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Technical Note

The use of mirrors during an assembly task: a study of ergonomics and productivity

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Industrial assembly tasks often require awkward, sustained neck and/or shoulder postures that can lead to increased musculoskeletal discomfort and reduced productivity. The aim of this study was to investigate the effects of mirror and periscope visual aids as ergonomic interventions designed to eliminate awkward postures of the cervicobrachial region during assembly tasks. Participants simulated a simple assembly task by using a cordless screwdriver to drive screws into a pre-tapped aluminium block. Trials of 15 min were run for each of four distinct assembly workstation configurations: industry standard (in-line screwdriver, work at elbow height, no visual aid); pistol grip (pistol grip screwdriver, work at shoulder height, no visual aid); mirror (in-line screwdriver, work at elbow height, single mirror visual aid); and periscope (in-line screwdriver, work at elbow height, two-mirror visual aid system). Muscular activity, discomfort, body posture, productivity and operator subjective assessment were recorded to determine the effects of the visual aid interventions. The results show that when comparing the interventions to the industry standard condition, there was a 45% reduction in average cervical erector spinae activity, a 90% reduction in average neck flexion angle and a 72% reduction in neck discomfort with the interventions. When comparing these interventions to the pistol grip condition there was an 80% reduction in activity of the dominant side deltoid, a 92% reduction in shoulder flexion angle and an 81% decrease in shoulder discomfort with the interventions. Productivity was greatest in the industry standard configuration followed by the pistol grip (9% lower), the periscope (13% lower) and the mirror (23% lower) configurations. A follow-up study that compared the productivity of the periscope configuration with that of the industry standard configuration showed that within a 4-h work period this productivity differential decreased by over 33%.

1. Introduction

There are many occupations in industry that require prolonged static neck flexion and/or shoulder flexion. Inspection, assembly and video display unit (VDU) usage are a few examples of tasks that involve postures with some level of deviation from neutral neck and shoulder positions. These deviated postures have been shown to be associated with the development of musculoskeletal discomfort and disorders (Kilbom and

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Persson 1987, Visser and Straker 1994, Miedema *et al*. 1997, Straker *et al*. 1997a, b, Zetterberg *et al*. 1997, Finsen *et al*. 1998). For example, Straker *et al*. (1997b) found that greater neck discomfort occurred with laptop computer usage than with desktop computer usage due to increased neck flexion and head tilt. A cross-sectional study conducted by Kilbom and Persson (1987) involving 96 female workers in the electronics manufacturing industry revealed a relationship between symptoms in the neck and trapezius region and forward flexion of the neck and elevation of the shoulder.

Biomechanically, deviation from the neutral position increases postural load in the cervicobrachial region leading initially to local muscle fatigue and discomfort and in the long term to musculoskeletal illness (Westgaard and Aaras 1984, Colombini *et al*. 1986, Kilbom *et al*. 1986, Aaras and Westgaard 1987, Marshall *et al*. 1997, Turville *et al*. 1998). In a biomechanical evaluation of six different seated postures, Colombini *et al*. (1986) illustrated a 3 – 8% increase in myoelectric activity of the superior trapezius and a 20 – 30% increase in computed compressive load in the C6/C7 intervertebral joint when participants assumed a bent forward head position as compared to a neutral, upright posture. In an epidemiological study of an electro-mechanical assembly plant, Aaras and Westgaard (1987) documented that ergonomic adaptations that were designed to improve worker posture had the effect of reducing the load on the trapezius muscles and contributed to a significant reduction in sick-leave in several departments in the facility.

Postures that promote fatigue and/or discomfort have been shown to decrease human performance, which can lead to decreased productivity and quality (Bhatnager *et al*. 1985, Kroemer and Grandjean 1997, Miedema *et al*. 1997, Straker *et al*. 1997b). Studying the effects of shoulder posture while using a keyboard and a VDU, Straker *et al*. (1997b) showed that a 0° shoulder flexion corresponded to less discomfort, less fatigue and better performance than a 30° shoulder flexion. Straker *et al*. (1997b: 8) stated that 'The performance improvement achieved in this study, by adopting 0° shoulder flexion, is important as it justifies ergonomic intervention on productivity criteria alone'. In another study linking posture to human performance, Bhatnager *et al*. (1985) showed that poor defect detection performance was found in forward flexed postures of the trunk when compared to more neutral postures.

An association between non-neutral postures and increased discomfort and productivity has established the need for quantitative evaluation of ergonomic interventions in the workplace. The aim of this study was to assess the effects of visual aids (mirrors) on ergonomics and productivity during an assembly task. Two separate experiments were conducted to evaluate these effects. The first aimed at understanding the short-term effects of these interventions, while the second sought to provide a greater understanding of the changes (particularly in productivity) that came with longer term use of the interventions.

2. Methods

2.1. *Experiment 1*

2.1.1. *Participants*: There were six male and six female participants in this study. All participants were recruited from the university population (age range from 21 to 38 years), were in good health and had no history of significant musculoskeletal injury of the neck or upper extremities. Eleven participants were right-hand dominant and one participant was left-hand dominant.

Each participant signed an informed consent form before participation.

2.1.2. *Apparatus*: The simulated assembly task performed by the participants was to drive machine screws into 7.5 cm $\times$15 cm aluminium blocks. Each block had four rows of pre-tapped holes. Each row consisted of 9 tapped holes, 1.27 cm apart. The Phillips-head screws used in this experiment were 2.54 cm long, were 0.64 cm in diameter and had 20 threads per 2.54 cm.

Participants performed these assembly tasks on a height adjustable workstation that could be arranged into four different 'assembly workstation configurations': (1) Industry Standard Configuration (ISC); (2) Mirror Configuration (MC); (3) Periscope Configuration (PC); and (4) the Pistol Grip Configuration (PGC), as shown in figure 1.

Mirror heights and work surface heights were established based on the individual participant's anthropometric measurements. For the ISC, MC and PC assembly workstation configurations, the height of the worksurface was set so that the participant's elbow was at approximately a 90° flexion angle when using the in-line screwdriver. The horizontal distance of the centre of the workpiece from the anterior surface of the participant was a constant distance of 15 cm. For the PGC position, the height of the workpiece was set at the participant's standing acromion height and the horizontal distance was taken to be the participant's horizontal arm reach with fingers extended.

Mirrors were used in the MC and the PC assembly workstation configurations. Each mirror had a 16.5 cm high by a 11.4 cm wide viewing surface and was angle-adjustable to accommodate the participant's height and viewing angle. One mirror was utilized in the MC condition (figure 1b). The height of the centre of the mirror's viewing surface was set at the participant's standing eye height, resulting in a zero degree viewing angle relative to the horizontal. The participant was permitted to adjust the mirror tilt to optimize the view of the work area. Two mirrors were utilized for the PC condition (figure 1c). The first mirror (Mirror 1) was positioned with its reflective surface facing downward in a horizontal position at the participant's standing eye height. The second mirror (Mirror 2) was positioned below the first with its reflective surface facing the reflecting surface of Mirror 1 in an acute angle determined by the participant in order to sufficiently view the work area. The average viewing angle of the participants using the periscope was approximately $-5°$ from the horizontal.

Each participant in the experiment used four Craftsman™ (model no. 315.11690, Sears, Roebuck and Co., Hoffman Estates, IL, USA) cordless screwdrivers (mass = 0.624 kg). The screwdrivers had an adjustable feature that allowed them to be used in either a pistol grip position or an in-line position. The pistol grip position was only used in the PGC trial while the in-line position was used for the ISC, MC and PC trials. The pistol grip position places the handle of the screwdriver at 120° to its spindle axis while the in-line position keeps the handle along the spindle axis. To maintain its maximum turning speed throughout each trial, a different screwdriver of the same model was used for each of the four 15-min trials.

As the participants performed these assembly tasks, a video camera recorded all postures and movements by the participant in the sagittal plane. Reflective markers were placed on each participant's dominant side at the following locations: tragus; canthus; C7 spinous process; rotation point on the humerus; lateral epicondyle of the humerus; styloid process; and greater trochanter of the femur. The video data were analysed

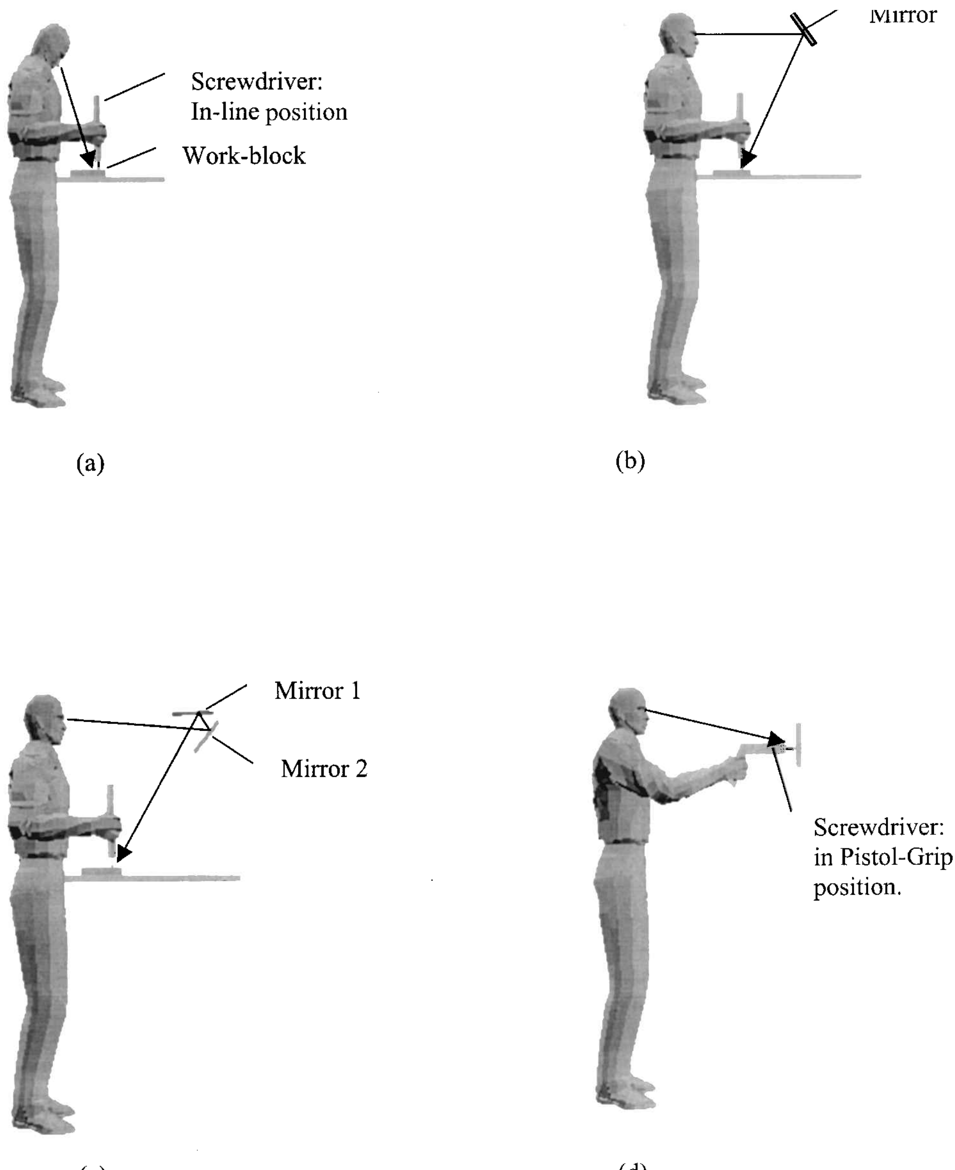

Figure 1. Assembly workstation configurations: (a) Industry Standard Configuration; (b) Mirror Configuration; (c) Periscope Configuration; and (d) Pistol Grip Configuration.

using the Peak Motus motion measurement system (Peak Performance Technologies Inc., Englewood, CO) to generate the postural angles of interest.

Myoelectric activity was collected using 21 bipolar Ag–AgC1 surface electrodes having an inner diameter of 4 mm (model EE22x, InVivo Metric, Healdsburg, CA). An inter-electrode distance of 2 cm was used between the 10 electrode pairs. The pre-amplified signal was carried by way of shielded cables to the electromyographic (EMG) system (Data Design, Inc., Columbus, OH). The EMG hardware amplified, rectified and filtered (notch filter at 60 Hz and a low-pass filter of 1000 Hz) the EMG signals. Since activities performed by participants in this experiment were static in nature, a large averaging window of 200 ms was used.

A Kin-Com isokinetic dynamometer (Chattecx Corporation, Chattanooga, TN) was used during the collection of isometric maximum voluntary contractions of the neck. The dynamometer allowed the research team to precisely position the participant in the necessary postures during the collection of the maximum voluntary contraction (MVC) exertions.

2.1.3. *Experimental task*: Participants were tasked with driving screws into a pre-tapped aluminium block for a period of 15 min per condition. Participants were instructed to work as fast as possible (simulating a piece-rate system) and to alternate between the first and third rows to better assess productivity effects of the visual aids. The aluminium block was secured in a three-sided fixture and the screws were placed in a bin adjacent to the fixture on the participant's non-dominant side. Upon completion of a block, the participant removed the filled block from the fixture and moved it, along with the empty bin, to the side and replaced it with an empty block and a full bin of screws.

2.1.4. *Experimental design*

2.1.4.1. *Independent variables*: The independent variable in this study was workstation configuration, which had four levels as illustrated in figure 1. The presentation order of these assembly workstation configurations was counterbalanced across participants to control for order and carryover effects.

2.1.4.2. *Dependent variables*: There were four dependent variables as follows.

(1) *Posture*. The reflective markers placed on each participant were used to calculate the absolute values of the postural angles of interest: head tilt angle; neck angle; trunk angle; elbow angle; and shoulder angle. These angles were then compared to the neutral posture angles collected as the participant stood upright with arms at sides, looking straight ahead. The deviations from the neutral posture angles are the posture-related dependent measures.
(2) *Muscle activity*. The EMG-based dependent measures were the normalized, integrated EMG (NIEMG) data from: the right trapezius; left trapezius; right cervical erector spinae; left cervical erector spinae; right thoracic erector spinae; left thoracic erector spinae; right levator scapulae; left levator scapulae; right deltoid; and left deltoid. Muscle activity was sampled for 3 s at 1 min intervals throughout each task.
(3) *Discomfort questionnaire and subjective assessment*. Immediately after the completion of each 15-min task interval, participants were asked to fill out a discomfort questionnaire. A discomfort survey similar to the one described by Corlett and Bishop (1976) was used. Discomfort questionnaires displayed a human outline with lines pointing to the following areas: neck, right trapezius; left trapezius; right shoulder; left shoulder; upper back; and lower back. Participants were asked to rank discomfort in each area from a scale from 0 (no discomfort) to 5 (painful) and describe to what they attributed their discomfort.

Questionnaires presented after the MC, PC and PGC assembly workstation configurations also asked participants to compare the position recently completed to the ISC position in terms of comfort and efficiency. After completing all four assembly workstation configurations the participants completed a summary questionnaire that enquired about assembly workstation configuration preferences for neck and shoulder comfort and general position preferences concerning productivity and adaptation.

(4) *Performance*. Performance was assessed by productivity. Productivity was measured for each 15-min trial by quantifying the mean time required to complete a block.

2.1.5. *Procedure*: Participants participated in two experimental sessions. Session 1 was a practice session that allowed the participants to get familiar with the assembly task in all four postures and also included gathering anthropometric measurements. Session 2 consisted of warm-up exercises, reflective marker and electrode placement, maximal voluntary contractions, the four experimental tasks, discomfort questionnaires and a final subjective assessment.

2.1.5.1. *Session 1*: The participant was informed of the experimental requirements and procedures and was asked to read and sign the informed consent form. Anthropometric measurements were taken and used to calculate workstation dimensions. The participants then practised driving screws using each assembly workstation configuration. Practice for the ISC and PGC positions consisted of filling one aluminium block. Practice for the MC and the PC consisted of driving screws for a 15-min time period for each. More time was given to practise these unconventional assembly workstation configurations in order to give adaptation time for the novel hand-eye co-ordination demands of these configurations.

2.1.5.2. *Session 2*: Session 2 began with a series of warm-up exercises for the neck and shoulder muscles. The participant's neck, shoulders and upper back were then prepared for electrode placement by using established guidelines (Marras 1990). Surface electrodes were then applied to the participant's skin.

Each participant performed a total of 8 maximal isometric exertions. Maximal exertions were performed for 5 s and verbal encouragement was given to motivate the participants during these exertions. The first four exertions were performed with the participant in a seated posture. The first exertion was a neck extension from a neutral posture against a padded attachment on the dynamometer. This posture simulated the neck posture during the PC, MC and PGC tasks. The second exertion was similar to the first, but with the neck bent at approximately a 45° angle to simulate the neck posture during the ISC task. The third and fourth exertions consisted of right and left deltoid flexion, respectively, against manual resistance with arms flexed to 90° in the sagittal plane. This shoulder posture simulated the shoulder posture during the PGC task. The fifth and sixth exertions were also isometric shoulder flexion against manual resistance but with the shoulder only flexed 20° in the sagittal plane to simulate the shoulder posture used in the ISC, PC and MC tasks. The seventh exertion was a maximum shoulder shrug against a stationary bar with arms hanging vertically from the shoulders with elbows fully extended. The eighth, and final, maximum exertion was a maximum thoracic extension against manual resistance in a supine position.

After maximum exertions were collected, the participant was taken to the assembly workstation. Each participant was read an identical script concerning the idea of working by piece rate to motivate for maximum productivity. The participant was then given time to completely fill one aluminium block as practice in the particular assembly workstation configuration before data collection. During the actual trial, IEMG readings were taken approximately once every minute and lasted for 3 s. To maintain consistency in the data, the IEMG data collection occurred as the participant was driving a screw. Upon completion of the 15-min data collection period, the participant was seated in a chair for a 15-min rest break. During this time the participant completed a discomfort questionnaire concerning the assembly workstation configuration just completed.

After the rest break, the participant was placed in the next assembly workstation configuration as defined by the counterbalanced sequence. The same sequence of steps described for the first assembly workstation configuration were completed for this and the remaining assembly workstation configurations. After completing work in all assembly workstation configurations, the participant was given the final questionnaire to complete.

2.1.6. *Data analysis*: Task IEMGs (of 3-s duration at 1-min intervals) were normalized with respect to posture-specific maximum values for each muscle. One minute interval 'snapshots' were taken from the videotapes and were evaluated using the peak 2-D system and deviations from neutral were calculated. To simplify the interpretation of the results, the data from the one left-handed participant in this study was adjusted so that his data was consistent with the rest of the data set (i.e. right side muscle activities were transformed to left side and vice versa, and the video data was re-interpreted to be consistent with the rest of the dataset). Discomfort variables were tabulated from the participants' responses on the questionnaires. The productivity during each 15-min interval measure was calculated by dividing 15 min by the number of blocks (including partial blocks) completed. ANOVA techniques were used to assess the effects of the different workstation configurations on posture, muscle activation, discomfort and productivity. The Ryan-Einot-Gabriel-Welsch Multiple Range *post-hoc* test was used to test for significant differences between levels of assembly workstation configuration for each dependent variable.

2.2. *Experiment 2*

Eight new people participated in this experiment. The principal methodological differences between this experiment and Experiment 1 outlined above are that the duration of the experimental trials was extended to 4 h per condition (allowing for a more realistic evaluation of the adaptation of the workers to the novel workstation configuration) and the participants only worked in the industry standard configuration and the periscope configuration. A 15-min break was given at a point 2 h into the experiment to simulate the mid-morning break period. To reduce fatigue effects, subjects performed only one condition per day.

3. Results

3.1. *Experiment 1*

The results of the ANOVA procedure (table 1) and subsequent *post-hoc* tests

Table 1. Summary of ANOVA results for the effect of the independent variable 'workstation configuration'.

Data type	Dependent variables	df	F value	p
EMG	Left deltoid	3	8.00	0.0004
	Right deltoid	3	67.40	<0.0001
	Left trapezius	3	24.91	<0.0001
	Right trapezius	3	18.43	<0.0001
	Right levator scapulae	3	9.42	<0.0001
	Left cervical erector spinae	3	12.06	<0.0001
	Right cervical erector spinae	3	17.26	<0.0001
	Right thoracic erector spinae	3	6.17	0.0019
	Left levator scapulae	3	18.03	<0.0001
	Left thoracic erector spinae	3	5.84	0.0029
Posture	Elbow angle	3	2.48	0.0808
	Neck angle	3	94.57	<0.0001
	Trunk angle	3	2.6	0.0715
	Head tilt angle	3	81.66	<0.0001
	Shoulder angle	3	142.48	<0.0001
Productivity	Average time/block	3	18.31	<0.0001
Discomfort	Left trapezius	3	4.32	0.0112
	Right trapezius	3	9.46	0.0001
	Neck	3	9.73	<0.0001
	Left shoulder	3	13.93	<0.0001
	Right shoulder	3	43.92	<0.0001
	Upper back	3	2.9	0.0496
	Lower back	3	1.03	0.3906
	Overall average	3	14.56	<0.0001

demonstrated several important results that were consistent across dependent variables. The workstation configuration had a significant effect on the posture of the neck, head and shoulder, while there were no significant differences in elbow or trunk angles (figure 2). The PGC had the greatest shoulder angle deviation from neutral (39°) while the mean neck angle during the ISC trials was 32° forward from neutral, and the mean head angle during the ISC trials was 47° from neutral.

The response of NIEMG activity was consistent with these posture results (figures 3 and 4). The muscle activity for both the deltoid and the trapezius muscles was much higher for the PGC as compared to the other assembly workstation configurations, while the ISC generated greater muscle activity in the cervical and thoracic erector spinae muscles. It is interesting to note that the PGC also generated high values for the erector spinae muscles. In all configurations the relatively high left deltoid output is a result of the non-dominant hand reaching for the next screw, a fairly consistent activity of the participants while the dominant hand is driving the screw into the block.

The PGC position had the highest overall subjective discomfort rating (PGC = 3.67, ISC = 1.29, PC = 0.70, MC = 0.67) while body part-specific subjective assessment of the upper back, left and right trapezius, neck, and left and right shoulder were consistent with the posture and NIEMG data (figure 5). The low-back discomfort ratings showed no significant difference across assembly workstation configurations. Discomfort was ranked lowest in the left and right trapezius, left and right shoulder, upper back and neck when the mirror and periscope were used.

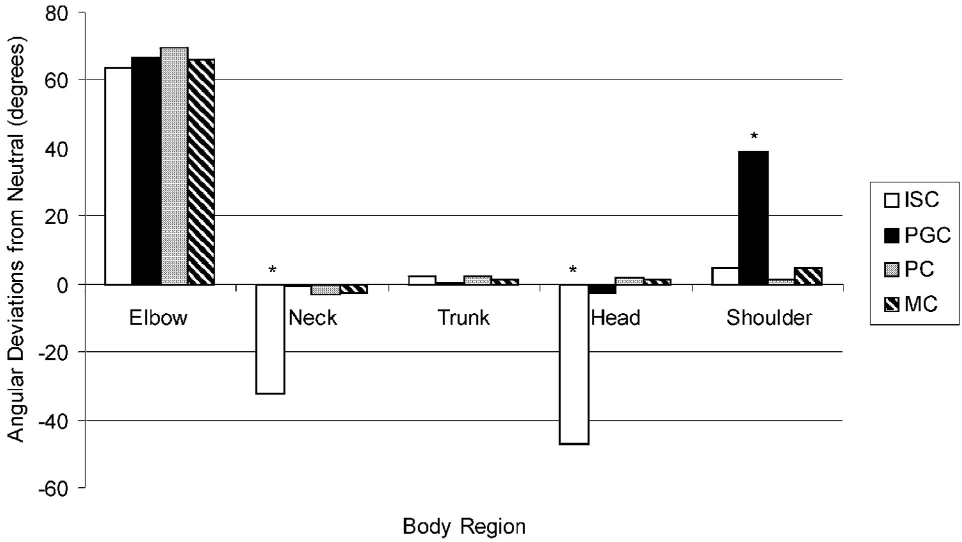

Figure 2. Angle deviation from neutral (* indicates the condition that was significantly different from the others in that grouping).

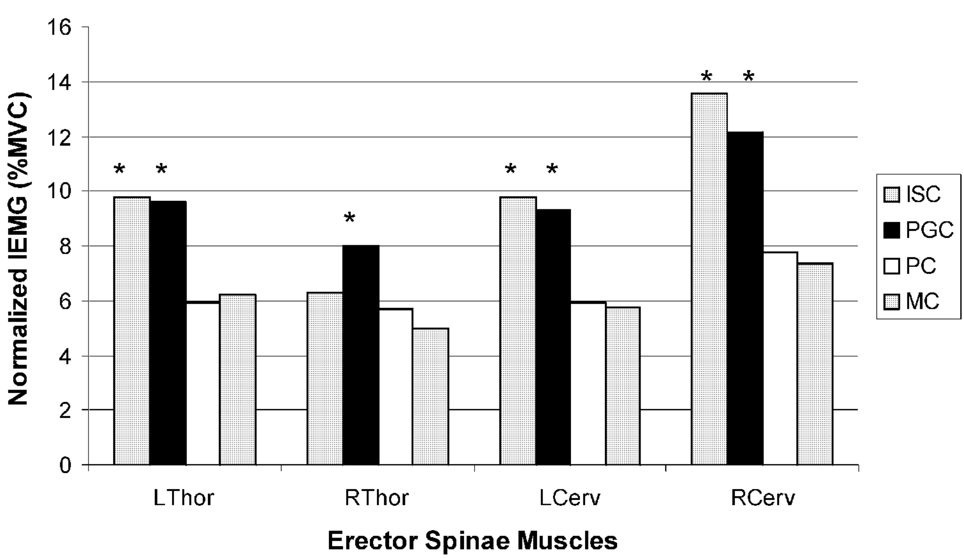

Figure 3. NIEMG output of the erector spinae muscles (* indicates those conditions that were significantly different from the others in that grouping).

In contrast to the positive biomechanical impact that these interventions had on human performance, figure 6 illustrates the negative impact that these interventions had on the productivity during these 15-min trials. Not surprisingly, participants showed the highest productivity in those configurations that

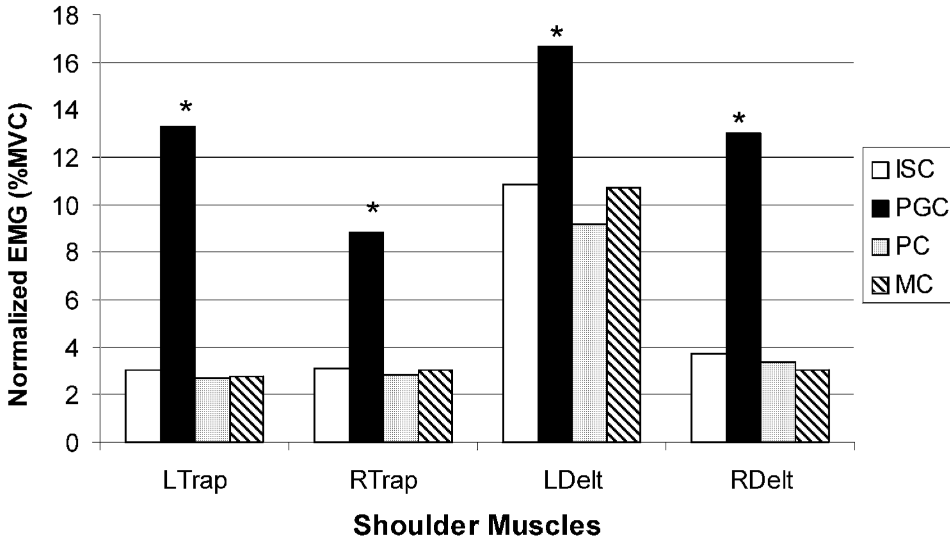

Figure 4. NIEMG output of the trapezius and deltoid muscles (* indicates the condition that was significantly different from the others in that grouping).

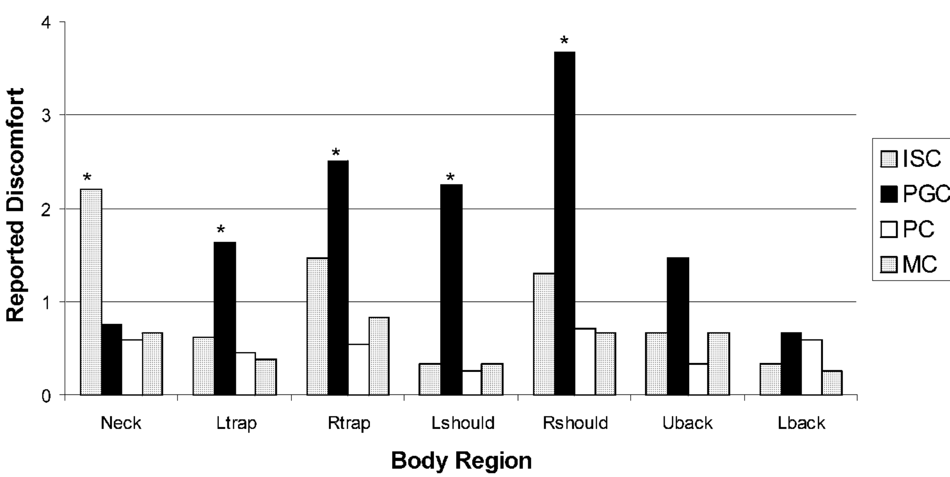

Figure 5. Body part-specific discomfort ratings (* indicates the condition that was significantly different from the others in that grouping).

did not rely on an indirect view of the tool/screw interface.

3.2. *Experiment 2*

An evaluation of the time per block measure of productivity in Experiment 2 showed that productivity in the both conditions improved over the 4-h period. However, averaged across subjects, the productivity differential between the ISC and the PC dropped by over 33% over the 4-h period (figure 7), indicating that the improvements when using the periscope were greater than those when using the

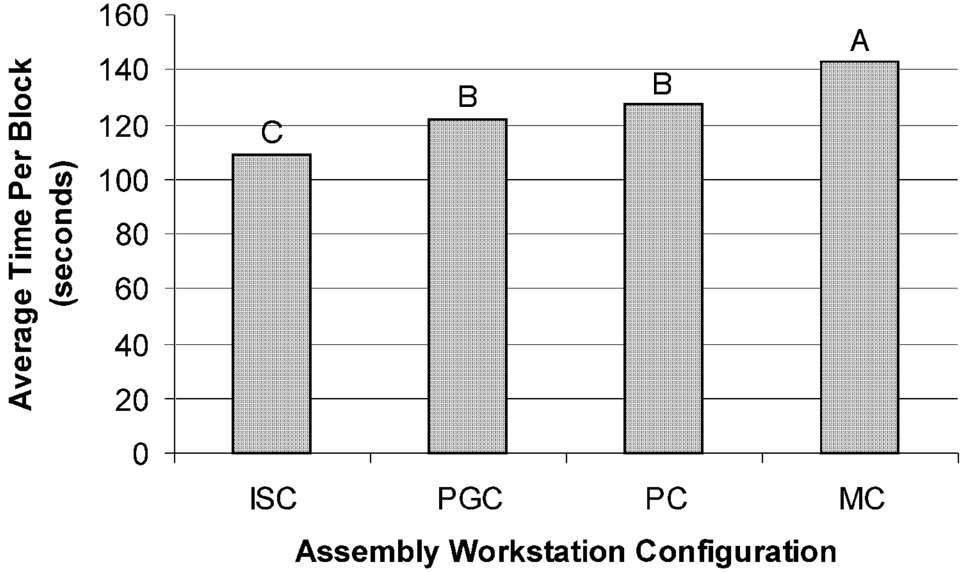

Figure 6. Productivity assessment: average time per block (vertical bars with the same letter are not significantly different).

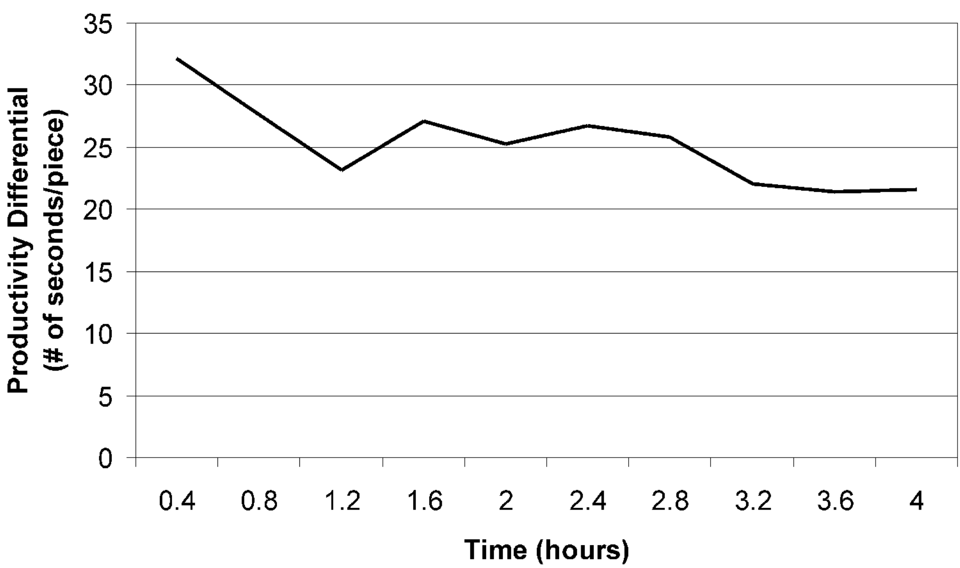

Figure 7. Change in productivity differential over the 4-h experimental period.

industry standard configuration. In fact, three of the eight participants in Experiment 2 showed levels of productivity at the end of the 4-h period that were the same as those of the industry standard configuration (figure 8). There were no significant difference in NIEMG or working posture between Experiments 1 and 2.

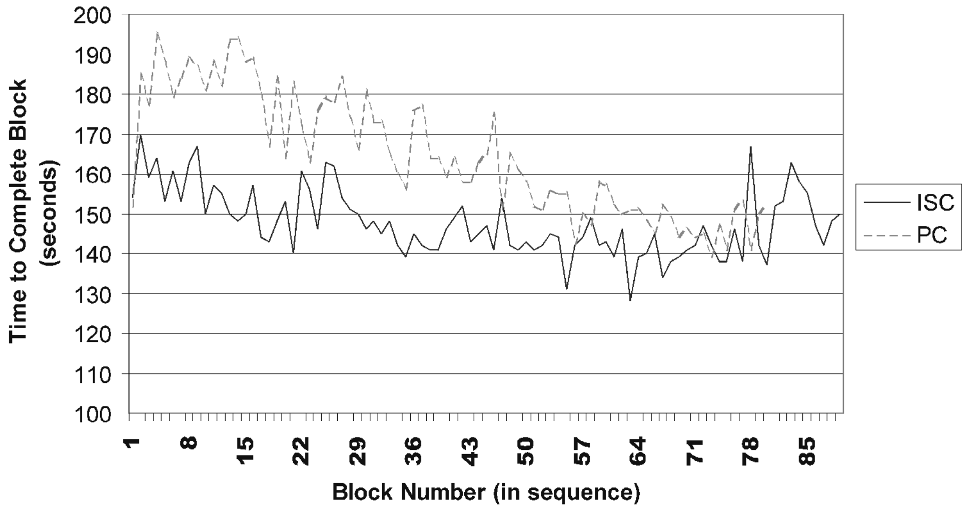

Figure 8. One participant's productivity change as a function of time into experiment.

4. Discussion

The two assembly workstation configurations tested in Experiment 1 that did not include the visual aid of the mirror(s) generated levels of posture, muscle activity and discomfort that would indicate a point of concern for ergonomists. Shoulder postures during the PGC conditions and head and neck postures during the ISC conditions were beyond those that should be required of workers (Kroemer and Grandjean 1997, Miedema *et al.* 1997). Muscle activity levels of the trapezius and deltoid muscles during the PGC condition and the cervical and thoracic erector spinae during the ISC condition were both greater than the recommended static muscle load limits that have been recommended to minimize discomfort and fatigue (Jonsson 1982, Schuldt *et al.* 1987, Aaras 1994). The result of holding these deviated postures for extended periods of time is acute discomfort and reduced blood flow to the muscle. This reduced blood flow can result in impaired muscle metabolism and can lead to more serious musculoskeletal conditions. The results of the analysis of the discomfort data confirmed that these participants experienced significant levels of discomfort in the shoulder region during the PGC condition and in the neck and upper back region during the ISC condition. To minimize neck discomfort over an 8-h workday, 11 of the 12 participants in Experiment 1 said that they would prefer to use the interventions (10 periscope, 1 mirror). These figures are supported by the observation of the number and magnitude of gross body movements (head rolling, shoulder shrugs, trunk flexions) made by the subjects in Experiment 2 when in the industry standard configuration.

While the biomechanics perspective overwhelmingly identified the two visual aid conditions as being superior, the authors' productivity measure identified the more traditional industry standard configurations as being superior. A total of 75% of the participants said that they would prefer the industry standard configuration if they were being paid using a piece-rate system. This leads to an apparent conflict between ergonomics and productivity in this study that would seem to necessitate a management decision between these two objectives. There are, however, studies that have considered broader measures of productivity and have found that these two objectives are not necessarily at odds with one another (Bhatnager *et al.* 1985, Visser and Straker 1994, Straker *et al.* 1997b). With regard to the results of the current studies, it is noteworthy that 100% of the participants in Experiment 1 believed that they would become more proficient with using both the mirror and periscope aids if they were given more time for adaptation. In fact, by the end of the 4-h work period, three of eight participants in Experiment 2 showed the same levels of productivity while using the periscope as in the industry standard condition. It is reasoned, therefore, that with greater training and adaptation, productivity with the interventions would increase. On the other hand, standard industry assembly methods may lead to losses in productivity due to local muscle fatigue and discomfort as well as long-term losses in productivity due to increased prevalence of musculoskeletal illness and lost workdays. Combining these two concepts, it is reasonable to assume that in the long term there would be a narrowing in the gap between the productivity of the industry standard methods and the methods that employ the visual aid interventions.

There are several limitations to the current studies that should be mentioned. First, these studies involved a very structured and consistent task, which may not accurately simulate assembly work in any particular industry. Consequently, the application of the visual aid intervention to more varied types of tasks found in industry should be done with caution. Second, while the participants did have an opportunity to practise using the visual aid interventions, the task durations for each experiment were relatively short. These experimental trials may not provide adequate adaptation time for the participants to become accustomed to the visual demands and the hand-to-eye coordination required. (The trends shown in Experiment 2 support this notion). These results may therefore be underpredicting the true productivity levels as the worker would reach steady-state using these devices. Finally, it should be noted that the participants in these studies were required to use the ergonomic interventions (i.e. they were not allowed to look directly at the workpiece when under the intervention conditions). A more realistic industrial application of these interventions would allow the operators to use these interventions on an as-needed basis, thereby giving themselves the beneficial intermittent postural rest breaks while maintaining high levels of productivity.

5. Conclusions

This study has shown that the use of single mirror and dual mirror visual aids provide relief from shoulder and neck discomfort so often noted in assembly tasks. The results also showed that as compared to a more standard work method, these interventions decreased productivity by about 13% in the periscope configuration and 23% in the single mirror configuration. It is reasoned, however, that with greater training and adaptation, productivity with the interventions will increase. It is further hypothesized that in the more standard work methods, local muscle fatigue and discomfort may reduce productivity. The combination of these two phenomena may lead to a narrowing of the productivity differential gap.

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References

Aaras, A. 1994, Relationship between trapezius load and the incidence of musculoskeletal illness in the neck and shoulder, *International Journal of Industrial Ergonomics*, **14,** 341–348.

Aaras, A. and Westgaard, R. H. 1987, Further studies of postural load and musculoskeletal injuries of workers at an electro-mechanical assembly plant, *Applied Ergonomics*, **18,** 211–219.

Bhatnager, V., Drury, C. G. and Schiro, S. G. 1985, Posture, postural discomfort, and performance, *Human Factors*, **27,** 189–199.

Columbini, D., Occhipinti, E., Frigo, C., Pedotti, A. and Grieco, A. 1986, Biomechanical, electromyographical and radiological study of seated postures, in E. N. Corlett, J. R. Wilson and I. Manenica (eds), *Ergonomics of Working Postures* (London: Taylor & Francis), 331–344.

Corlett, E. N. and Bishop, R. P. 1976, A technique for assessing postural discomfort, *Ergonomics*, **19,** 175–182.

Finsen, L., Christensen, H. and Bakke, M. 1998, Musculoskeletal disorders among dentists and variation in dental work, *Applied Ergonomics*, **29,** 119–125.

Jonsson, B. 1982, Measurement and evaluation of local muscular strain in the shoulder during constrained work, *Journal of Human Ergology*, **11,** 73–88.

Kilbom, A. and Persson, J. 1987, Work technique and its consequences for musculoskeletal disorders, *Ergonomics*, **30,** 273–279.

Kilbom, A., Persson, J. and Jonsson, B. 1986, Risk factors for work-related disorders of the neck and shoulder–with special emphasis on working postures and movement, in E. N. Corlett, J. R. Wilson and I. Manenica (eds), *Ergonomics of Working Postures* (London: Taylor & Francis), 44–53.

Kroemer, K. and Grandjean, E. 1997, *Fitting the Task to the Man*, 5th ed. (London: Taylor & Francis).

Marras, W. 1990, Guidelines: industrial electromyography, *International Journal of Industrial Ergonomics*, **6,** 89–93.

Marshall, E. D., Duncombe, L. M., Robinson, R. Q. and Kilbreath, S. L. 1997, Musculoskeletal symptoms in New South Wales dentists, *Australian Dental Journal*, **42,** 240–246.

Miedema, M. C., Douwes, M. and Dul, J. 1997, Recommended maximum holding times for prevention of discomfort of static standing postures, *International Journal of Industrial Ergonomics*, **19,** 9–18.

Schuldt, K., Ekholm, J., Harms-Ringdahl, K., Nemeth, G. and Arborelius, U. P. 1987, Effects of arm support or suspension on neck and shoulder muscle activity during sedentary work, *Scandinavian Journal of Rehabilitative Medicine*, **19,** 77–84.

Straker, L. M., Jones, K. J. and Miller, J. 1997a, A comparison of the postures assumed when using laptop computers and desktop computers, *Applied Ergonomics*, **28,** 263–268.

Straker, L. M., Pollock, C. M. and Mangharam, J. E. 1997b, The effect of shoulder posture on performance, discomfort and muscle fatigue whilst working on a visual display unit, *International Journal of Industrial Ergonomics*, **20,** 1–10.

Turville, K., Psihogios, J., Ulmer, G. and Mirka, G. 1998, The effects of video display terminal height on the operator: a comparison of the 15° and 40° recommendations, *Applied Ergonomics*, **29,** 239–246.

Visser, J. L. and Straker, L. M. 1994, An investigation of discomfort experienced by dental therapists and assistants at work, *Australian Dental Journal*, **39,** 39–44.

Westgaard, R. H. and Aaras, A. 1984, Postural muscle strain as a causal factor in the development of musculoskeletal illness, *Applied Ergonomics*, **15,** 162–174.

Zetterberg, C., Forsberg, A., Hansson, E., Johansson, H., Nielsen, P., Danielsson, B., Inge, G. and Olsson, B.-M. 1997, Neck and upper extremity problems in car assembly workers. A comparison of subjective complaints, work satisfaction, physical examination and gender, *International Journal of Industrial Ergonomics*, **19,** 277–289.