the hand switch were left up to the subject. Subjects were instructed to process as many plates as possible, but to work at the same pace under all sets of experimental conditions tested.

7.2.3 Independent variables

The six sets of experimental conditions consisted of different combinations of reach distance and working height. Reach distance was defined as the fore/aft distance (i.e. along the X-axis of the coordinate system; refer to figure 7.1) between the shoulder top (table 7.2; location of M7) and the centre of the stamp on the press (denoted as centre of press or c.o.p.), with the subject using the buttock rest, having the trunk upright, the upper arms hanging down, and the forearms horizontal. Working height was defined as the distance between the floor and the plate within the stamp. At a working height equal to the individual elbow height, shoulder-c.o.p. fore/aft distances 70cm, 80cm, 90cm, and 100cm were tested. At a working height equal to the individual elbow height +10cm, shoulder-c.o.p. fore/aft distances 80cm and 90cm were tested. Elbow height was defined as the distance from the floor to the elbow (underside) with the subject using the buttock rest, having the trunk upright, the upper arms hanging down, and the forearms horizontal. The particular experimental conditions mentioned above were chosen on the basis of anthropometric data, as well as on the basis of the posture effects seen during a small pilot study.

7.2.4 Experimental procedure

Each subject worked in six experimental sessions of 25 minutes followed by breaks of 10 minutes. In each session one of the six sets of experimental conditions was presented. The experiment lasted half a day for each subject. The order of presentation of the sets of experimental conditions was balanced over subjects and sessions as well as possible.

The duration of an experimental session was chosen roughly in accordance with the average of continuous work periods seen during a normal working day (data acquired from the test subjects). It is assumed that the experimental results are valid for regular daily task execution, as workers' perceptions in terms of postural discomfort are linearly related to the duration of postures (refer to § 7.2.5, sub B). In other words, it is expected that the subjective differences to be found between particular workstation adjustments remain as they are if the duration of task execution is increased.

Experimental working heights were adjusted by raising or lowering the floor (i.e. by a scissor lift table). Prior to the first session the subject selected a comfortable adjustment of the buttock rest, which was kept constant during almost all sessions. In a few sessions the seat of the buttock rest had to be changed slightly, because the working height could not be realized by changing floor height only. During a session the shoulder-c.o.p. fore/aft distance tested was kept constant by regular checks on the position of the buttock rest with respect to a mark on the floor, as well as on the fore/aft position of the subject's buttocks with respect to the seat of the buttock rest.

7.2.5 Dependent variables and measurement techniques

Working posture and *vision characteristics* were measured by an opto-electronic VICON-system. Retro-reflective markers were put on the skin overlying selected body segments and joints, as well as on the press (table 7.2 and figure 7.1). Because of the symmetrical character of the posture while placing a plate in the stamp, only the left side of the head and the left upper extremity had markers. The three-dimensional positions of the markers were determined while the subjects were in a reference posture (using the buttock rest, trunk 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 set of experimental conditions.

Table 7.2 Markers; names and locations.

Marker	Name	Location
M1	eye	near the lateral corner
M2	ear	just ventrally of the lobe
M3	neck	intervertebral disc C7-T1
M4	low back	intervertebral disc L5-S1 (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	wrist	distal radio-ulnar joint, at the dorsal side
M10	visual target	at the front edge of the plate within the stamp, halfway the long side (location calculated from the location of M11)
M11	---	at the sides of the press, at the same X and Z coordinates as the centre of the plate within the stamp

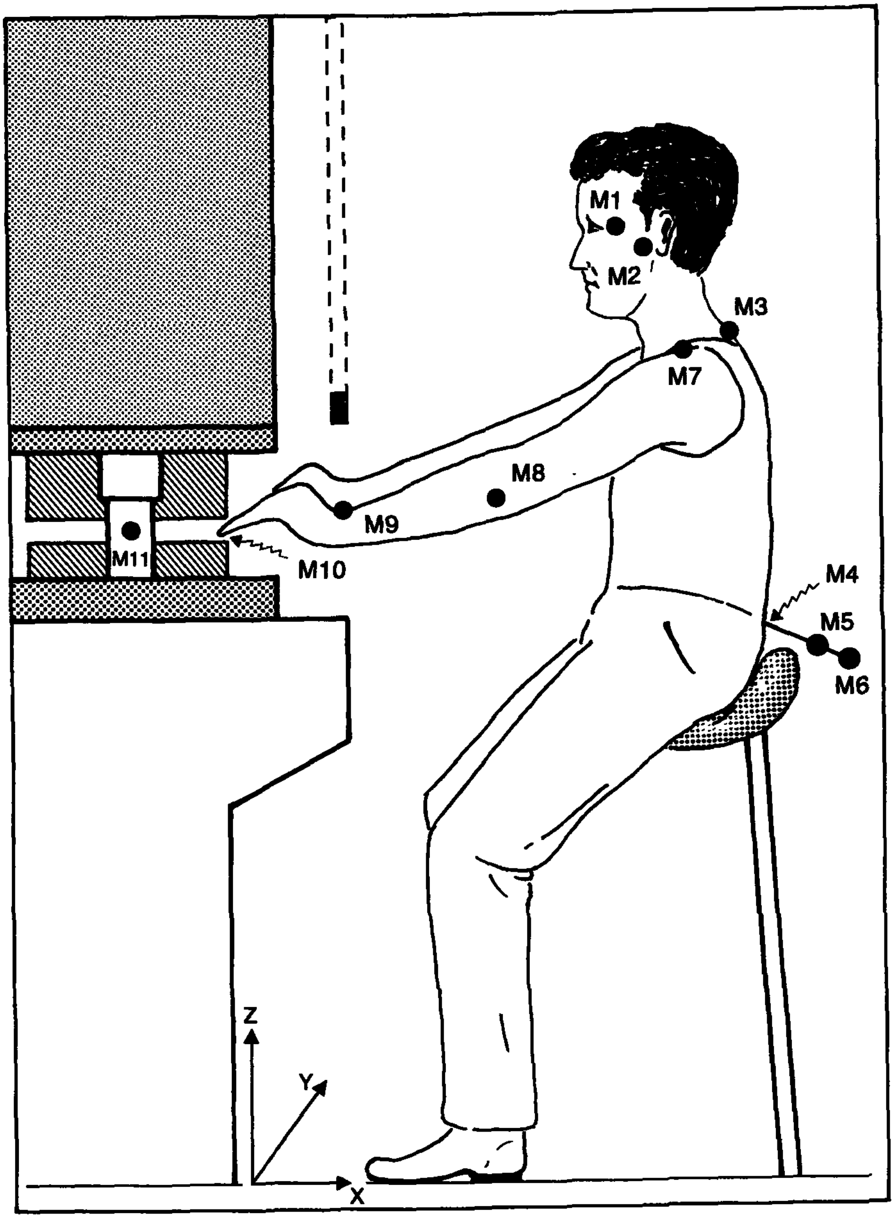

Figure 7.1 The marker positions for measurement of working posture and vision characteristics (refer also to table 7.2). The orthogonal axes shown represent the coordinate system used. The Y-axis is aligned parallel to the front edge of the stamp and the press. The Z-axis is vertical. The YZ-plane corresponds to the frontal plane of the subject's body. The XZ-plane corresponds to the sagittal plane of the subject's body.

Table 7.3 Working posture and vision; names and definitions of dependent variables (refer also to table 7.2 and figure 7.1).

Name	Definition
Viewing distance	distance between M1 and M10, projected in the XZ-plane
Gaze inclination	angle between the horizontal and the line M1-M10, projected in the XZ-plane (a negative value means the subject looks downward)
Head inclination for-/backwards	angle between the line M1-M2 during operation and the line M1-M2 in the reference posture, projected in the XZ-plane (a negative value means the head is inclined forwards)
Trunk inclination for-/backwards	angle between the line M3-M4 during operation and the line M3-M4 in the reference posture (a positive value means the trunk is inclined forwards)
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 along the X-axis of the coordinate system
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 (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 (a positive value means the upper arm is elevated outwards)
Elbow flexion	angle between the lines M7-M8 and M8-M9 during operation minus this angle in the reference posture
Forearm inclination	angle between the line M8-M9 and the horizontal, projected in the XZ-plane (a positive value, i.e. M9 has a higher Z-coordinate than M8, means that the forearm is inclined upward; it should recognized that the line M7-M8 may not exactly match the long axis of the forearm)

On the basis of the marker positions various dependent variables with respect to vision, head-neck-trunk, and upper extremities were calculated (table 7.3). In accordance with the hypothetical effects of reach distance and working height, most of these dependent variables describe the sagittal plane posture. For data analysis average scores on 2 measurements done between 15 and 20 minutes after the beginning of each experimental session were used. Measurement was restricted to the time period that the plate was positioned at the stamp on the press, i.e. the posture at the end position of reach.

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, that may be matched directly with working posture variables. The modules 'Estimated endurance time' and 'Judgement on workstation adjustment' focus on integral responses. The modules (A–D) and the dependent variables are described below.

A Perceived posture

The subject was asked to rate his perception of the posture of the head, neck, back, left shoulder, right shoulder, left upper arm, and right upper arm. Directly after the session a written response was given on a seven-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 seven body parts mentioned were used as dependent variables.

B Localized postural discomfort

The subject was asked to rate his postural discomfort in 40 regions shown on a diagram of the rear view of a human body (figure 7.2; modified after Corlett and Bishop, 1976), using a category-ratio scale by Borg (1982) ranging from 0 (no discomfort) to 10 (extreme discomfort, close to maximum) (Van der Grinten and Smitt, 1992). A written 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 7.4), guided by the information presented in the introduction (§ 7.1.3). Finally, an overall dependent variable was constructed, i.e. postural discomfort of the whole body, the sum of the resulting scores on all 40 body regions (table 7.4). 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 subjects reasonably linear relationships were found between gravitational load and discomfort in a body region (e.g. Boussenna *et al.*, 1982; Van der Grinten and Smitt, 1992), as well as between discomfort and the percentage of the maximum holding time for a posture (e.g. Manenica, 1986; Meijst *et al.*, 1995).

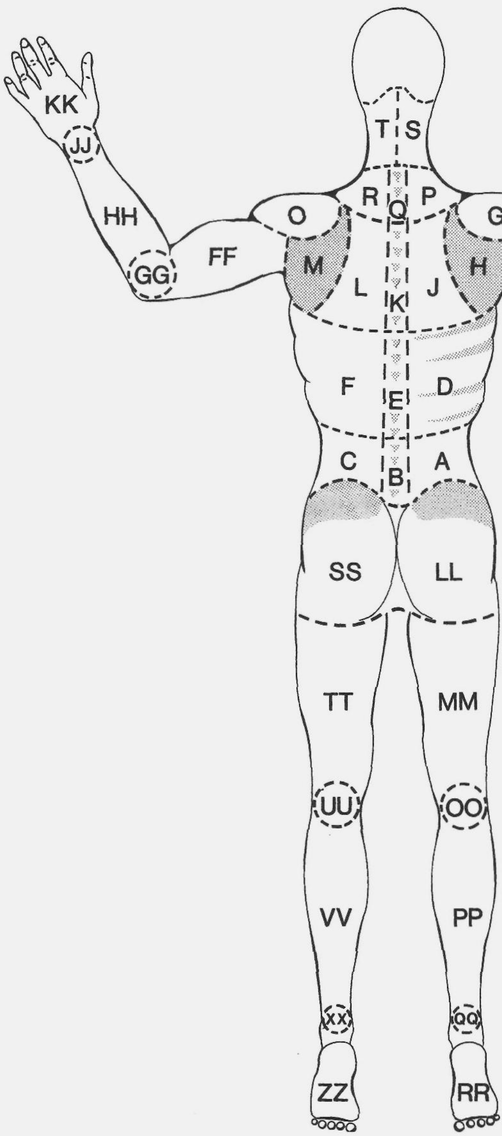

Figure 7.2 Diagram of the rear view of a human body, that was used in the questionnaire module on localized postural discomfort. Forty regions are distinguished.

Table 7.4 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/shoulders	T, S, R, Q, P, O, G
Left shoulder/arm	KK, JJ, HH, GG, FF, O, M
Right shoulder/arm	EE, DD, CC, BB, AA, G, H
Whole body	all 40 body regions

C *Estimated endurance time*

The subject was asked to estimate, on the basis of his perceptions, how much longer he could continue operation at the experimental workstation adjustment without difficulty. Directly after the session a written response was given on a five-point scale (1 = ½ working day (4 hours) to 1 working day (8 hours), 2 = 2 hours to ½ working day (4 hours), 3 = 1 to 2 hours, 4 = 25 minutes to 1 hour, 5 = less than 25 minutes). The estimated endurance time was used as a dependent variable.

D *Judgement on workstation adjustment*

Firstly, the subject was asked to judge the reach distance. Directly after the session a written response was given on a five-point scale (1 = much too small (i.e. too close), 2 = a little too small (i.e. too close), 3 = right, 4 = a little too large (i.e. too far away), and 5 = much too large (i.e. too far away)). Secondly, the subject was asked to judge the working height. Directly after the session a written response was given on a five-point scale (1 = much too low, 2 = a little too low, 3 = right, 4 = a little too high, and 5 = much too high). Finally, the subject was asked to judge the whole workstation adjustment. Directly after the session a written response was given on a seven-point scale (1 = very favourable, 3 = favourable, 5 = unfavourable, 7 = very unfavourable. Scores of 2, 4, and 6 were available for intermediate responses). The judgements on reach distance, working height, and the whole workstation adjustment were used as dependent variables. For part of the statistical analyses (§ 7.2.6, paired comparisons of sets of experimental conditions) the actual scores on reach distance and working height given were converted, i.e. 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).

Task performance was measured by the number of metal plates processed. The number of plates was used as a dependent variable.

7.2.6 Data analysis

On the basis of the literature described in § 7.2.5 (at 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, vision, and task performance were analysed by parametric statistical tests. Data on dependent variables with respect to perceived posture, estimated endurance time, and judgement on workstation adjustment were analysed by non-parametric (distribution-free) statistical tests, due to the ordinal character of the scales used.

The main effect of shoulder-c.o.p. fore/aft distance (70cm, 80cm, 90cm, and 100cm at a working height equal to elbow height) on variables relating to working posture, vision, and task performance, as well as on the variables relating to localized postural discomfort was tested by an Analysis of Variance (ANOVA) for Repeated Measures (4 * 1 design). Furthermore, the main and interaction effects of shoulder-c.o.p. fore/aft distance (80cm and 90cm) and working height (elbow height and elbow height +10cm) on the variables mentioned above were tested by an Analysis of Variance (ANOVA) for Repeated Measures (2 * 2 design). Differences between sets of experimental conditions were tested by a post-hoc Tukey test (paired comparisons).

The effect of shoulder-c.o.p. fore/aft distance (70cm, 80cm, 90cm, and 100cm at a working height equal to elbow height) on the variables relating to perceived posture, estimated endurance time, and judgement on workstation adjustment was tested by a Friedman test. Differences between shoulder-c.o.p. fore/aft distances were tested by a Wilcoxon Matched-pairs Signed-ranks Test (paired comparisons). The effect of working height on the variables mentioned above was tested at shoulder-c.o.p. fore/aft distance 80cm as well as at shoulder-c.o.p. fore/aft distance 90cm by a Wilcoxon Matched-pairs Signed-ranks Test (paired comparisons). Paired comparisons at the variables 'judgement on reach distance' and 'judgement on working height' were done on the basis of converted scores (§ 7.2.5, sub D).

The selected level of significance in all tests was $p=.05$ (two-tailed). The description of the results (refer below) will be focussed on significant (combined) effects of shoulder-c.o.p. fore/aft distance and 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 ≥.8660 (i.e. R^2≥.75), as moderate if ≥.7071 and <.8660 (i.e. .50≤R^2<.75), and as low if <.7071 (i.e. R^2<.50).

7.3 Results

§ 7.3.1 contains results for working posture and related workers' localized physical perceptions on vision and head-neck-trunk. In § 7.3.2 working posture and related workers' localized physical perceptions on the upper extremities will be described. In §§ 7.3.3 and 7.3.4 workers' integral perceptions and task performance are presented, respectively.

7.3.1 Vision and head-neck-trunk

7.3.1.1 Viewing distance

At a working height at elbow height the viewing distances for shoulder-c.o.p. fore/aft distances 70 cm and 80 cm were significantly different from the viewing distances for shoulder-c.o.p. fore/aft distances 90 cm and 100 cm (table 7.5). Furthermore, at shoulder-c.o.p. fore/aft distance 80 cm the viewing distances for both working heights differed significantly (table 7.5).

Table 7.5 Viewing distance (VD, cm), manipulation distance (MD, cm), and horizontal manipulation distance (HMD, cm) as a function of working height and shoulder-c.o.p. fore/aft distance (average group scores).

Working height		Shoulder-c.o.p. fore/aft distance			
		70cm	80cm	90cm	100cm
+10cm	VD	---	60.5	60.2	---
	MD	---	75.5	75.3	---
	HMD	---	68.3	68.1	---
0cm	VD	64.7	64.0	57.6	56.6
	MD	74.6	76.2	76.5	75.0
	HMD	62.1	63.5	64.3	63.8

7.3.1.2 Gaze inclination

Within the range of experimental conditions the majority of the subjects show a linear relationship between gaze inclination and head inclination for-/backwards with low correlation (table 7.6). Figure 7.3 shows the 48 data pairs (8 subjects * 6 sets of experimental conditions).

Table 7.6 Head inclination for-/backwards versus gaze inclination for individual subject. Head inclination for-/backwards = A * gaze inclination + B (where n = 6 sets of experimental conditions); #: number of subject; r: Pearson correlation coefficient. Range of gaze inclinations measured: -29.6° to -52.1°.

#	A	B	r
1	-.78	-61.42	-.29
2	-1.06	-91.46	-.48
3	-2.18	-125.37	-.92
4	-.60	-56.97	-.43
5	.56	13.14	.32
6	-1.69	-113.05	-.63
7	-2.45	-143.99	-.83
8	-.78	-59.70	-.22

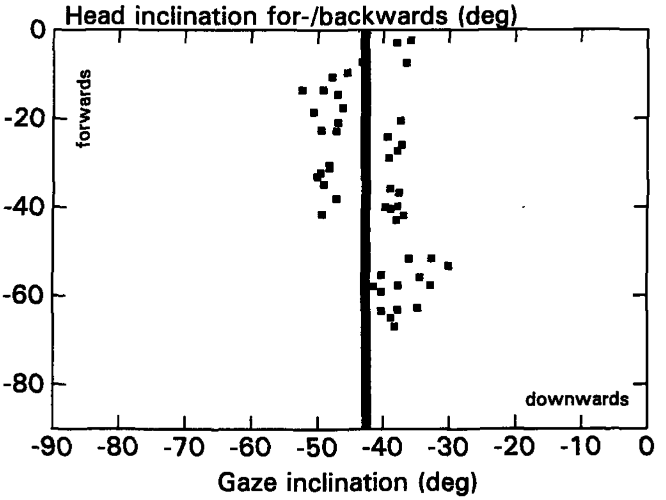

Figure 7.3 Gaze inclination versus head inclination for-/backwards (48 data pairs, i.e. 8 subjects * 6 sets of experimental conditions).

7.3.1.3 Head inclination for-/backwards

At a working height at elbow height the head inclination for-/backwards for shoulder-c.o.p. fore/aft distances 70cm and 80cm were significantly different from the head inclination for-/backwards for shoulder-c.o.p. fore/aft distances 90cm and 100cm (figure 7.4a; p=.08 for distances 80cm and 100cm). Furthermore, at shoulder-c.o.p. fore/aft distance 90cm the head inclinations for-/backwards for both working heights differed significantly (figure 7.4a).

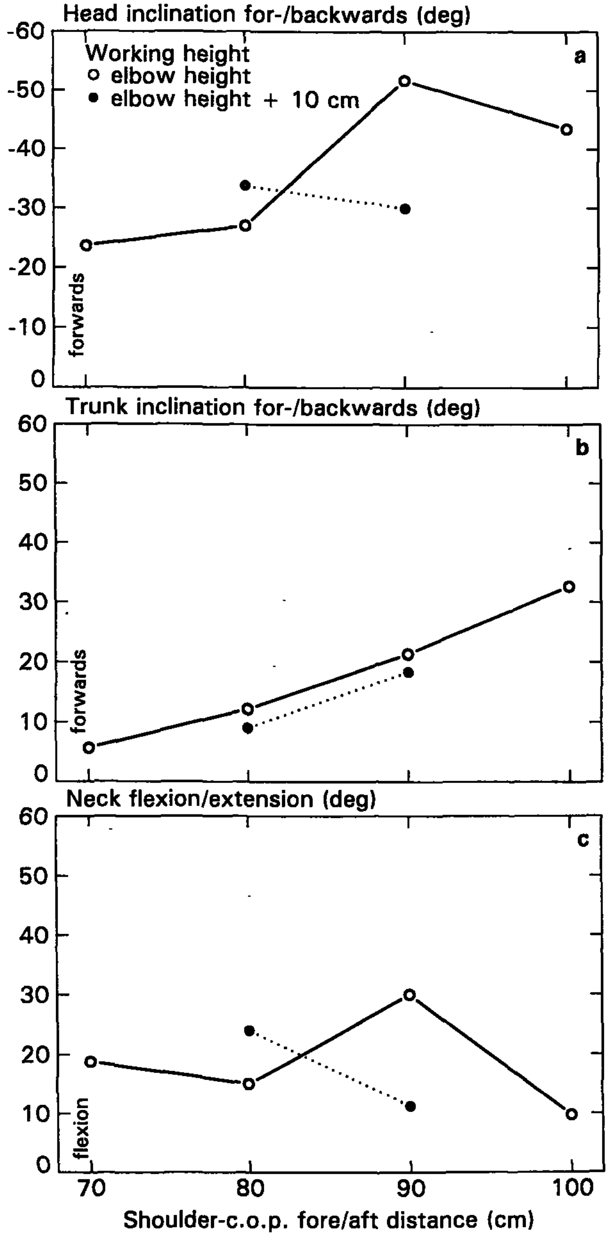

Figure 7.4 Head inclination for-/backwards (a), trunk inclination for-/backwards (b), and neck flexion/extension (c) versus experimental conditions (average group scores).

7.3.1.4 Trunk inclination for-/backwards

Trunk inclination for-/backwards is significantly affected by the shoulder-c.o.p. fore/aft distance (figure 7.4b). On average, a 10 cm increase of the shoulder-c.o.p. fore/aft distance caused the trunk to incline forward by 9.0°. Trunk inclination for-/backwards differed between both working heights (figure 7.4b; p=.053).

7.3.1.5 *Neck flexion/extension*

At a working height at elbow height the neck flexion for the shoulder-c.o.p. fore/aft distance 90cm was significantly different from the neck flexion for the shoulder-c.o.p. fore/aft distance 100cm (figure 7.4c). At the shoulder-c.o.p. fore/aft distance 90cm the neck flexion differed between both working heights (figure 7.4c; p=.08).

Table 7.7 Workers' physical perceptions; worse results (p<.10) for various shoulder-c.o.p. fore/aft distances with respect to the shoulder-c.o.p. fore/aft distance showing the best result for the particular variable, i.e. the optimum (most favourable) shoulder-c.o.p. fore/aft distance. p.p. = perceived posture, p.d. = postural discomfort. Example: at a working height at elbow height (0cm) the perceived posture of the back for the shoulder-c.o.p. fore/aft distance 90cm is significantly worse than for its optimum shoulder-c.o.p. fore/aft distance (70cm).

Shoulder -c.o.p. fore/aft distance	Working height	Significant effects	Effects approaching significance	Optimum (most favourable) shoulder-c.o.p. fore/aft distance for dependent variable
70cm	0cm	---	---	
80cm	0cm	---	---	
90cm	0cm	p.p. back	judg. wh. workst. adj. (p=.09)	70cm
		p.d. back		70cm
		p.d. neck/back		70cm
		judg. reach dist.		80cm
100cm	0cm	p.p. back	judg. wh. workst. adj. (p=.09)	70cm
		---	p.d. back (p=.07)	70cm
		---	p.d. neck/back (p=.052)	70cm
		judg. reach dist.		80cm
80cm	+10cm	---	---	
90cm	+10cm	p.p. back	p.p. back (p=.07)	80cm
		p.p. neck	judg. reach dist. (p=.07)	80cm
		p.d. back	judg. wh. workst. adj. (p=.09)	80cm
		p.d. neck/back		80cm

7.3.1.6 Workers' perceptions

Effects on workers' localized physical perceptions with respect to the head-neck-trunk as well as on postural discomfort of the whole body are summarized in tables 7.7 and 7.8. Figure 7.5 shows the perceived postures of the neck and the back. The results on the perceived postures of the head are not shown due to the very strong resemblance to the results on perceived postures of the neck. Figure 7.6 shows the postural discomfort in the neck/back. Most discomfort was located at the low and middle back (figure 7.2, body regions A–F), far less at the upper back (figure 7.2, body regions J–L), hardly any at the lower neck (figure 7.2, body regions P–R), and none at the upper neck (figure 7.2, body regions S and T). The results on postural discomfort in the back are not shown due to the very strong resemblance to the results on postural discomfort in the neck/back.

Table 7.8 Workers' perceptions; differences between both working heights ($p<.10$). p.p. = perceived posture, p.d. = postural discomfort. Example: at a shoulder–c.o.p. fore/aft distance 80cm the perceived posture of the back for the working height at elbow height (0cm) is worse than for its optimum working height (elbow height +10cm).

Shoulder –c.o.p. fore/aft distance	Significant effects	Effects approaching significance	Optimum (most favourable) working height for dependent variable
80cm	p.p. head	p.p. back (p=.07)	+10cm
	p.p. neck	p.d. back (p=.07)	+10cm
	p.d. whole body	p.d. neck/back (p=.07)	+10cm
	judg. work. hght.	judg. wh. workst. adj. (p=.07)	+10cm
90cm	p.d. whole body	p.d. back (p=.07)	+10cm
		p.d. neck/back (p=.07)	+10cm
		judg. work. hght. (p=.07)	+10cm

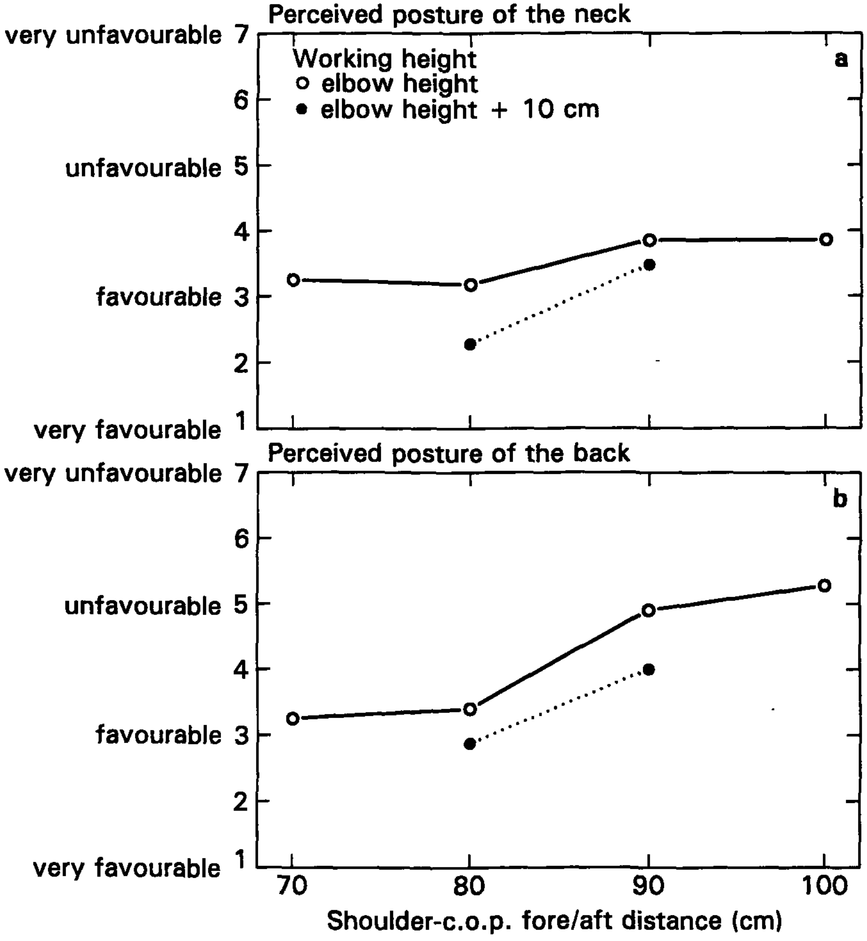

Figure 7.5 Perceived posture of the neck (a) and back (b) versus experimental conditions (average group scores).

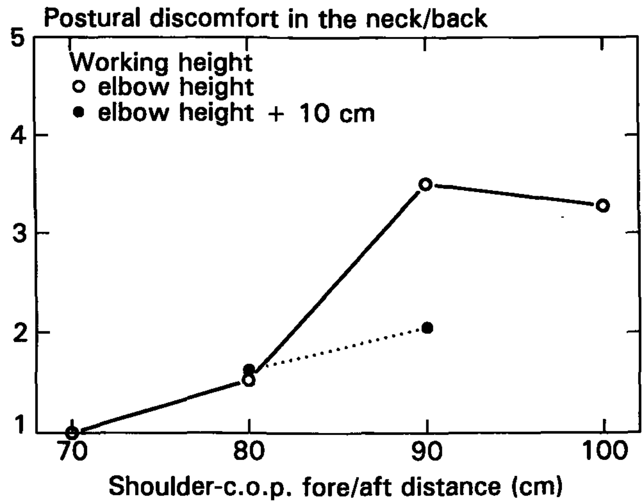

Figure 7.6 Postural discomfort in the neck/back versus experimental conditions (average group scores).

7.3.2 Upper extremities

7.3.2.1 Manipulation distance

At a working height at elbow height the horizontal manipulation distance was affected by the shoulder-c.o.p. fore/aft distance (table 7.5; p=.06). For this working height the horizontal manipulation distance for shoulder-c.o.p. fore/aft distance 70cm was shorter than for shoulder-c.o.p. fore/aft distance 90cm (p=.0502). Furthermore, the horizontal manipulation distances for both working heights differed significantly (table 7.5). At a working height at elbow height the manipulation distance was affected by the shoulder-c.o.p. fore/aft distance (table 7.5; p=.07). However, no differences between pairs of shoulder-c.o.p. distances were found on manipulation distance (all p-values >.10).

7.3.2.2 Upper arm elevation

The upper arm elevation forwards for shoulder-c.o.p. fore/aft distance 70cm differed significantly from the upper arm elevation forwards for shoulder-c.o.p. fore/aft distance 80cm, whereas for both working heights the upper arm elevation forwards for shoulder-c.o.p. fore/aft distance 80cm differed significantly from the upper arm elevation forwards for shoulder-c.o.p. fore/aft distance 90cm (figure 7.7a). Upper arm elevation forwards was significantly affected by the working height (figure 7.7a). At a working height at elbow height the upper arm elevation sidewards for shoulder-c.o.p. fore/aft distance 100cm differed significantly from all other shoulder-c.o.p. fore/aft distances (figure 7.7b). Upper arm elevation sidewards was significantly affected by the working height (figure 7.7b).

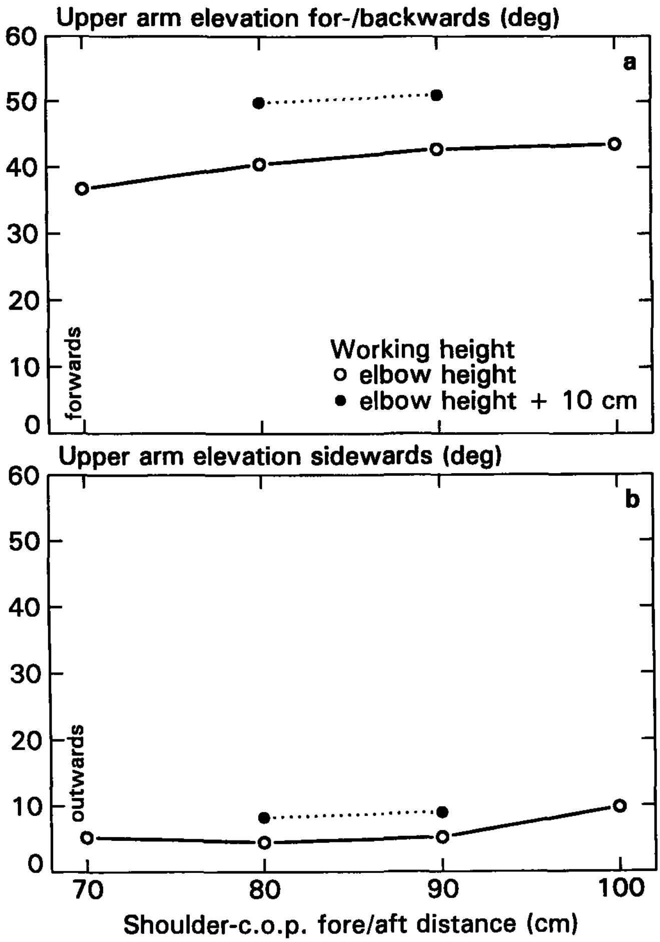

Figure 7.7 Upper arm elevation for-/backwards (a) and sidewards (b) versus experimental conditions (average group scores).

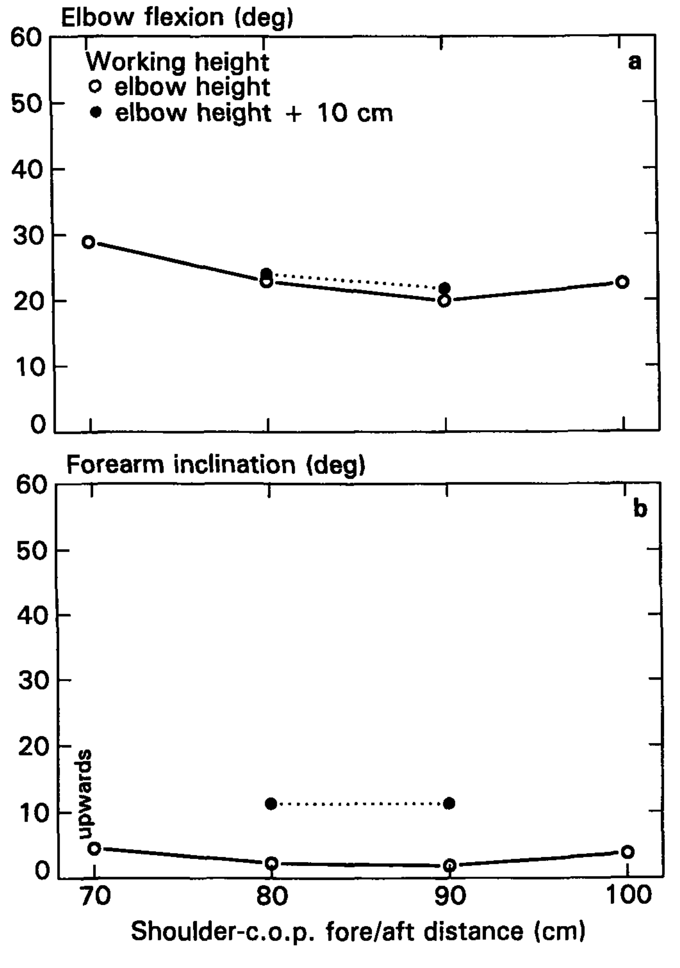

Figure 7.8 Elbow flexion (a) and forearm inclination (b) versus experimental conditions (average group scores).

7.3.2.3 *Elbow flexion/forearm inclination*

At a working height at elbow height elbow flexion for shoulder-c.o.p. fore/aft distance 70cm was significantly greater than elbow flexion for all other shoulder-c.o.p. fore/aft distances (figure 7.8a). At a working height at elbow height the forearm inclination for shoulder-c.o.p. fore/aft distance 70cm differed from the forearm inclination for shoulder-c.o.p. fore/aft distance 90cm (figure 7.8b; p=.06). The forearm inclination differed significantly between both working heights (figure 7.8b).

7.3.2.4 Workers' perceptions

No (combined) effects of shoulder-c.o.p. fore/aft distance and working height were found for workers' physical perceptions with respect to the upper extremities (all p-values >.10). Hardly any postural discomfort was mentioned for the left and right shoulder/arm. Average scores on perceived postures of the left shoulder, right shoulder, left upper arm, and right upper arm were less than or equal to 3.25 for all sets of experimental conditions, except for shoulder-c.o.p. fore/aft distance 100cm (average scores ranging from 3.75 to 4). Figure 7.9 shows a typical example, i.e. of the left upper arm posture (the other three variables mentioned showed about the same average scores).

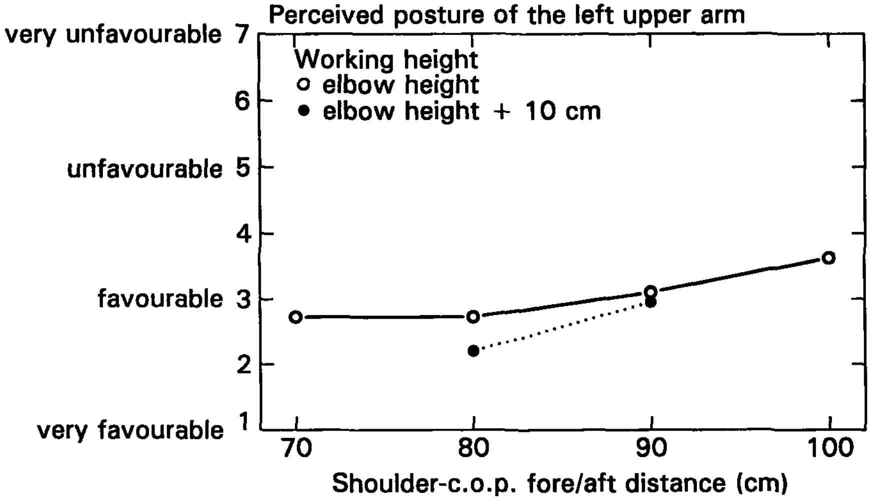

Figure 7.9 Perceived posture of the left upper arm versus experimental conditions (average group scores).

7.3.3 Integral workers' perceptions

Effects on integral workers' perceptions are summarized in tables 7.7 and 7.8. Figure 7.10 shows the estimated endurance time. Figure 7.11 shows the judgements on reach distance, working height, and the whole workstation adjustment.

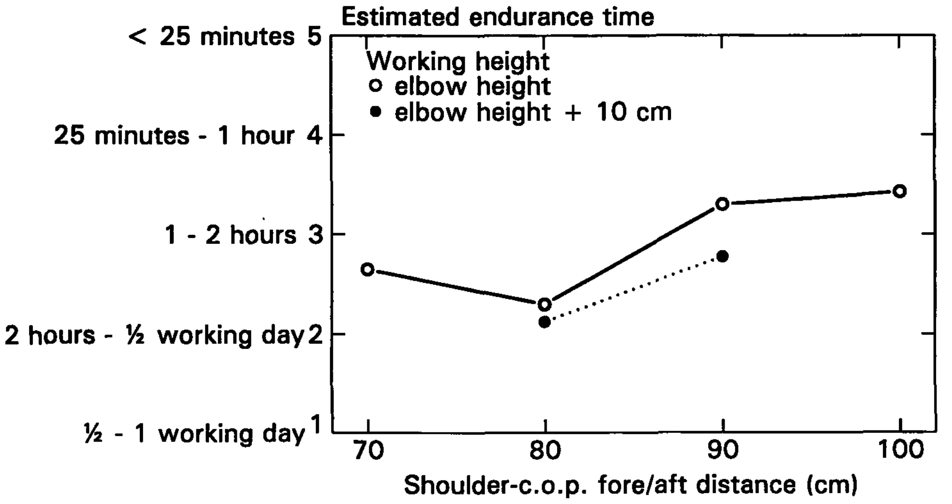

Figure 7.10 Estimated endurance time versus experimental conditions (average group scores).

7.3.4 Task performance

No (combined) effects of shoulder-c.o.p. fore/aft distance and/or working height were found with respect to task performance (all p-values >.10). On average, 128 plates were processed at an experimental session.

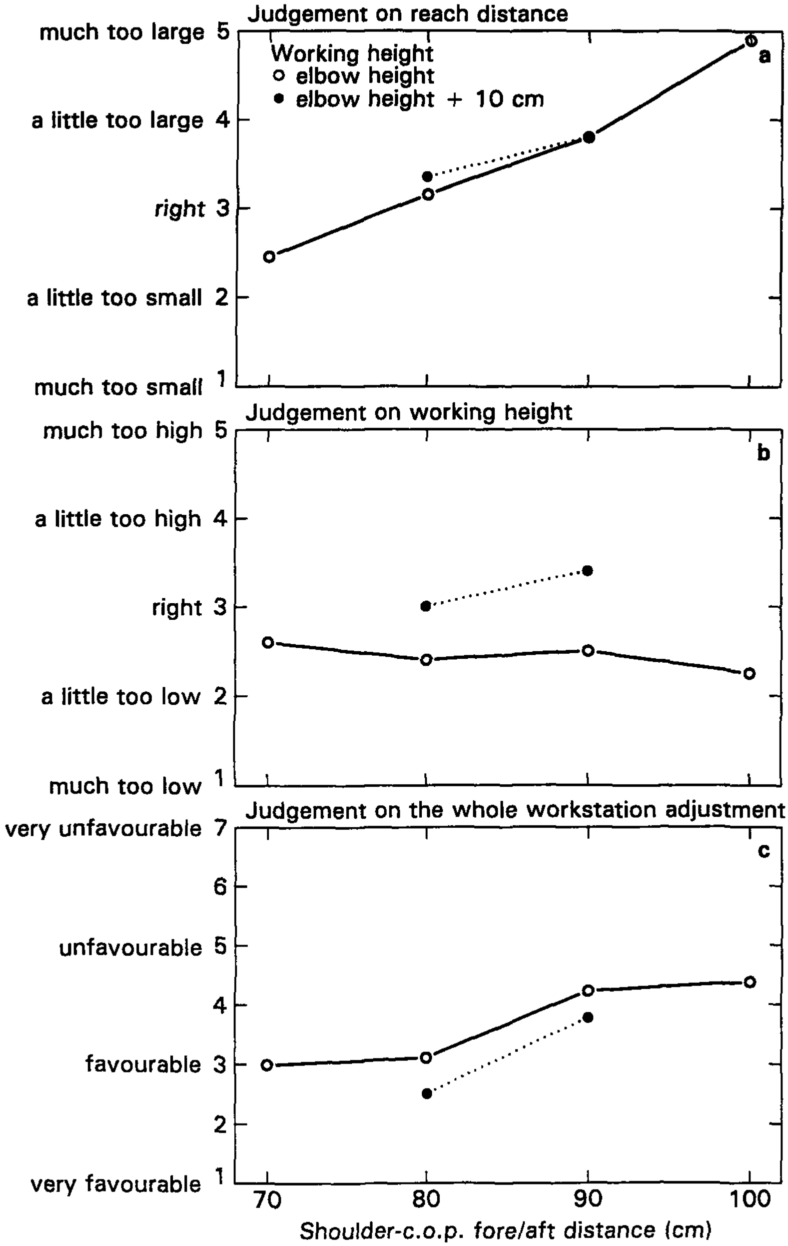

Figure 7.11 Judgements on reach distance (a), working height (b), and the whole workstation adjustment (c) versus experimental conditions (average group scores).

7.4 Discussion

7.4.1 Vision

7.4.1.1 Gaze inclination

Studies by Brues (1946), Conrady *et al.* (1987), and Straumann *et al.* (1991), as well as chapters 4-6 have pointed out that head inclination for-/backwards is determined by gaze inclination through a strict relationship, as well as the fact that normally the contribution of head inclination for-/backwards to gaze inclination is between 0% and 100% (the remaining fraction contributed by an up-/downward rotation of the eye with respect to the head/orbit). However, at the experimental conditions of the present study, with one exception, neither a strict relationship (table 7.6; parameter r), nor a contribution between 0% and 100% (table 7.6; parameter A) could be demonstrated. Inspection of the experimental worksite disclosed that the lower edge of the safety screen was not transparent due to a rubber protection strip. For a certain range of gaze inclination this strip created visual interference. Figure 7.3 (refer to the vertical line at a gaze inclination of about 40-45° below the horizontal) shows clearly that subjects choose either to look over the strip (i.e. gaze directed more downwards) or to look underneath (i.e. gaze directed more towards horizontal). The latter in particular led to unnatural head/neck postures. Such is most obvious in figure 7.3, at the cloud of 14 data pairs around gaze inclination -35° (i.e. downwards) and head inclination -60° (i.e. forwards). In order to look underneath the strip, the height of the eye is lowered by increasing head inclination forwards. The fact that the resulting head inclination forwards is greater than the gaze inclination, means that the eye was rotated in the opposite direction, i.e. more upwards with respect to the head/orbit. That is to be considered an unnatural phenomenon according to the literature mentioned above. The following sets of experimental conditions were affected: at a working height at elbow height the shoulder-c.o.p. fore/aft distances 80cm (1 data pair), 90cm (6 data pairs), and 100cm (4 data pairs), as well as at a working height at elbow height +10cm the shoulder-c.o.p. fore/aft distances 80cm (2 data pairs), and 90cm (1 data pair).

7.4.1.2 Viewing distance

Within the experimental conditions tested a systematic variation of viewing distance with both independent variables was found. The viewing distances measured (table 7.5) appear to be a result of head inclination for-/backwards (figure 7.4a). That is, as the head inclines forwards, the eyes are lowered and get closer to the visual target, and vice versa. Because head inclination for-/backwards was clearly affected by the experimental artefact described in § 7.4.1.1, it is not possible to draw a definite conclusion. At maximum it can be stated that the viewing distance does not seem to be a determinant of working posture.

7.4.2 Head, neck, and trunk

In the introduction the issue was raised as to whether neck load is determined by the for-/backward inclination of the head and/or neck segment or by neck flexion/extension. However, due to the unnatural head/neck postures observed in the present study (§ 7.4.1) is not possible to draw conclusions on this matter.

At shoulder-c.o.p. fore/aft distance 70cm for all subjects trunk inclination was between 0° and 10° (i.e. forwards). All of them show a linear relationship between shoulder-c.o.p. fore/aft distance and trunk inclination for-/backwards with high correlation (table 7.9). Subjects 2–7 increase their trunk inclination forwards by 9–10° for each 10 cm the shoulder-c.o.p. fore/aft distance is increased. Subject 8 increases his trunk inclination forwards at about half this rate. The same is found for subject 1 until shoulder-c.o.p. fore/aft distance 90cm. Above the latter distance a sharp increase of trunk inclination forwards is seen, such that trunk inclination forwards at shoulder-c.o.p. fore/aft distance 100cm is within the range of trunk inclinations found for subjects 2–7. No clear relationship between anthropometrics (stature, segment lengths of the upper extremities) and trunk inclination for-/backwards could be demonstrated. Though, within the shorter experimental shoulder-c.o.p. fore/aft distances the shorter subjects 2, 3, and 5 (stature: 178 cm, 168 cm, and 171 cm, respectively) tended to increase trunk inclination forwards at a slower rate than the longer subjects 4, 6, and 7 (stature: 181 cm, 189 cm, and 182 cm, respectively).

Table 7.9 Trunk inclination for-/backwards versus shoulder-c.o.p. fore/aft distance for *individual subjects. Trunk inclination for-/backwards = A * shoulder-c.o.p. fore/aft* distance + B (where n = 4 shoulder-c.o.p. fore/aft distances at a working height at elbow height); #: number of subject; r = Pearson correlation coefficient.

#	A	B	r
1	.75	-48.37	.94
2	.91	-60.78	.99
3	.95	-60.78	.99
4	.98	-68.28	.99
5	1.00	-69.69	.99
6	.91	-54.50	.99
7	.92	-53.28	.99
8	.46	-30.88	.98

For reaching positions that are increasingly further away, figures 7.4b, 7.7a, and 7.8a indicate the existence of a transition phase as far as the contribution of the upper extremities and the contribution of the trunk is concerned. It seems that at shoulder-c.o.p. fore/aft distances below 60–70 cm only the upper extremities are involved, whereas at shoulder-c.o.p. fore/aft distances above 90 cm the upper extremity segment and joint positions are at a maximum (upper arm elevation forwards) or a minimum (elbow flexion) and the remaining shoulder-c.o.p. fore/aft distance has to be bridged by the trunk. Data by Snyder *et al.* (1971) support these observations.

Assuming that the musculoskeletal load at the low back increases with trunk inclination forwards, the resemblance of figures 7.4b and 7.5b gives confidence with respect to the reliability of the results on perceived posture of the back. Combining the workers' localized perceptions and posture data, leads to the conclusion that repetitive forward inclinations of the trunk of more than about 20° on average are perceived as unfavourable.

7.4.3 Upper extremities

The results do not give support to the hypothesis that a subject will try to retain a favourable horizontal manipulation distance, in order to minimize the effect of gravity on the various upper extremity segments and the object. Within the experimental conditions tested for this horizontal component of the manipulation distance a systematic variation with working height was found for instance. It may be that the hypothesized effect emerges for heavier hand-held objects than the ones used in the present experiment. The manipulation distance, however, turned out to be a determinant of working posture (table 7.5). That is, at all six sets of experimental conditions tested the manipulation distance is kept relatively constant. Beyond the shoulder-c.o.p. fore/aft distance 80cm this is supported by a constant elbow flexion of 20–25°.

Remarkable is the greater upper arm elevation sidewards for shoulder-c.o.p. fore/aft distance 100cm as compared to shorter distances at a working height at elbow height (figure 7.7b; cf. Van der Grinten, 1991). The only plausible reason advanced for this phenomenon is that the position of the upper arm with respect to the trunk, i.e. shoulder flexion (defined as the sum of trunk inclination forwards and upper arm elevation forwards), at shoulder-c.o.p. fore/aft distance 100cm is significantly greater than for the other experimental conditions (table 7.10). At the 100cm condition the shoulder flexion for the subjects involved ranged from about 66° to 96°. In the case of an upright trunk, Pronk (1991) showed that the scapula (shoulder-blade) protracts during upper arm elevation in the sagittal plane of the trunk (denoted forward flexion) from 0° to 60°, and retracts during forward flexion from 60° to maximum (pro-/retraction is defined as a rotation of the scapula around the one axis within the scapular plane that is perpendicular to the spina scapulae (spine of the scapula), where retraction means that the scapula rotates towards the frontal plane). A retracting scapula and an increasing upper arm elevation forwards presumably move the humeral head closer to the limits of the gleno-humeral joint. A sideward rotation would bring the upper arm to a less unfavourable section of its range of motion. Of all the conditions tested, only at the 100cm condition did the perceived postures of the shoulders and upper arms tend to be unfavourable. Remarkable in this context is a study by Bjelle *et al.* (1981), who found that upper arm elevation (i.e. forward flexion and/or 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° was significantly more frequent as well as sustained for a longer duration in workers with acute shoulder-neck pains than in matched controls. The upper extremity postures and related workers' perceptions found in the present study suggest that this 60° limit should be used for the evaluation of the position of the upper arm with respect to the trunk, rather than for the evaluation of the amount of deviation from the hanging posture.

Table 7.10 The position of the upper arm with respect to the trunk, i.e. shoulder flexion (defined as the sum of trunk inclination forwards and upper arm elevation forwards), as a function of working height and shoulder-c.o.p. fore/aft distance (average group scores and ranges).

Working height		Shoulder-c.o.p. fore/aft distance			
		70cm	80cm	90cm	100cm
+10cm	average	---	57.7°	68.6°	---
	(range)		(46.4°-73.3°)	(57.1°-86.2°)	
0cm	average	41.3°	52.0°	62.9°	75.3°
	(range)	(31.7°-59.3°)	(43.4°-68.4°)	(51.4°-79.2°)	(66.3°-95.9°)

A greater upper arm elevation forwards for a higher working height at shoulder-c.o.p. fore/aft distances 80cm and 90cm is accompanied by a greater upper arm elevation sidewards (figure 7.7). No other explanation was found for this phenomenon than that is part of the natural course of movement at the shoulder and shoulder girdle. This is supported by the fact that the postures of the shoulders and upper arms for the experimental conditions mentioned above were perceived as favourable.

No invariant inclination of the forearm was found (figure 7.8b), like that for keyboard operation in VDU work (chapter 5). So, there is no reason to suppose that in the present experiment either the grip of the object required or the wrist posture was a determinant of working posture.

7.5 Formulation of guidelines

The second purpose of the paper was to formulate ergonomic guidelines for adjustment (and redesign) of press workstations. In order to formulate guidelines, results on working posture and workers' perceptions are to be discussed regarding their mutual relationships in the process of evaluation of experimental conditions. Task performance was affected neither by the shoulder-c.o.p. fore/aft distance nor by the working height. Therefore, guidelines for workstation adjustment can be formulated without mentioning positive or negative side-effects with respect to task performance.

The effects on perceived postures of the head and the neck as well as on postural discomfort in the back and the neck/back, described in tables 7.7 and 7.8, will not be used for the formulation of the guidelines, due to the experimental artefact described in § 7.4.1. Because discomfort in the back and neck/back affects postural discomfort of the whole body, the latter will also not be considered in the sections following. In addition, the results on postural discomfort of the whole body were doubted, because they were affected considerably by discomfort of the lower extremities, though lower extremity posture was not varied systematically during the experiments. A closer look at the data revealed that discomfort at the lower extremities was higher for the lower working height and shorter shoulder-c.o.p. fore/aft distances. Therefore, most likely the discomfort was evoked by a limited leg space at the press used in the experiments.

The exclusion of the results on several dependent variables in the process of formulating guidelines described in the previous paragraph should not withdraw from the fact that the trunk and upper extremities show a natural reaching posture behaviour (cf. Snyder *et al.*, 1971).

7.5.1 Reach distance

The judgement on reach distance was significantly worse for shoulder-c.o.p. fore/aft distances 90cm and 100cm than for shoulder-c.o.p. fore/aft distance 80cm (table 7.7). A shoulder-c.o.p. fore/aft distance of 80cm was considered 'right' on average (figure 7.11a). A similar result, though not statistically significant, was found in the judgements on the whole workstation adjustment (figure 7.11c). These integral perceptions are supported by the perceived postures of the back (table 7.7 and figure 7.5b), as well as by the forward inclinations of the trunk measured (figure 7.4b). These results show that the maximum shoulder-c.o.p. fore/aft distance should be somewhere between 80cm and 90cm. Since it is known that a distance of 80cm still guarantees favourable reach conditions and not known what happens if the distance is even slightly increased, a safe maximum shoulder-c.o.p. fore/aft distance, i.e. 80cm, will be used for formulating a guideline. Before doing this, it should be realized that the maximum distance determined depends on the particular anthropometric characteristics of the eight subjects involved in the present study. Furthermore, a guideline in terms of a maximum fore/aft distance between the shoulder top and some unique point at or near the hands or the stamp (as used in the present experiment) is not the most easy option for use in industry. A solution for both problems is to formulate the guideline in terms of body posture. At the 80cm shoulder-c.o.p. fore/aft distance on average the trunk was about 12° inclined forwards, and the upper extremities were rather close to full stretch, i.e. elbow flexion is about 22° on average. Such a guideline, however, would also not be usable for workers. Therefore, this particular working posture at the maximum shoulder-c.o.p. fore/aft distance had to be reformulated to a more or less unique posture. On the basis of goniometrical calculations, it was found that the maximum reach distance is equivalent to the position that can be reached with a full stretch of the upper extremities, when holding the trunk upright. As a consequence, the guideline is to do a reach test: check whether the object (held the same way as during actual task execution) can be placed in the stamp as well as be removed without bending the trunk forward (figure 7.12a).

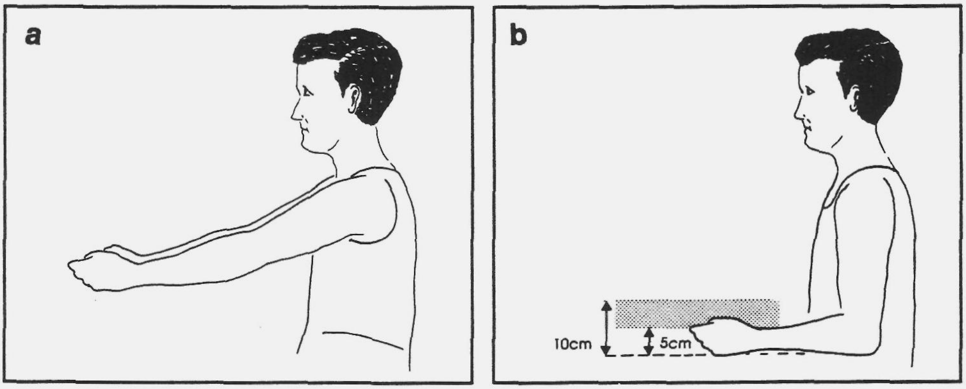

Figure 7.12 Guidelines on maximum reach distance (a) and optimum working height (relative to elbow height) (b) for press operation. Reach test: compliance with the maximum reach distance is tested by checking whether the object (held the same way as during actual task execution) can be placed in the stamp and removed without bending the trunk forward. Working height is defined as the height of the hands when placing the object in the stamp and when removing it. Elbow height is defined as the distance from the floor to the elbow (underside), having the trunk upright, the upper arms hanging down, and the forearms horizontal, while the main working posture (sitting, standing or using a buttock rest) is the same as during actual task execution.

Of course, to the guideline on maximum reach distance is added that a shorter reach distance should be chosen if this results in a more favourable posture. In practice, however, this may often be difficult due to various obstructions, like a safety screen, or a lack of space for the lower extremities when using a chair or a buttock rest. In the present experiment, for example, this led to somewhat worse perceptions for shoulder-c.o.p. fore/aft distance 70cm than for shoulder-c.o.p. fore/aft distance 80cm (figures 7.10 and 7.11a).

7.5.2 Working height

At shoulder-c.o.p. fore/aft distance 80cm the judgement on working height was significantly worse for elbow height than for elbow height +10cm (table 7.8). A working height at elbow height +10cm was considered 'right' on average, whereas a working height at elbow height received an average judgement between 'right' and 'a little too low'. A similar result, though not statistically significant, was found for the judgements on the whole workstation adjustment (figure 7.11c). These integral perceptions are supported, though not statistically significant, by the perceived postures of the back (table 7.8 and figure 7.5b) and the forward inclinations of the trunk measured (table 7.4b). Similar, but non-significant, differences were found at shoulder-c.o.p. fore/aft distance 90cm. On the basis of these results it is concluded that a general tendency towards a working height at elbow height +10cm exists.

Goniometric calculations disclosed that at the forward elevations of the upper arm measured (figure 7.7a), the elbow is raised 5-7 cm with respect to the hanging posture. Placing the plate in the stamp at elbow height then requires an increase of trunk inclination forwards and/or an increase of elbow extension, whereas placing the plate in the stamp at 10 cm above elbow height requires a more upright trunk and/or an increase of upper arm elevation forwards. Because the results of the present experiment showed that workers' perceptions on the trunk posture were rather decisive with respect to the overall judgements, the working height should not be lower than 5 cm above elbow height. Together with the general tendency towards a working height at 10 cm above elbow height, this leads to the guideline that the working height should be adjusted between 5 and 10 cm above elbow height (figure 7.12b).

7.6 Conclusions

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

1 visual interference (related to the gaze inclination) is a determinant of working posture;

2 the viewing distance does *not* seem to be a determinant of working posture;
3 the horizontal manipulation distance is *not* a determinant of working posture when processing light-weight objects;
4 the manipulation distance is a determinant of working posture;
5 the position of the upper arm with respect to the trunk, i.e. shoulder flexion in particular, seems to be a dominant determinant of shoulder and shoulder girdle load, as compared to upper arm elevation;
6 the maximum reach distance is not exceeded if the object (held the same way as during actual task execution) can be placed in the stamp as well as be removed without bending the trunk forward;
7 the working height, i.e. the height of the hands when placing the object in the stamp and when removing it, should be adjusted between 5 and 10 cm above elbow height.

Acknowledgements

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Chapter 8

Determinants of working postures (chapters 4–7 and literature)

8.1 Introduction

In this chapter data concerning determinants of working postures from the studies described in chapters 4–7, as well as from the literature (§§ 2.2–2.5) are brought together, i.e. on vision (§ 8.2), hand control (§ 8.3), and stability (§ 8.4), as well as on their interactions (§ 8.5, including foot control). Furthermore, answers are provided to the research questions put forward in § 2.6 (for a summary, refer to § 8.6).

8.2 Vision

8.2.1 Gaze direction

Studies on the relationship between gaze direction and working posture either focus on the horizontal gaze direction (left/right), on the vertical gaze direction (up/down, gaze inclination), or on a combination of both, i.e. an oblique gaze direction (§ 2.2.1). Below the data on vertical gaze direction from chapters 4–7 will be used to answer the research question in this respect as well as to reflect on the literature data.

Vertical gaze direction (up/down, gaze inclination)
For four of the six operations studied, i.e. sewing machine operation, touch-typing VDU operation, pneumatic wrenching, and grinding (chapters 4–6), it was found that gaze inclination is a determinant of working posture as a postural strategy. That is, gaze inclination and head inclination for-/backwards are linearly related. For the remaining operations studied, i.e. oxy-gas cutting and press operation (chapters 6 and 7), visual interference was found to be a determinant of working posture (§ 8.2.3).

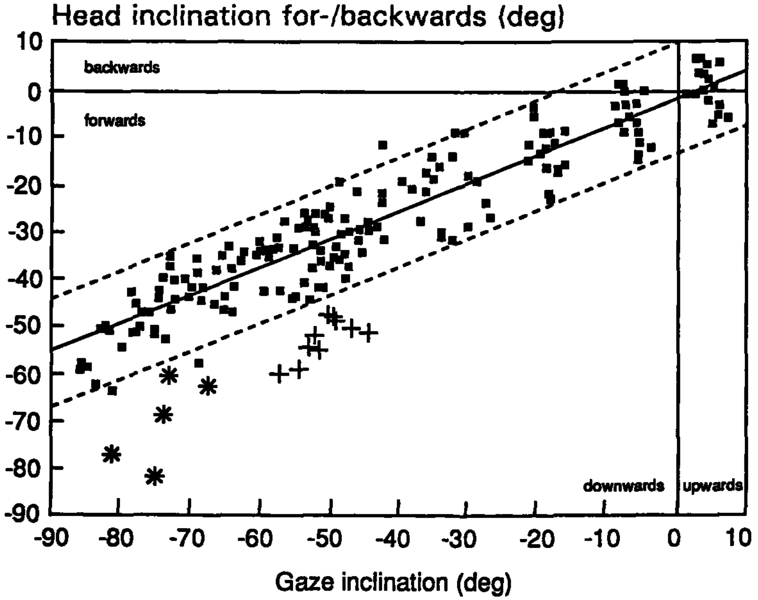

Figure 8.1 The relationship between gaze inclination and head inclination for-/backwards (174 data points, each representing one subject operating at a particular experimental workstation adjustment). By definition at a gaze inclination equal to 0° (horizontal), head inclination for-/backwards equals 0° (upright). Data are taken from studies on sewing machine operation, touch-typing VDU operation, pneumatic wrenching, and grinding (chapters 4-6). The linear regression line and 95% confidence interval are shown. For this, the outlying data points for one of the sewing machine operators (#1) at all workstation adjustments tested (10 data points, marked +), as well as for one of the subjects involved in grinding (#16) at all workstation adjustments tested (5 data points, marked *), were not used.

Grouped data on sewing machine operation, touch-typing VDU operation, pneumatic wrenching, and grinding disclose a linear relationship between gaze inclination and head inclination for-/backwards. The contribution of head inclination for-/backwards to a change of gaze inclination equals 59% (R^2=.88)[16] while excluding two outlying subjects from a total of 28 subjects (figure 8.1), and 63% (R^2=.80)[17] while including them. R^2 values were not improved by

[16] Head inclination for-/backwards = 0.59 * gaze inclination - 2.1°.

[17] Head inclination for-/backwards = 0.63 * gaze inclination - 2.1°.

using higher order regression. The head contribution to a gaze change found in the grouped data confirms the figures taken from Straumann *et al.* (1991) and Conrady *et al.* (1987), i.e. 55-60%. This particular ratio resembles the relative size of the so-called favourable section of the range of motion for the eyes and the head. Weston (1953) mentioned that, in order to prevent fatigue, workers generally avoid going beyond a downward rotation of the eyes within the head/orbit of about 25° on average (reference posture according to Weston: head erect and gaze directed approximately horizontal). According to table 9.1 the head may be inclined forwards somewhat more, i.e. on average between 27° and 36° till neck flexion becomes unfavourable (reference posture: trunk upright, head upright, and looking straight ahead along the horizontal). Presumably the body uses the particular ratio mentioned above for approaching the unfavourable section of both ranges of motion involved at about the same relative rate, thereby sharing the musculoskeletal load equally.

At figure 8.1 it seems as if head contribution increases when gaze inclination gets within 10-15° of the straight-down direction, as observed in the data presented by Brues (1946; figure 2.4). This may very well be due to the eyes getting closer to the end of their range of motion.

At figure 8.1 it can be seen that the regression line does not go through the origin (0°, 0°). However, at gaze inclination 0° (horizontal) head inclination for-/backwards should have been 0° (upright), because head inclination for-/backwards during operation was measured with respect to the head inclination for-/backwards at a reference posture (trunk upright, symmetric with respect to the sagittal plane, looking straight ahead along the horizontal, arms hanging down along the trunk). The question was raised as to whether a 'natural' head inclination for-/backwards would be found while looking straight ahead along the horizontal at the reference posture. Fortunately, in the study on touch-typing VDU operation (chapter 5) visual target heights above and below eye height were tested, leading to gaze inclinations above and below the horizontal (0°). For each operator a linear relationship between gaze inclination and head inclination for-/backwards was determined. The head inclination for-/backwards at gaze inclination 0° taken from each individual relationship was used as a 'natural' reference posture. Using the latter the 95% confidence interval was reduced to 50% of the interval found while using the original reference posture concerning head inclination for-/backwards.

The mean results from Brues (1946; figure 2.4) at gaze inclinations -90° and 0° lie on the regression line of figure 8.1, while the Brues' results for gaze inclinations -67.5°, -45°, and -22.5° lie about halfway between the regression line and the upper edge of the 95% confidence interval. Reducing the interval by 50%, which is considered realistic on the basis of the reasoning presented in the previous paragraph of this section, would then mean that the Brues' results at gaze inclinations -90° and 0° lie about halfway between the regression line and the upper edge of the corrected confidence interval, while the Brues' results for gaze inclinations -67.5°, -45°, and -22.5° lie at about the upper edge of the corrected interval.

8.2.2 Viewing distance

It could not be demonstrated that viewing distance is a determinant of working posture as a postural strategy. Neither for the operations that presumably pose high visual demands, i.e. sewing machine operation, touch-typing VDU operation, oxy-gas cutting, nor for pneumatic wrenching and grinding, did subjects retain one particular viewing distance under various conditions (chapters 4-7). Instead, at all six operations studied the viewing distance seems to be a result of the head inclination for-/backwards (refer also to § 8.2.1) and/or of the trunk inclination for-/backwards (refer to the discussion sections on viewing distance in chapters 4-7). It could not be demonstrated either that the viewing distance is a determinant of working posture as regards the postural space. Only for grinding does a maximum viewing distance seem to have been reached at working heights beneath 35 cm below elbow height (chapter 6). However, it is considered to be more likely that the steep increase in head inclination forwards (caused by trunk inclination forwards) reduces eye height, which compensates to a large extent for the lower target position.

8.2.3 Interface with visual target

Angle between line of sight (gaze direction) and target surface

For sewing machine operation (chapter 4) it could not be demonstrated that the gaze-desk angle is a determinant of working posture as regards the postural space (i.e. no minimum angle was found) or as a postural strategy (i.e. operators did not retain one particular angle under various conditions).

Operating a sewing machine at a 10° desk slope led to a more upright posture of the head, neck, and trunk, while leaving upper arm posture unchanged. However, the underlying mechanism did not turn out to be based upon the gaze-desk angle. Instead, it was shown that the slope effect is no more than a simple height effect, i.e. by rotating the desk around its front edge the needle (the visual target) is raised.

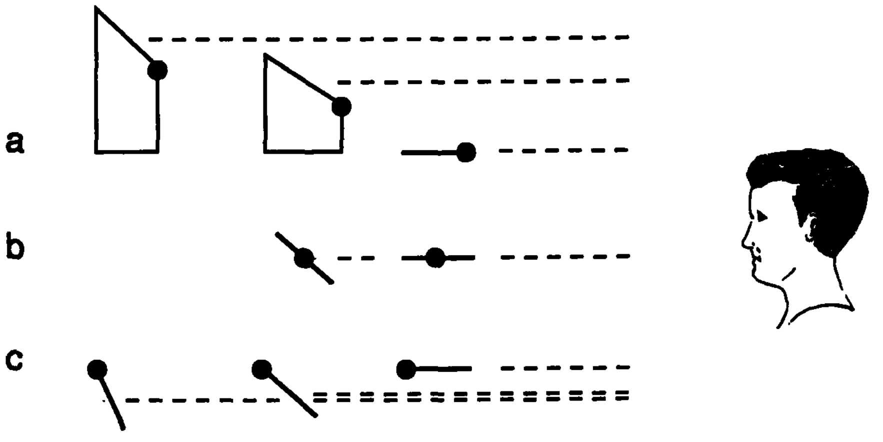

Figure 8.2 Side view of the slopes tested by (a) Bendix and Hagberg (1984), (b) Douwes *et al.* (1992), and (c) Kumar and Scaife (1979). ● = axis of rotation. ---- = working height. For visualization purposes, dimensions and angles deviate from the actual experimental conditions.

Three studies on other visual-manual operations were found that may add to the understanding of a possible generic mechanism behind a slope effect (figure 8.2). Bendix and Hagberg (1984) measured the postural effects of three desk slopes, i.e. 0° (horizontal), as well as 22° and 45° inclined towards reading subjects. The latter two conditions were realized by placing special desks on top of the horizontal desk, their lowest point being elevated 6 cm and 8 cm, respectively. It was found that the forward inclination of the head and cervical spine was reduced by 8.4° after changing from a 0° desk slope to a 22° desk slope, and by 5.1° after changing from a 22° desk slope to a 45° desk slope (forward inclination of the trunk reduced by 4.3° and 3.4°, respectively). This means that about the same increase of desk slope induces different postural changes. Assuming that here also the slope effect is in fact a height effect, this may be explained by the changes concerning the elevation of the desk top lower edge, i.e. 6 cm from a 0° desk slope to a 22° desk slope, and 2 cm from a 22° desk slope to a 45° desk slope. However, it must be said that the study by Bendix and Hagberg (1984) does not allow for fully unravelling the single effects of height and slope. Douwes *et al.* (1992) studied the effects of an object inclined by 10° towards assembly workers, who were using a vertically-aligned balanced pneumatic screwdriver. Working height, defined as the point of operation on the object, was the same for the object when positioned flat on the desk and the object in the inclined position. Due to this absence of a working height difference, any postural effect would have represented a pure effect of the gaze-object angle. However, no significant effects on head, neck, and/or trunk posture were found. In contrast, it was demonstrated that a change of the working height by as little as 5 cm did in fact induce significant effects on upper body posture. Among other conditions, Kumar and Scaife (1979) tested desk slopes 0°, 2.5°, and 5° towards operators involved in threading computer memories with the aid of a stereoscopic microscope. While the gaze-desk angle stayed at about 90° due to the particular orientation of the microscope tubes, the forward inclination of the head and trunk increased as the desk slope increased. A drawing of the experimental set-up showed that the rotation axis of the desk was behind the operation area at the desk. Giving the desk a slope towards the operator then lowers this operation area, as well as the height of the eyes at the top of microscope tubes, thereby explaining the forward inclination of the head and trunk. The studies described suggest that most often an apparent slope effect is actually a height effect.

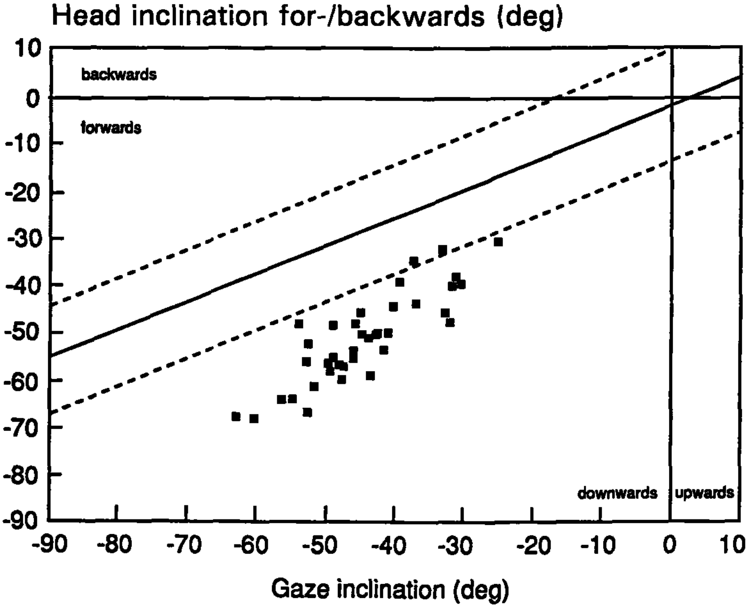

Figure 8.3 The relationship between gaze inclination and head inclination for-/backwards for oxy-gas cutting (n = 40, each data point representing one subject operating at a particular experimental workstation adjustment, refer to chapter 6). By definition at a gaze inclination equal to 0° (horizontal), head inclination for-/backwards equals 0° (upright). The linear regression line and 95% confidence interval from figure 8.1 are also shown.

Visual interference

In the studies on oxy-gas cutting (chapter 6) and press operation (chapter 7) it was demonstrated that visual interference is a determinant of working posture as regards the postural space. During oxy-gas cutting the workers wore particular dark glasses, which severely reduced the effective range of motion of the eyes, due to the small area of glass left for proper visual control. Therefore, each change of gaze had to be created almost completely by the head. Furthermore, it was found that during operation the eyes of most maintenance workers involved 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). Consequently, head inclination forwards is mostly greater than gaze inclination downwards. The effect of visual interference can be seen at figure 8.3, where the data points clearly deviate from the 95% confidence interval obtained from the studies on sewing machine operation, touch-typing VDU operation, pneumatic wrenching, and grinding (chapters 4-6).

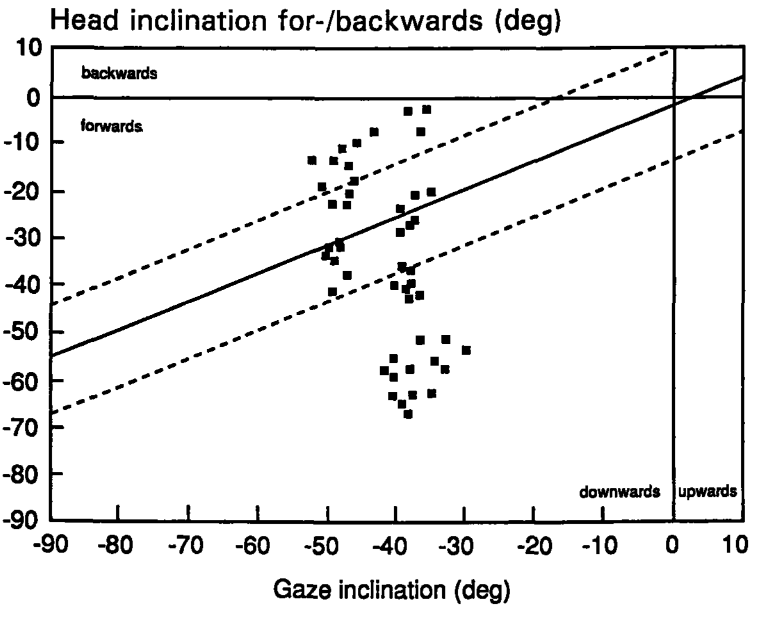

Figure 8.4 The relationship between gaze inclination and head inclination for-/backwards for press operation (n = 48, each data point representing one subject operating at a particular experimental workstation adjustment, refer to chapter 7). By definition at a gaze inclination equal to 0° (horizontal), head inclination for-/backwards equals 0° (upright). The linear regression line and 95% confidence interval from figure 8.1 are also shown.

During press operation the lower edge of the safety screen was not transparent, due to a rubber protection strip. For a certain range of gaze inclination this strip interfered with the line of sight. Figure 8.4 (refer to the vertical band without data points at a gaze inclination of about 40–45° below the horizontal) shows clearly that operators choose either to look over the strip (i.e. gaze directed more downwards) or to look underneath (i.e. gaze directed more towards the horizontal). The latter in particular led to unnatural head/neck postures. This is most obvious in figure 8.4, where the cloud of 14 data points around gaze inclination −35° (i.e. downwards) and head inclination −60° (i.e. forwards) deviates considerably from the 95% confidence interval (included in figure 8.4), obtained from the studies on sewing machine operation, touch-typing VDU operation, pneumatic wrenching, and grinding (chapters 4–6). In order to look underneath the strip, the height of the eye is lowered by increasing head inclination forwards. The resulting head inclination forwards is greater than the gaze inclination downwards, meaning that the eyes were rotated upwards with respect to the head/orbit, as was found at oxy-gas cutting (refer above).

8.3 Hand control

8.3.1 Reach direction

The effects of reach direction were not studied quantitatively in the studies on visual-manual operations described in chapters 4–7. However, during pneumatic wrenching and oxy-gas cutting (chapter 6) it was observed that the workers prefer a displacement of the feet, and a rotation around the vertical of the body as a whole (with the exception of the head/neck and upper extremity segments) instead of twisting the musculoskeletal system between the pelvis and vertebra C7, in order to compensate for the asymmetric positions of the hands caused by the tool used.

8.3.2 Reach distance

Regarding the study on press operation (chapter 7) it may be concluded that all experimental reach distances were chosen in such a range, that an almost maximum or maximum use of the upper arm and elbow/forearm is present any time. Hardly any trunk inclination forwards was found at the shortest reach distance tested, whereas inclination increased rapidly at greater reach distances. These results, as well as the experimental data by Snyder *et al.* (1971), support the hypothesis by Hsiao and Keyserling (1991), stating that the trunk is the least likely segment to move away from its neutral posture (i.e. upright). Furthermore, it is concluded that the simultaneous contribution of the upper arm and the trunk found during press operation as well as in the data by Snyder and colleagues does not confirm the strategy put forward by Evershed (1970), Korein (1985), and Case *et al.* (1990), stating that a body segment will only be moved, if a target cannot be reached by all segments located more distally. This means, for instance, that the trunk would only move after the hand reached the maximum position given by the lengths and ranges of motion of all upper extremity segments.

For the visual-manual operations studied in chapters 4-7 it was hypothesized that a worker would try to retain a favourable reach position of the hand(s) with respect to the upper trunk (manipulation distance). This postural behaviour was supposed to be guided by an optimization of the upper extremity joint positions (i.e. an optimization of the manipulation distance), or 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), due to the weight of the upper extremities and a tool/object in the hand, if any. It could not be demonstrated for any of the operations studied that the horizontal manipulation distance is a determinant of working posture as a postural strategy, not even for pneumatic wrenching with a relatively heavy tool in the hand. The manipulation distance, however, turned out to be a determinant of working posture as a postural strategy for oxy-gas cutting (chapter 6) and press operation (chapter 7). At oxy-gas cutting the distance was kept constant for all working heights tested (elbow flexion 90-95°). At press operation the distance was kept constant beyond a particular reach distance. In this respect, it is interesting that the trunk seemed to get involved in reaching when elbow flexion became less than about 30° (at greater reach distances elbow flexion stabilized at 20-25°). Exactly the same phenomenon was seen for grinding (chapter 6), where workers preferred to react on a stepwise lowering of the working height mainly by reducing their elbow flexion (extending their elbow), until the angle of 30° was reached. From this point onwards trunk inclination forwards increased significantly. Hsiao and Keyserling (1991) stated that in their experiments elbow flexion was never less than 30°. This may be due to the fact that, when a target was too far away, subjects shifted their pelvis rather than inclining their trunk away from its upright posture. Pelvis shifting (forwards) was not an option for press operation, due to the fixed position of the buttock rest, as well as of the buttocks with respect to the seat. Apparently, during grinding pelvis shifting (downwards), by standing with slightly bent knees for five minutes, was not a realistic alternative either. It may be concluded that workers seem to optimize the manipulation distance in relation to the trunk inclination for-/backwards. It could not be demonstrated that the manipulation distance is a determinant of working posture as regards the postural space. For none of the operations studied did an elbow ever reach a limit of its range of motion.

8.3.3 Interface with actuator/tool/object

In the study on touch-typing VDU operation (chapter 5) it was found that operators kept the forearm at a typical invariant inclination. This forearm inclination showed a strong resemblance to the inclination of the top of the keyboard used, suggesting that operators strive for a neutral wrist posture, i.e. the forearm and the hand in line. Because wrist posture was not measured, it is only demonstrated to a certain extent that the interface with the actuator is a determinant of working posture as a postural strategy. Furthermore, for oxy-gas cutting and grinding (chapter 6) at particular working heights the wrist seemed to reach a limit of its range of motion due to the grip orientation of the tool used, thereby forcing the upper arm into an unfavourable posture. Again, because wrist posture was not measured, it has only been demonstrated to a certain extent that the interface with the tool is a determinant of working posture as regards the postural space.

8.4 Stability

The study on oxy-gas cutting (chapter 6) demonstrated that an interface with the workstation, concerning a type of body support other than that involved in sitting, is a determinant of working posture as regards the postural space. Trunk inclination for-/backwards is largely determined by the fact that the left elbow is positioned on the table top, in order to create a stable posture. At the lowest height tested the great trunk inclination forwards together with a forced head inclination forwards (through gaze inclination; § 8.2.1), almost brought the neck (i.e. head vs. trunk) into an extended position, which is known to be unfavourable (refer also to chapter 5).

8.5 Interactions of vision, control, and stability demands

Section 2.5 started off with a study by Nakaseko *et al.* (1993), saying that head/neck inclination for-/backwards affects thoracic spine curvature (a 'top-down' effect), whereas raising or lowering the upper legs when sitting affects lumbar spine curvature (a 'bottom-up' effect). The latter effect was given a detailed description in § 2.4, stressing the role of the lower legs and pelvis as well. The top-down effect mentioned was also observed in the studies on touch-typing VDU operation, pneumatic wrenching, and grinding (chapters 5 and 6). This all adds up to the concept of a so-called spinal bow, symbolizing the flexible system between the head and the pelvis. At the upper end this bow is fixed to the visual target through a sort of extension by the relationship between the gaze inclination and the head inclination for-/backwards (§ 8.2). The amount of head inclination for-/backwards affects the tension of the spinal bow. At the lower end bow tension may be affected by pelvis and lower extremity posture (refer above), as well as by moving the pelvis/hips (in practice most often for-/backwards). In studies by Bendix *et al.* (1988) and Derksen *et al.* (1994) it was observed that neck flexion/extension compensates for a change of trunk inclination for-/backwards because head inclination for-/backwards was more or less fixed for visual control. Studies on sewing machine operation (chapter 4) and typing (Lepoutre *et al.*, 1986) indicate that some sort of optimum (i.e. most favourable) bow tension exists. For sewing leg space was increased by positioning the pedal somewhat further away from the operator under the workstation. Operators, however, used this opportunity for approaching the needle more closely only when the workstation desk was also given a certain slope. This created a more upright trunk posture as well as more neck flexion (reducing the radius of curvature and increasing tension of the spinal bow). Better workers' perceptions for trunk posture as well as for neck posture were found as compared to other combinations of desk slope and pedal position tested. Such a phenomenon was observed also by Lepoutre and colleagues (1986). By reducing the backrest-keyboard distance (fore/aft direction), the lumbar curvature at vertebra L3 decreased and the dorsal curvature at vertebra T1 increased, meaning a more upright trunk and more neck flexion. This spinal posture was well appreciated by the subjects involved.

In § 2.5 the question was raised as to whether hand control demands or vision demands are the dominant determinant of working posture. For a proper comparison a common denominator is needed. The hand - forearm - upper arm - shoulder girdle chain and the eye - head - cervical spine chain meet at the top end of the thoracic spine. Therefore, at least the effects of both types of demands on trunk posture are to be compared. The gaze inclination was found to be a determinant of working posture as a postural strategy for four of the six operations studied (§ 8.2.1), as well as regarding the postural space in terms of visual interference, for the other two (§ 8.2.3). However, only for three operations, i.e. touch-typing VDU operation, pneumatic wrenching, and grinding, it was demonstrated that the gaze inclination affected thoracic spine posture via the for-/backward inclination of the head/neck segment. In terms of trunk inclination for-/backwards a relatively small effect was found. The manipulation distance turned out to be a determinant of working posture as a postural strategy for oxy-gas cutting, grinding, and press operation (§ 8.3.2). For all three operations a relatively large effect on trunk inclination for-/backwards was found, demonstrating that hand control demands are the dominant determinant of working posture.

8.6 Answers to research questions

The series of studies on visual-manual operations described in chapters 4–7 led to the following answers to the research questions put forward in § 2.6:

- Vision
  - The *gaze inclination* is a determinant of working posture as a postural strategy.
  - It could not be demonstrated that the *viewing distance* is a determinant of working posture as regards the postural space or as a postural strategy.
  - It could not be demonstrated that the interface with the visual target, in terms of the *angle between line of sight (gaze direction) and target surface,* is a determinant of working posture as regards the postural space or as a postural strategy.
  - It was demonstrated that the interface with the visual target, in terms of *visual interference*, is a determinant of working posture as regards the postural space.
- Hand control
  - It was demonstrated that the *manipulation distance* is a determinant of working posture as a postural strategy, whereas it could not be demonstrated that it is a determinant as regards the postural space.
  - It could not be demonstrated that the horizontal component of the manipulation distance (*horizontal manipulation distance*) is a determinant of working posture as a postural strategy.
  - It was demonstrated to a certain extent that the interface with the target, i.e. actuator/tool/object (*type and orientation of grip/contact*), is a determinant of working posture as regards the postural space or as a postural strategy.
- Stability
  - It was demonstrated that the interface with the workstation (*type of body support*) is a determinant of working posture as regards the postural space.
- Interactions of vision, control, and stability demands
  - It was demonstrated that hand control demands are the dominant determinant of working posture as compared to vision demands, considering the size of effects concerning trunk inclination for-/backwards.

Chapter 9

Evaluation of working postures (chapters 4-7 and literature)

9.1 Introduction

Chapters 4-7 contain a series of studies on visual-manual operations, using a standardized research approach (Delleman, 1991). These papers describe the effects of the adjustment of workstations 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 and Bishop, 1976). Below, data concerning the evaluation of working postures from the studies described in chapters 4-7, as well as from the literature (§§ 3.2 and 3.3) are brought together, focussing on head/neck posture (§ 9.2) and upper arm posture (§ 9.3). Furthermore, answers are provided to the research questions put forward in § 3.4 (for a summary, refer to § 9.4).

9.2 Head/neck posture

For each of the visual-manual operations studied two potential determinants of neck load were given a closer look, i.e. head inclination for-/backwards and neck flexion/extension (head inclination for-/backwards with respect to trunk inclination for-/backwards). Due to an experimental artefact, the data on press operation (chapter 7) will not be discussed below. It should be emphasized that some of the effects obtained could be demonstrated at the significance level used, and some could not. In the latter case, some remarkable tendencies could still be seen in the data (refer to chapters 4-6 for details). Finally, it is considered worth mentioning that in chapters 4-7 neck flexion/extension was studied by relating the for-/backward inclination of the head segment to the for-/backward inclination of the trunk segment. A detailed study in chapter 4 on the part of the cervical spine where neck flexion/extension takes place, was not considered worth while continuing in chapters 5-7 as no added value could be detected.

For sewing machine operation (chapter 4) the results on perceived neck posture were reflected by the neck flexion angles measured, and not by head inclination for-/backwards. The main difference between both variables was found when working at a workstation that was given a 10° desk slope and a pedal position 10 cm further away from the desk front edge as compared to the average pedal position at the operators' own industrial workstations. The neck flexion at this workstation adjustment was the greatest for each desk height tested. Judging from the tendencies towards a better perceived neck posture and less postural discomfort in the trapezius muscle regions, it seems that operators favour a greater neck flexion. Apparently, during sewing machine operation neck flexion/extension plays a dominant role with respect to the workers' perceptions of neck posture, as compared to head inclination for-/backwards.

For touch-typing VDU operation (chapter 5) workers' perceptions revealed an optimum (i.e. most favourable) visual target height at 10 cm below eye height, for an upright backrest as well as for a backward inclined backrest. The perceptions for visual target heights of 40 cm and 25 cm below eye height were worse than for the optimum target height. It is very likely that the more forward inclined head at the latter two target heights is counteracted by a higher force of the muscles in the neck and upper back. In addition, at these head inclinations the muscles may be stretched beyond their optimum (i.e. most favourable) length, reducing their active force capacity. Both a higher force level and a reduced force capacity lead to an earlier onset of muscle fatigue. At the optimum visual target height the chair backrest inclinations showed no significant differences with regard to workers' perceptions. However, especially for visual target heights of 40 cm below and 5 cm above eye height remarkable differences between both backrest inclinations were found. For a visual target height of 40 cm below eye height the perceptions for the backward inclined backrest tended to be worse than for the upright backrest. An explanation was found in the postural data, i.e. a considerably greater neck flexion was measured for the backward inclined backrest than for the upright backrest. Gravitational effects are not considered a likely cause, due to the fact that the head inclination forwards for the backward inclined backrest was even slightly less than for the upright backrest. The latter result suggests that further head inclination forwards is limited in the case of the backward inclined backrest because neck flexion has reached its maximum (table 9.1). For a visual target height of 5 cm above eye height the workers' perceptions for the upright backrest tended to be worse than for the backward inclined backrest. Gravitational effects can be excluded as a causal factor, due to the same head inclination backwards found at both backrest inclinations. Apart from the fact that a backward inclined backrest may be more favourable because it supports body weight somewhat more, here too neck flexion/extension is the most likely cause for the differing workers' perceptions. A considerably smaller neck flexion was found at the upright backrest than at the backward inclined backrest. This smaller angle may shorten the muscles in the neck and upper back beyond their optimum lengths, reducing active force capacity. The same explanation most probably holds for the workers' perceptions for a visual target at 5 cm above eye height which were worse than for the optimum visual target height at 10 cm below eye height. The above considerations stress the role of neck flexion/extension with respect to musculoskeletal load on the neck structures, apart from head inclination for-/backwards. The study suggests that a slightly/moderately flexed neck is optimum (cf. Conrady *et al.*, 1987; Van der Grinten and Smitt, 1992)[18].

For all three maintenance operations (chapter 6) for the working heights that were considered favourable, the head was inclined forwards, i.e. average inclinations roughly between 20° and 60°. This range does not match the most favourable head inclinations suggested in the literature, i.e. less than 15° inclined forwards (Chaffin, 1973) or even inclined backwards (Snijders *et al.*, 1991; De Wall *et al.*, 1991;1992). 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 for the experimental set-up used (5 minutes of operation) a working height becomes unfavourable only at a rather great head inclination forwards (N.B.: for all operations the lowest working height tested showed the greatest head inclination forwards, and tended to be considered unfavourable for the neck). If this were true, a higher working height, showing less head inclination forwards, would always have to be relatively favourable. However, there is then no explanation for the fact that a working height of 20 cm above elbow height for oxy-gas cutting is most unfavourable. So, it seems that the head inclination for-/backwards is not the dominant determinant of neck load. All unfavourable working heights (20 cm below elbow height for pneumatic wrenching, 20 cm above elbow height for oxy-gas cutting, and 45 cm below elbow height for grinding) can be explained by the neck flexion angle measured, however. At each of these heights an unfavourable maximum neck flexion seemed to have been reached (table 9.1). The neck flexion angle also does seem to explain the ambiguous result for a working height of 20 cm above elbow height for oxy-gas cutting, that is, an equal number of workers considered it favourable and unfavourable. At this height neck flexion was rather small (close to extension), which is known to be a somewhat unfavourable neck position (refer to touch-typing VDU operation, as described above). From the above it seems that neck flexion/extension is the dominant determinant of neck load, as compared to head inclination for-/backwards.

[18] According to Conrady *et al.* (1987) and Van der Grinten (1996), in their experiments the trunk was upright.

Table 9.1 Neck flexion versus experimental conditions (average group scores). s.d. = standard deviation. n = number of operators/workers. For detailed information, refer to chapters 5 and 6. For grinding worker #16 was excluded for reasons described in chapter 6.

Operation	Average	s.d.	n
Touch-typing VDU operation (chair backrest inclination -15°, visual target height -40cm)	32.6°	11.3°	8
Pneumatic wrenching (working height -20cm)	33.6°	4.9°	7
Oxy-gas cutting (working height +20cm)	27.4°	8.8°	8
Grinding (working height -45cm)	36.0°	9.7°	7

For particular experimental conditions described above, neck flexion seemed to have reached a maximum (table 9.1). Results for touch-typing VDU operation, pneumatic wrenching, and grinding are rather close, considering for instance the different subject groups involved, and the different position of one of the markers for measurement of trunk posture, i.e. the upper edge of the greater trochanter for touch-typing VDU operation, and the intervertebral disc L5-S1 for pneumatic wrenching and grinding. A direct comparison of the maximum neck flexion angles found is only possible for oxy-gas cutting and grinding, because in the experiments on these operations seven of the subjects involved were the same (chapter 6). At maximum the group averages for these seven subjects were 29.1° for oxy-gas cutting (working height +20cm), and 36.0° for grinding (working height -45cm). One reason for the difference seems to be that during oxy-gas cutting at higher working heights (i.e. 10 cm and 20 cm above elbow height) the possibility of bending the thoracic region of the spine forwards is limited, simply due to obstruction by the scissor lift table used. Because head inclination forwards is made possible partly by bending the thoracic spine forwards (§ 8.5), the maximum neck flexion is not as high as without the limitation.

One should be aware that neck load may equally well be determined by other factors. The posture of the shoulder girdle, for example, is such a factor, i.e. 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 posture of the upper arm (Pronk, 1991; Van der Helm, 1991), at least the latter deserves a closer look in relation to neck load. However, for most experimental conditions in the visual-manual operations studied, the posture of the upper arm does not seem to have played a role with respect to the workers' perceptions for the neck, discussed above. Only for oxy-gas cutting at 20 cm above elbow height may the unfavourable position of the upper arm with respect to the trunk (§ 9.3) have had an effect on perceptions for the neck.

Bringing together the data from the literature (chapter 3) and the data from the studies described in chapters 4–7, it is concluded that neck flexion/extension is a determinant of neck load, that is to be used as an evaluation criterion for working postures, besides the traditionally used for-/backward inclination of the head and/or neck segment.

9.3 Upper arm posture

In the studies on visual-manual operations (chapters 4–7) it could neither be demonstrated that the upper arm elevation for-/backwards (i.e. projected in the sagittal plane of the upright trunk) is the dominant determinant of shoulder (girdle) load, as compared to the upper arm elevation sidewards (i.e. projected in the frontal plane of the upright trunk), nor vice versa. In the discussion sections of the various studies the position of the upper arm with respect to the trunk, that is shoulder flexion/retroflexion in particular, was given a closer look.

For touch-typing VDU operation (chapter 5), the operators elevated their upper arms more forwards if the trunk was more inclined backwards. It seemed that the trunk and upper arms stayed in a fixed geometric configuration, no matter what trunk inclination for-/backwards was chosen (cf. Grandjean *et al.*, 1983). This suggests that the operators strive for an optimum (i.e. most favourable) position of the upper arm with respect to the trunk, i.e. the elbows somewhat in front of the trunk. This posture may be chosen in order to preserve upper arm mobility. Another reason could be that not increasing upper arm elevation forwards while leaning more backwards would have brought the upper arm close to a probably unfavourable shoulder retroflexion position. Due to the rather small upper arm elevations measured during VDU operation, the study does not add to the understanding of the role of gravity as a determinant of shoulder (girdle) load.

For all three maintenance operations (chapter 6) particular working heights were found to be more unfavourable for the upper arm than others. For pneumatic wrenching, a working height of 20 cm above elbow height was considered more unfavourable than working heights below elbow height. For this, the very small upper arm elevation measured, which was also about the same for all heights, cannot be accepted as a reasonable explanation. It seems more likely that the position of the upper arm with respect to the trunk plays a role in this matter, i.e. the upper arm approaches a shoulder retroflexion position when the working height is raised more than 10 cm above elbow height.

For oxy-gas cutting, working heights above elbow height were considered less favourable than a working height at elbow height, while upper arm elevation was about the same.

So, here too the amount of elevation does not seem to play a role with respect to the localized physical perceptions. Again, the position of the upper arm with respect to the trunk constitutes a more likely explanation, i.e. while the working height is raised above elbow height, the upper arm gets rapidly closer to a shoulder retroflexion position. That is, for working height +20cm in particular. Furthermore, for oxy-gas cutting a working height of 20 cm below elbow height was considered less favourable than a working height at elbow height. No such result was found for a working height of 10 cm below elbow height. Because upper arm elevation was about the same for working heights of 10 cm and 20 cm below elbow height, it does not provide an explanation. The fact that the rather great angle between the upper arm and the trunk (that is mainly shoulder flexion) for a working height of 10 cm below elbow height gets even greater when lowering working height to 20 cm below elbow height, points to this parameter as being a reasonable explanation.

For grinding working heights of 15 cm and 5 cm below elbow height were considered less favourable than lower heights. Basically, these results can be explained by the greater upper arm elevation as well as by the position of the upper arm with respect to the trunk, i.e. the upper arm approaches or has reached a shoulder retroflexion position. Though, upper arm elevation measured still seems to be rather small (40–45° at maximum). Bjelle *et al.* (1979;1981) found upper arm elevation[19] 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. Here too, it seems likely that the position of the upper arm with respect to the trunk plays a dominant role in localized physical perceptions, because of its resemblance to the unfavourable postures found for pneumatic wrenching and oxy-gas cutting.

For press operation (chapter 7) all experimental conditions tested were considered equally favourable, except for a 100 cm shoulder-c.o.p. fore/aft distance at elbow height (c.o.p. = centre of press). The latter tended to less favourable localized physical perceptions. No convincing explanation was found in terms of upper arm elevation. The only plausible reason brought up for this phenomenon is that shoulder flexion (defined as the sum of trunk inclination forwards and upper arm elevation forwards) is greater than for the other experimental conditions, i.e. for the 100 cm reach distance at elbow height the flexion angles measured for the subjects involved ranged from 66° to 96°. The upper extremity postures and related workers' perceptions for press operation suggest that the 60° limit established at the studies by Bjelle *et al.* (1979;1981), should be used for the evaluation of the position of the upper arm with respect to the trunk, rather than for the evaluation of the amount of deviation from the hanging posture.

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[19] That is, forward flexion and/or 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.

Somehow this may be related to the results obtained by Pronk (1991), showing that, in the case of an upright trunk, the scapula (shoulder-blade) protracts during upper arm elevation in the sagittal plane of the trunk (denoted forward flexion) from 0° to 60°, and retracts during forward flexion from 60° to maximum. Pro-/retraction is defined as a rotation of the scapula around the one axis within the scapular plane that is perpendicular to the spina scapulae (spine of the scapula), where retraction means that the scapula rotates towards the frontal plane.

For sewing machine operation (chapter 4) no effect of desk height on localized physical perceptions was found. Probably the relatively small upper arm elevation measured at the various desk heights (roughly between 15° and 35°, cf. Bjelle *et al.*, 1979;1981), as well as their small mutual differences are of a relatively low importance as regards shoulder (girdle) load. It should be recognized, however, that the amount of elbow/forearm support on the desk may have affected shoulder (girdle) load. Furthermore, none of what was disclosed before on unfavourable positions of the upper arm with respect to the trunk was found at any of the experimental conditions tested.

On the basis of the studies summarized above, it is concluded that the position of the upper arm with respect to the trunk, that is shoulder flexion/retroflexion in particular, is a determinant of shoulder (girdle) load, that is to be used as an evaluation criterion for working postures, besides the traditionally used elevation of the upper arm.

9.4 Answers to research questions

The series of studies on visual-manual operations described in chapters 4–7 led to the following answers to the research questions put forward in § 3.4:

- *Head/neck posture*
  - Neck flexion/extension is a determinant of neck load, that is to be used as an evaluation criterion for working postures, besides the traditionally used for-/backward inclination of the head and/or neck segment.
- Upper arm posture
  - It could neither be demonstrated that the upper arm elevation for-/backwards is the dominant determinant of shoulder (girdle) load, as compared to the upper arm elevation sidewards, nor vice versa.
  - The position of the upper arm with respect to the trunk, i.e. shoulder flexion/retroflexion in particular, is a determinant of shoulder (girdle) load, that is to be used as an evaluation criterion for working postures, besides the traditionally used elevation of the upper arm.

Chapter 10

Epilogue

10.1 Introduction

This thesis started off with a statement by Haslegrave (1994), that we have reached a stage where we are now able to measure posture with a high degree of accuracy, but have not yet had time to use this research capability to develop an understanding of human behaviour in different work activities which would allow us to specify the criteria for 'good working postures' or to predict the postures which will actually be adopted by operators in industry. With this opinion as foundation, it was decided that the thesis should serve as an exploration stage for the development of a posture prediction and evaluation tool for designers of workstations. For this, determinants of working postures, as well as evaluation criteria for working postures were described (chapters 2 and 8, as well as chapters 3 and 9, respectively). §§ 10.2 and 10.3 summarize in short where we are now and what may be done in the near future, in order to end up eventually with a tool for posture prediction and evaluation.

10.2 Can we predict a working posture?

The prediction of a working posture on the basis of the characteristics of the worker, the workstation, and the operation relies on our knowledge concerning various determinants of working postures. This thesis demonstrates that important determinants are formed by visual interferences, as well as by the interfaces with an actuator, tool, or object (type and orientation of grip/contact), and the workstation (type of body support). However, for prediction purposes the relationships between determinants and working postures need to be quantified. Currently, on the basis of systematic research, we know quite well quantitatively the single postural effects of the vertical gaze direction (up/down, gaze inclination; § 8.2.1), the reach position for the hands in the sagittal plane (Snyder *et al.*, 1971), and the reach position for the feet in the sagittal plane (as characterized by lower extremity posture; Bridger *et al.*, 1989a/b; Eklund and Liew, 1991). Such a position cannot yet be taken up for a horizontal gaze direction (left/right) or an oblique gaze direction (left/right/up/down), nor for a reach direction for a hand or a foot out of the sagittal plane. However, an interesting beginning has been made to extending knowledge in this respect by Hsiao and Keyserling (1991) and Radau *et al.* (1994) for gaze direction[20], and by Snyder *et al.* (1971)[21] and Verriest *et al.* (1994)[22] for hand-reach direction and distance. Furthermore, very little is known about possible interactions of the single postural effects of the various demands concerning vision, hand/foot control, and stability. Therefore, for the near future, straightforward systematic kinematic research is warranted, for establishing the single (in an additional sense) and combined effects of the generic operation demands just mentioned.

10.3 Can we evaluate a working posture?

For a full evaluation of a working posture as regards physical load, many other parameters should be taken into account, such as the total duration of the operation in question, the holding times and recovery times in the case of a static load, the movement frequency in the case of repetitive movements, etc. However, for a relative evaluation (mutual comparison) of working postures, for instance such as measured at various workstation adjustments, where other parameters are kept constant (task performance, duration of operation, etc.; chapters 4-7), the spatial orientation of body segments is mainly to be considered. In this thesis particular attention has been given to the head/neck and upper arm.

For head/neck posture a considerable body of knowledge is available already in the literature (§§ 3.1 and 3.2), pointing to neck flexion/extension as a determinant of neck load, that is to be used as an evaluation criterion for working postures, besides the traditionally used for-/backward inclination of the head and/or neck segment. The results regarding almost all operations studied in chapters 4-7 support this position (§ 9.2). Furthermore, these studies provide insight into relatively unfavourable neck postures, i.e. a particular, likely maximum, flexion position (table 9.1), as well as an extension position. Such a knowledge base does not exist for asymmetric head/neck postures.

For upper arm posture, a few literature sources point to the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk,

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[20] The studies on horizontal gaze direction (§ 2.2.1) were carried out under trunk/chest-fixed conditions, while the two studies mentioned here are characterized by much less restricted circumstances (§ 2.2.1, sub *oblique gaze direction*).

[21] Due to missing data on the position of a particular surface marker at the pelvis, a proper three-dimensional analysis of trunk posture is hampered. Refer to § 2.3.2 for additional information.

[22] A pilot study concerning a particular limited space of reach positions, most probably not inducing trunk movement. Refer to § 2.3.1 for additional information.

respectively) as a determinant of shoulder (girdle) load. This could not be demonstrated by means of the results obtained in chapters 4–7. The latter results, however, lead to the conclusion that the position of the upper arm with respect to the trunk, i.e. shoulder flexion/retroflexion in particular, is to be used as an evaluation criterion for working postures, besides the traditionally used elevation of the upper arm.

On the basis of the foregoing it is concluded that the knowledge base for evaluation of head/neck posture is less immature than for upper arm posture. As regards the directions for future research with respect to the evaluation of working postures, however, it is considered even more important to realize that our generic knowledge on the effects of time domain parameters (duration, frequency) is relatively scarce.

Summary

To date, workstation designers cannot see the effects of a design on working posture before a mock-up/prototype is available. At that moment, usually the margin for creating the conditions required for adopting favourable working postures is still very limited. Posture prediction at an early design phase, i.e. at the CAD screen, would enhance full consideration of ergonomics among other design aspects, as well as reducing costs for proper workstation design. For prediction, however, the determinants of postures have to be known. This thesis describes those determinants, as well as evaluation criteria for working postures. Data are obtained from the literature, as well as from studies by the author on visual-manual operations, i.e. sewing machine operation, VDU operation, pneumatic wrenching, oxy-gas cutting, grinding, and press operation. Using a standardized research approach, these studies describe the effects of the adjustment of workstations 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. The following summarizes in short where we are now and what may be done in the near future in order to end up eventually with a posture prediction and evaluation tool for designers of workstations.

This thesis demonstrates that important determinants of working postures are formed by visual interferences, as well as by the interfaces with an actuator, tool, or object (type and orientation of grip/contact), and the workstation (type of body support). In a quantitative way we know now quite well the single postural effects of the up-/downward gaze direction, and the reach positions for the hands and the feet straight in front of the body. Such a position cannot yet be taken up as regards sideways directions for gaze and reach. Furthermore, very little is known about possible interactions of various demands concerning vision, hand/foot control, and body stability. Therefore, straight-forward systematic kinematic research is indicated, for establishing the single (in an additional sense) and combined effects of the generic operation demands just mentioned.

For a full evaluation of a working posture as regards physical load, many other parameters should be taken into account, such as the total duration of the operation in question, the holding times and recovery times in the case of a static load, the movement frequency in the case of repetitive movements, etc. However, for a relative evaluation (mutual comparison) of working postures, for instance such as those measured at various workstation adjustments, where other parameters are kept constant (task performance, duration of operation, etc.), the spatial orientation of body segments is mainly to be considered. In this thesis particular attention is given to the head/neck and upper arm segments.

For head/neck posture a considerable body of knowledge is already available in the literature, pointing to neck flexion/extension as an evaluation criterion, besides the traditionally used for-/backward inclination of the head and/or neck segment. The results regarding almost all visual-manual operations studied support this position. Furthermore, these studies provide insight into relatively unfavourable neck postures, i.e. a particular, likely maximum, flexion position, as well as an extension position. Such a knowledge base does not exist for asymmetric head/neck postures.

For upper arm posture, a few literature sources point to the direction of the elevated upper arm (for-/sidewards, i.e. projected in the sagittal/frontal plane of the upright trunk, respectively) as a determinant of shoulder (girdle) load. This could not be demonstrated by means of the experimental results obtained. The latter results, however, lead to the conclusion that the position of the upper arm with respect to the trunk, i.e. shoulder flexion/retroflexion in particular, is to be used as an evaluation criterion for working postures, besides the traditionally used elevation of the upper arm.

On the basis of the foregoing it is concluded that the knowledge base for evaluation of head/neck posture is less immature than for upper arm posture. As regards the directions for future research with respect to the evaluation of working postures, however, it is considered even more important to realize that our generic knowledge on the effects of time domain parameters (duration, frequency) is relatively scarce.

Samenvatting

Tot op heden kunnen ontwerpers van werkstations de gevolgen van een ontwerp voor de werkhouding niet zien voordat een mock-up/prototype beschikbaar is. Op dat moment is er echter gewoonlijk nog maar een zeer beperkte speelruimte over voor het (alsnog) realiseren van de noodzakelijke voorwaarden voor het innemen van gunstige werkhoudingen. Houdingsvoorspelling in een vroeg stadium van een ontwerpproces, i.c. op het CAD-scherm, bevordert het volledig rekening houden met ergonomie te midden van andere ontwerpaspecten en reduceert de kosten voor het adequaat ontwerpen van een werkstation. Voor een voorspelling dienen echter de determinanten van houdingen bekend te zijn. Dit proefschrift beschrijft deze determinanten, alsmede beoordelingscriteria voor werkhoudingen. De betreffende gegevens zijn afkomstig uit de literatuur, als ook uit eigen studies gericht op visueel-manuele werkzaamheden, i.c. naaimachinebediening, beeldschermwerk, pneumatisch moeraanzetten, snijbranden, slijpen en persbediening. Met gebruikmaking van een gestandaardiseerde onderzoeksmethode, beschrijven deze studies de effecten van de instelling van werkstations op de werkhouding en percepties van betrokken werkers. Laatstgenoemde bevindingen betreffen korte-termijneffecten, zoals lokaal ervaren ongemak, ten gevolge van de blootstelling aan fysieke belasting gedurende beperkte tijd. Het onderstaande vat in het kort samen waar we nu staan, alsmede wat er in de nabije toekomst te doen staat om uiteindelijk te komen tot een instrument voor houdingsvoorspelling en -beoordeling ten behoeve van ontwerpers van werkstations.

Dit proefschrift laat zien dat belangrijke determinanten van werkhoudingen zijn gelegen in belemmeringen van het zicht en in de raakvlakken met een bedieningsmiddel, gereedschap of object (aard en stand van de greep/contact) en het werkstation (aard van de lichaamsondersteuning). In kwantitatieve zin kennen we momenteel tamelijk goed de enkelvoudige houdingseffecten van de kijkrichting naar boven/beneden en de reikposities voor de handen en de voeten recht voor het lichaam. Een dergelijk standpunt kan niet worden ingenomen voor zijwaartse kijk- en reikrichtingen. Daarnaast is zeer weinig bekend over mogelijke interacties van diverse eisen wat betreft zicht, hand/voet-acties en lichaamsstabiliteit. Derhalve is rechttoe rechtaan systematisch kinematisch onderzoek aangewezen, teneinde de enkelvoudige (in aanvullende zin) en gecombineerde effecten van de zojuist genoemde algemene eisen te bepalen.

Voor een volledig oordeel over een werkhouding ten aanzien van fysieke belasting dienen eveneens vele andere parameters in ogenschouw te worden genomen, zoals de duur van de werkzaamheid in kwestie, de volhoud- en hersteltijden in geval van statische belasting, de bewegingsfrequentie in geval van repeterende bewegingen, enz. Echter, voor een relatieve beoordeling (onderlinge vergelijking) van werkhoudingen, zoals bijvoorbeeld gemeten bij verschillende instellingen van een werkstation, waar andere parameters constant zijn gehouden (prestatie, werkduur, enz.), zijn hoofdzakelijk de standen van lichaamssegmenten van belang. In dit proefschrift is in het bijzonder aandacht besteed aan de segmenten hoofd/nek en bovenarm.

Voor de beoordeling van hoofd/nekhoudingen is al een aanzienlijke hoeveelheid kennis beschikbaar vanuit de literatuur, welke wijst in de richting van nekflexie/extensie als beoordelingscriterium, benevens de gewoonlijk gehanteerde mate van voor-/achterwaartse inclinatie van het hoofd- en/of neksegment. De resultaten voor bijna alle bestudeerde visueel-manuele werkzaamheden ondersteunen dit gegeven. Bovendien leveren deze studies inzicht in relatief ongunstige nekhoudingen, i.c. een specifieke (waarschijnlijk maximale) flexie-stand en een extensie-stand. Een dergelijke kennisbasis is er nog niet voor asymmetrische hoofd/nekhoudingen.

Voor de beoordeling van bovenarmhoudingen wijzen een beperkt aantal literatuurbronnen op de richting van een geheven bovenarm (voor-/zijwaarts, d.w.z. geprojecteerd in het sagittale respectievelijk frontale vlak van de rechtstandige romp), als determinant van de belasting van de schouder(gordel). Dit kon niet worden aangetoond door middel van de resultaten van de eigen experimenten. Laatstgenoemde resultaten echter leiden tot de conclusie dat de stand van de bovenarm ten opzichte van de romp, en wel schouderflexie/-retroflexie in het bijzonder, te gebruiken is als beoordelingscriterium, benevens de gewoonlijk gehanteerde mate van heffing van de bovenarm.

Op grond van het voorafgaande wordt geconcludeerd dat de kennisbasis voor de beoordeling van hoofd/nekhoudingen minder onvolwassen is dan voor bovenarmhoudingen. Wat betreft toekomstig onderzoek inzake de evaluatie van werkhoudingen wordt het van groter belang geacht om in te zien dat onze algemene kennis over de effecten van tijd-gerelateerde parameters (duur, frequentie) relatief schaars is.

Glossary

Determinant of musculoskeletal load:
: spatial orientation(s) of one or more (linked) body segments disclosing a systematic relationship with musculoskeletal load

Determinant of working posture:
: constraint as regards posture selection by the worker involved

Frankfurt plane:
: plane through the tragia (approximately the earholes) and the lowest points of the orbits (eye sockets)

Inclination:
: deviation of the segment defined (head and/or neck, trunk) from the upright posture or the vertical

— for-/backwards:
: — projected in the sagittal plane of the upright segment

— sidewards:
: — *projected in the frontal plane of the upright segment*

Neck flexion/extension:
: head and/or neck inclination for-/backwards with respect to trunk inclination for-/backwards

Postural space:
: all working postures that can be adopted voluntarily and momentarily, given a set of physical limitations

Postural strategy:
: systematic relationship between a determinant of working posture and the working posture

Shoulder flexion/retroflexion:
: upper arm elevation for-/backwards with respect to trunk inclination for-/backwards

Upper arm elevation:
: deviation of the upper arm from the hanging posture or the vertical

— for-/backwards:
: — projected in the sagittal plane of the upright trunk

— sidewards:
: — projected in the frontal plane of the upright trunk

Workers' perceptions:
: short-term effects, such as postural discomfort, due to physical load exposure of limited duration

Working posture:
: spatial orientation of body segments, or the sequence of orientations adopted over time, while performing a work task/operation

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