Evaluation of a dynamic arm support for seated and standing tasks: a laboratory study of electromyography and subjective feedback

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Evaluation of a dynamic arm support for seated and standing tasks: a laboratory study of electromyography and subjective feedback

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The goal of this study was to determine whether a new dynamic arm support system reduced shoulder and arm muscle load for seated and standing hand/arm tasks. The new system provides support for both horizontal and vertical arm motion. A total of 11 participants performed ten tasks (five seated and five standing) both with and without the arm support. Outcomes were assessed with electromyography and subjective feedback. Muscle activity was measured over the dominant side supraspinatus, triceps and forearm extensor muscles. Significant ($p < 0.01$) reductions in static muscle activity were observed in one of ten tasks performed with the support device for the supraspinatus muscle, in five tasks for the triceps and in one task for forearm extensor muscles. Likewise, a significant improvement in subjective measures was reported with the support device for 'ease of task' for two of ten tasks, for 'forearm comfort' for three of ten tasks and for 'shoulder effort' for six of ten tasks. The results suggest that a dynamic forearm support may improve subjective comfort and reduce static muscle loads in the upper extremity for tasks that involve horizontal movement of the arms. For rapid motions, the value of the support is limited due to internal inertia and friction.

Keywords: Forearm; Support; Electromyography; Shoulder; Muscle load

1. Introduction

Low force, static exertion during the performance of hand-intensive tasks has been identified as a risk factor for work-related musculoskeletal disorders (National Research Council and Institute of Medicine 2001). For example, Veiersted (1994) found that prolonged static tension in the trapezius muscle was a risk factor for trapezius myalgia among chocolate packers. Examples of other tasks that require prolonged static muscle

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loading include computer input, product assembly, pipetting, soldering and drilling. Previous studies have evaluated the ability of various types of arm suspension and support devices to reduce muscle load, discomfort and pain in the neck and shoulder regions for keyboarding and mousing (Lintula *et al.* 2001) and for assembly tasks as well (Schuldt *et al.* 1987). However, the findings are mixed. For example, Tepper *et al.* (2003) found no significant differences in average trapezius electromyography (EMG) or subjective comfort in a typing task performed with and without arm support. Conversely, Aarås *et al.*'s (1997) study found such differences in trapezius EMG and subjective comfort for typing. Other studies have found reduced trapezius activity but increased subjective discomfort with forearm support in typing tasks (Erdelyi *et al.* 1988, Lintula *et al.* 2001). The differences in findings may be due to different testing protocols, tasks and types of arm support.

Human factors and safety staff, together with mechanical engineers, at Lawrence Berkeley National Laboratory developed a dynamic device to support the upper extremities with the aim of reducing the static load on the shoulder and forearm muscles for a variety of repetitive, hand-intensive tasks. This device was different from previous forearm supports in several ways. First, it provided adjustable-force forearm support to both arms. Second, it provided support through a large range of horizontal and vertical arm motions for both seated and standing postures, thereby accommodating a broad variety of tasks. The new forearm support device accomplished this by incorporating a spring-loaded suspension system with a horizontally movable armature – a configuration not previously tested.

The purpose of the present study was to determine whether or not this dynamic forearm support system reduced static upper extremity and shoulder muscle activity and improved subjective measures of usability. Since flexibility was one of the design goals of the device, the testing was designed to incorporate a large number of common hand-intensive tasks and motions.

2. Methods and materials

This was a repeated-measure, full factorial, laboratory study in which participants performed ten arm-intensive tasks (five at a seated workstation and five at a standing workstation) with and without a forearm support device.

2.1. *Participants*

A total of 11 volunteers (five females, six males), without upper body musculoskeletal problems, participated in the study. (All 11 participants performed most of the experimental tasks, but only eight of these performed the 'standing arms extended' task.) Ten of the participants were right-handed. The participants' mean height was 173 (SD 9.1) cm and mean weight was 68 (SD 11.5) kg. Participant's ages ranged from 30 to 50 years. The average sitting and standing elbow heights of participants were 66.5 (SD 2.2) cm and 115 (SD 5.1) cm, respectively. The study was approved by the institutional review boards of Lawrence Berkeley National Laboratory, the University of California at Berkeley and the University of California at San Francisco.

2.2. *The dynamic forearm support device*

The dynamic forearm support device is a spring-loaded forearm support providing dynamic motion of 30 cm of vertical travel and a horizontal range of motion of roughly

64 cm (figure 1). The horizontal motion allows the supported arm to move toward or away from the body, as well as to left and right. Spring support is provided by large torsion springs wrapped around drums. The preload on the springs is adjustable to provide various levels of support at the forearm rest, depending on user preference and task. Support is commuted through a vertically oriented four-bar linkage constructed of stiff members. Three low-friction, rotary joints in the horizontal plane provide planar range of motion and allow for motion during reach or shoulder internal or external rotation. The support framework can also be manually adjusted vertically to accommodate a range of user heights. The armrest of the forearm support device is roughly 15 cm long, concave and contains a 1.3 cm thick gel pad.

2.3. *Environment*

The dynamic support device was positioned in a room with a standing workstation on one side of the arm support device and a sitting workstation on the other. In this way, the device could be easily rotated 180° to test at either the standing or sitting workstation. Chair and workstation heights were adjusted to each participant's anthropometry. The workstation height was set so that the keyboard key surface was 1.3 cm below seated elbow height. The worktable height was set to 23 cm below elbow standing height so that the hand elevation for the task was approximately at elbow height. The height of the forearm support device was adjusted to the participant's standing or sitting elbow height and participants could further adjust the height to accommodate the task demands. The spring tension of the dynamic support device was adjusted to a level where the participants reported that their arms were reasonably supported but were not being pushed up. Spring tension is defined in this case as the resultant vertical force that the springs delivered at the forearm support. The mean spring tension preferred by the participants was 9.8 (SD 2.8) N, with a range of 4.4 to 13.2 N.

Figure 1. The height-adjustable dynamic forearm support device surrounding the chair.

2.4. *Procedure*

Participants performed ten different tasks (five seated and five standing). The tasks were performed in a fixed order, both with and without the arm support device, for a total of 20 test conditions. Within a task, the order of whether the task was performed first with or without the support device was determined using a random number generator. Prior to data collection, participants practised each task, with and without the support system, until they were comfortable performing the task. Data collection captured a 1-min EMG sample for each task, capturing numerous task cycles, the number depending on the task (40 cycles for the tasks for which frequency was specified). Participants were not aware when the data collection began or ended. For dynamic tasks, data collection began when the hands were close to the body. After each task, users completed a short questionnaire asking them to rate forearm comfort, shoulder effort and ease of completing the task both with and without the device. The rest between tasks was approximately 5 min. Responses were captured on a continuous analogue scale, which had numeric anchors 1 to 5 and verbal anchors at the endpoints rated as 1 and 5. Forearm comfort used verbal anchors '1-comfortable' to '5-uncomfortable' and shoulder effort and ease of task both used verbal anchors '1-easy' to '5-difficult.'

2.5. *Task descriptions*

The tasks in this study were selected to represent real tasks and arm motions. Seven tasks mimicked simple arm motions over a work surface (e.g. reach motions), while the other three tasks simulated real work tasks (e.g. drilling, mousing and keyboarding). The tasks, in test order, were seated static posture, seated arm sweeping, seated reaching, seated keyboard data entry, seated mousing, standing static posture, standing arm sweeping, standing reaching, standing drilling simulation and standing static extended posture. Participants were instructed to perform dynamic tasks at a rate in time with a metronome set to 40 beats per min.

The seated and standing static posture tasks required participants to hold their upper arms at their sides and their forearms parallel to the ground with their fingers extended comfortably. The standing static extended posture was similar, but users maintained approximately $45°$ of shoulder flexion. These static tasks were intended to simulate arm resting postures in preparation to performing an operation.

During the seated and standing arm sweeping tasks, participants were instructed to start in the same posture as in the static tasks and rotate the forearms about the elbows while keeping the forearms parallel to the floor (internal/external shoulder rotation). These motions were from approximately $60°$ of internal shoulder rotation to approximately $30°$ of external shoulder rotation (figure 2). The low friction rotary joint for the support device was located directly below the participant's elbows; so this was a low-inertia motion for the device.

For the seated and standing dynamic arm reaching tasks, participants were instructed to keep their forearms in a plane parallel with the ground and reach their arms forward to approximately $45°$ of shoulder flexion. Wrists were held straight during this motion. Arm sweeping and reaching tasks were intended to represent moving the arms over a work surface while seated or standing.

The seated data entry task required participants to type a page from a book of fiction. Users positioned the chair-to-keyboard distance themselves based on their personal level of comfort. The seated mousing task presented circular targets on the computer monitor

at different distances, sizes and directions around the screen (as recommended by the pointing standard in ISO 9241–9; International Standards Organization 2000). The user was asked to click on the targets with the mouse as the targets appeared. Participants were encouraged to use their usual mousing technique. The data entry and mousing tasks are shown in figure 3.

The standing drilling simulation task (figure 4) was selected to represent a common manufacturing operation. Participants used either a 2.7 kg or a 1.8 kg drill (depending on the participant's preference) with their dominant hand and were instructed to push one of five spring-loaded pins into a pegboard, in sequence, with the tip of the drill. The spring force was less than 4 N, as springs were provided simply to return the pegs to the initial position. The pegboard distance from the shoulder was set to the location of the mid-palm when the shoulder was flexed to $45°$ and targets were positioned 10 cm above elbow height. The drill motor was not activated during this test.

2.6. *Electromyography*

Surface electromyograms were recorded using silver/silver chloride electrodes embedded in plastic with a preamplifier (Therapeutics Unlimited, Iowa City, IA, USA). Sensor contact diameter was 8 mm and inter-electrode distance was 20 cm. Skin was dry-shaved and cleaned with an alcohol wipe prior to placement of the sensors, which were then placed (with conductive gel) on the dominant arm. Data were smoothed at the amplifier
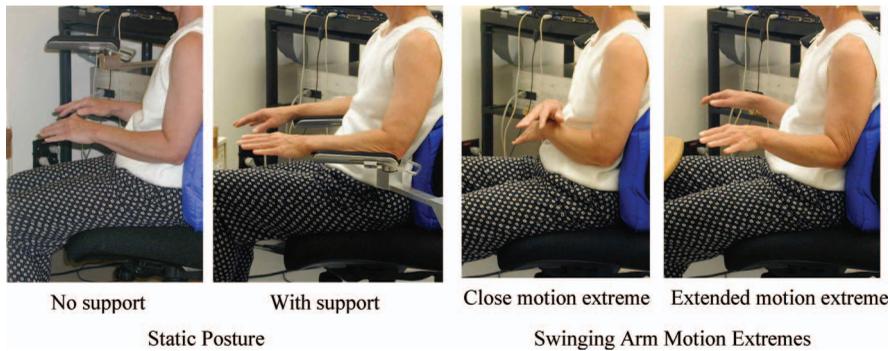

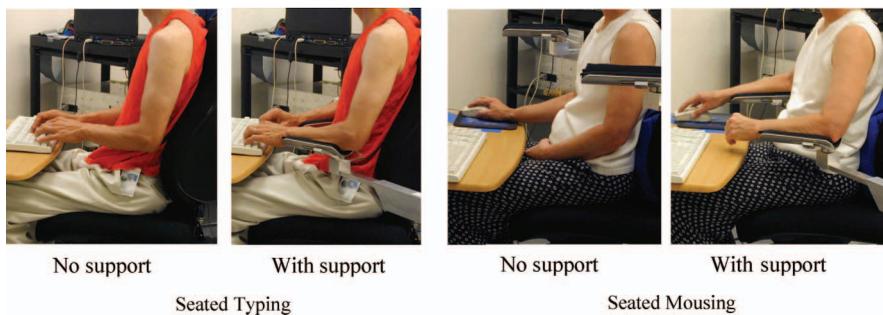Figure 2. Seated arm motions.

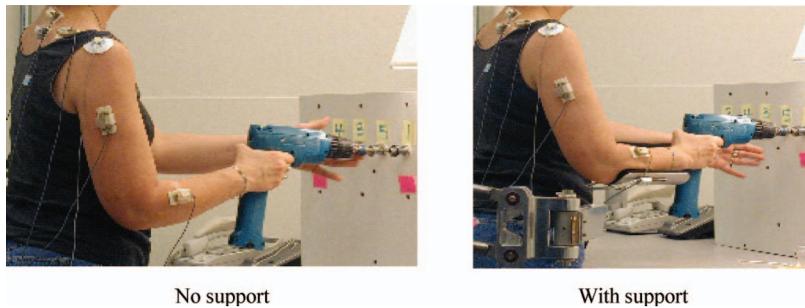Figure 3. Computer input tasks, with and without forearm support.

Figure 4. Standing and drilling without and with forearm support.

using a root mean square (RMS) filter with a 55 ms filtering window. The RMS EMG signal was captured with a data acquisition card to a personal computer, sampling at 250 Hz. The electrodes were placed over the following muscle groups of the dominant extremity: extensor carpi radialis; lateral head of the triceps; and supraspinatus. These muscle groups were selected based on their high susceptibility to fatigue or injury and the anticipated likelihood that their activity would be influenced by the support device. Sensors were oriented in the direction of the muscle fibres and placed according to the recommendations of Perotto *et al*. (2005).

2.7. *Maximum voluntary contraction*

To obtain reference, electrical signals representing maximum voluntary exertion, three separate activities were performed to fully load the muscles of interest. These included wrist extension, wrist ulnar deviation and elbow extension and shoulder abduction. Using a 5 s maximum voluntary contraction (MVC) sample period, the 95th percentile of the amplitude probability function was calculated for each trial and the highest value of the three trials was used as the MVC value for that particular muscle.

2.8. *Analysis*

The RMS EMG signals were normalized to isometric MVC. Summary measures of EMG data were prepared for each participant, task and support condition using amplitude probability distribution function (APDF) values (Hagberg and Jonsson 1975), at the 10% level. APDF values are amplitude signal percentiles; in other words, APDF 10% represents the 10th percentile value of the amplitude signal. APDF 10% is a representation of the static load of a given muscle throughout a task. The effect of the forearm support device on EMG APDF values and subjective data was evaluated for each task using a two-tailed paired t-test. Each task was considered to be independent of the others. In order to adjust for multiple comparisons within a task (three muscles and three subjective items), a *p*-value of 0.01 was used. The subjective data were analysed using Wilcoxon non-parametric statistics.

3. Results

Figures 5–10 show the results of each outcome measure by task, differentiated by the 'with device' and 'without device' experimental conditions. Figures 5–7 show the mean

EMG values at the APDF 10% level by muscle group. Figures 8–10 show the mean outcomes of the subjective measures.

The supraspinatus showed statistically significant static muscle load reduction for only the seated arm sweeping task (figure 5). For all tasks except for seated typing, a non-statistically significant beneficial trend in static load reduction was measured.

Muscles in the arm showed similar trends as the supraspinatus muscle in the shoulder. The lateral head of the triceps showed a significant reduction in static muscle load for five of the ten tasks – the most tasks of any muscle measured (figure 6). Muscle loads in general were low in this muscle for all of the tasks tested.

Unlike the triceps muscle, the static loads of the extensor carpi radialis were relatively high for all tasks (figure 7). Many tasks required higher static load levels than the generally recommended 5% of MVC to reduce the risk of fatigue and work-related musculoskeletal disorders (Schuldt *et al*. 1987). The only task that showed a statistically significant reduction in static loading for the forearm extensors was the static seated posture.

Across most tasks, participants reported improved ease of completing the task with the forearm support (figure 8). However, the improvement was statistically significant for only the two static tasks, the sitting and standing static posture with the elbows held at 90°. Participants reported little ease-of-use benefit of the forearm support for the more dynamic tasks, such as seated reaching, seated typing, seated mousing and standing drilling. This suggests that, while some aspects of the arm support may help make tasks easier to perform (e.g. arm suspension), other aspects of the support (e.g. additional inertia and friction) may increase task difficulty for dynamic tasks, balancing out the overall ease-of-use benefits.

The use of the dynamic arm rest was found to significantly improve forearm comfort for the seated static, standing static and standing drilling tasks (figure 9). For the remaining tasks, there was no significant improvement in forearm comfort.

Subjectively, participants found shoulder effort to be significantly reduced by the device for six of the tasks (figure 10).

4. Discussion

Overall, the dynamic forearm support reduced static muscle activity in the shoulder and arm for just the static tasks or the tasks that involved horizontal arm motions. For tasks involving vertical arm motions (drilling, typing, mousing), the forearm support provided little reduction in muscle load. These findings matched the subjective reports for ease of completing the tasks. The greatest benefit of the device was observed in the subjective reporting of shoulder effort and forearm comfort.

These findings may be explained to some degree by the mechanical properties of the forearm support. For the arm reaching tasks, participants had to move all of the arm support device's linkages and joints; therefore, for these tasks, the participants had to overcome the full friction and inertia of the device. As can be seen from the 'ease of task' results (figure 10), users felt that reaching was equally difficult with and without the device. This is likely because the extra force required to move the armature linkages offset the forearm support benefits for this task. This observation yields information about improving future forearm support designs for dynamic tasks – which should reduce the inertia and friction required to move the armature.

The typing task showed no statistically significant static muscle load benefit from participants using the arm support device, although trends of muscle load reduction were noted. One possible reason for this is that the workstation was set to a height to reduce
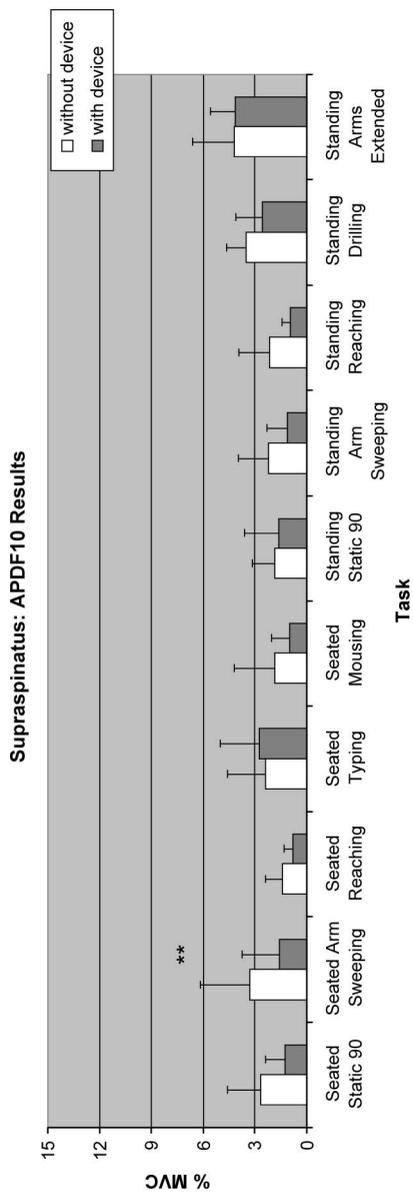
Figure 5. Supraspinatus static load results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects. APDF = amplitude probability distribution function; MVC = maximum voluntary contraction.

Figure 6. Triceps lateral head static load results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects. APDF = amplitude probability distribution function; MVC = maximum voluntary contraction.

Figure 7. Forearm extensor static load results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects. APDF = amplitude probability distribution function; MVC = maximum voluntary contraction.
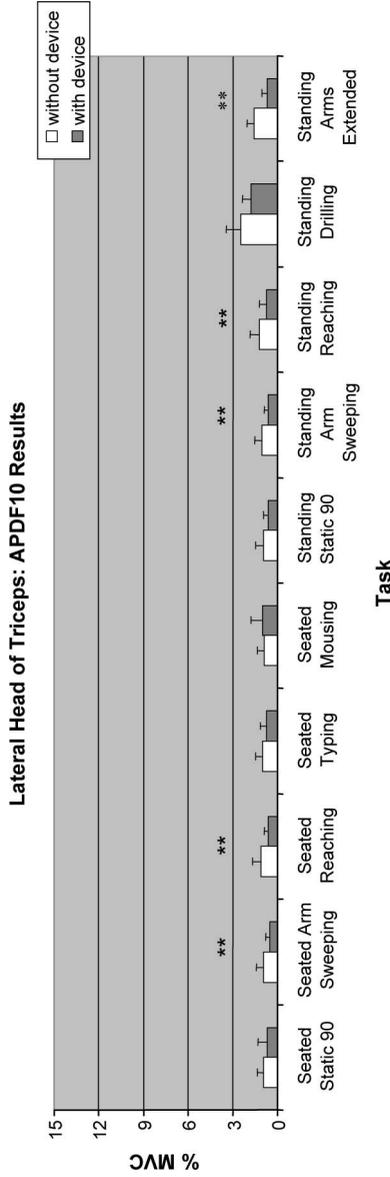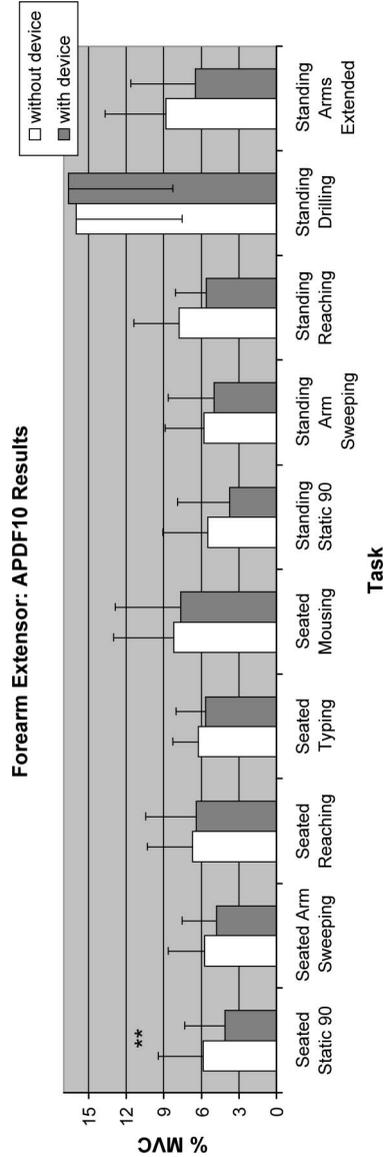
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Figure 8. Subjective feedback – Ease of task results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects.

Figure 9. Subjective feedback – Forearm comfort' results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects.
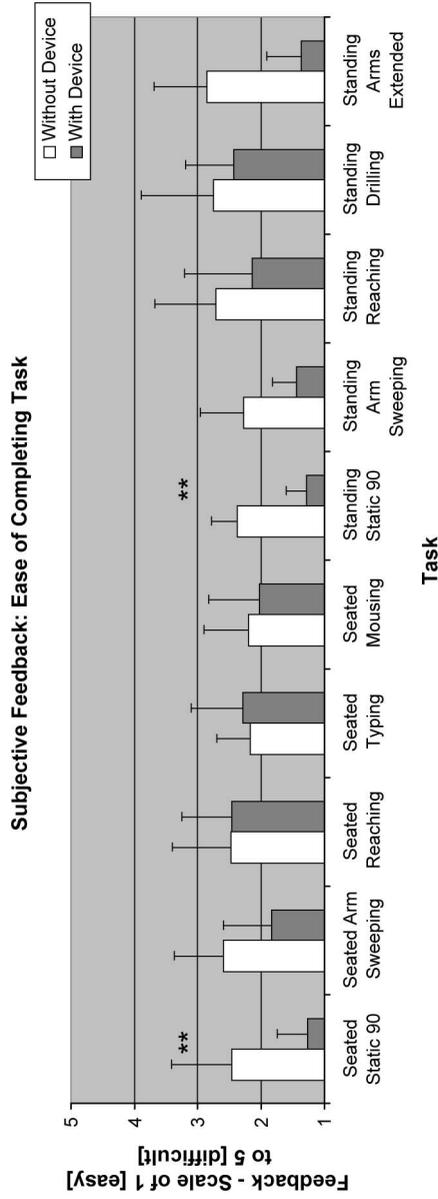
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Figure 10. Subjective feedback – Shoulder effort results. **Indicates a statistically significant difference at the 0.01 level. Error bars represent 1 SD. There were 11 subjects for all tasks except for 'standing arms extended', where there were eight subjects.
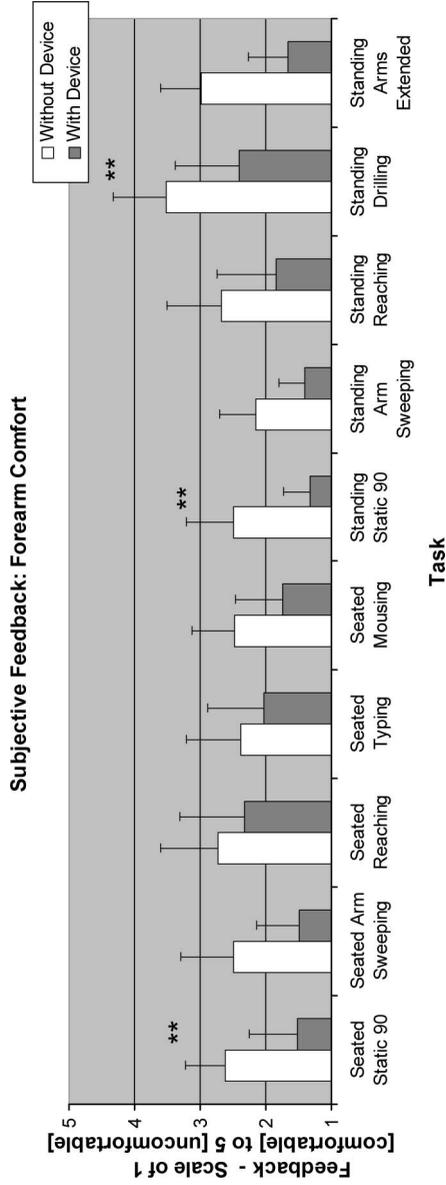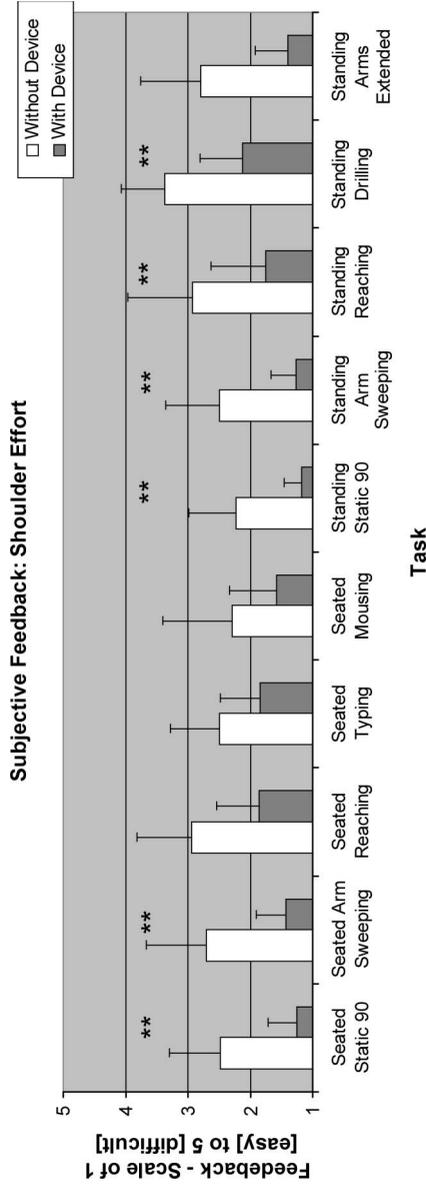
shoulder muscle load before testing began. The borderline significant ($p < 0.05$) 'shoulder effort' reduction that participants perceived may have included reductions in other shoulder muscles that were not studied in this experiment. Another study, for example, found the most dramatic muscle load reductions in the deltoid muscles with forearm support (Feng *et al.* 1997). Most previous studies have reported that forearm support reduces muscle loads for keying tasks (Erdelyi *et al.* 1988, Aaras *et al.* 1997, Feng *et al.* 1997, Visser *et al.* 2000).

Similar to the seated keyboard task, the support device demonstrated no statistically significant reduction in static muscle loading for the seated mousing task. Once again, the ergonomic alignment of the workstation may have corrected some of the loading normally associated with mousing at a standard workstation – reducing the effect of the forearm support. For the mousing task, the data show trends towards muscle load reduction for all muscles (except the triceps lateral head). The results of previous studies (Aaras *et al.* 1997, Visser *et al.* 2000) lend credence to this idea, as those studies found statistically significant static load reduction in the trapezius for a mousing task performed with arm support. It should be noted that this task required the forearm extensor carpi radialis muscle to exert a static force of more than 7.5% of MVC (higher than the recommended cut-off value of 5%; Schuldt *et al.* 1987). This finding indicates that intense mousing likely generates a long-term fatigue risk for the forearm extensors.

In addition to these findings for the mousing task, another important observation was made with regard to differences in individual behaviour between the 'with device' and 'without device' conditions. All participants were observed to 'plant' their wrists during unsupported mousing – resting their palms on the mouse pad. However, these same participants (n = 8) were observed to keep their wrists above the mousing surface while mousing with the support device. Figure 3 gives an example of this postural change. Contact pressure on the wrist and wrist extension have both been identified as possible risk factors for hand and wrist pain among computer users (Marcus *et al.* 2002). So, for the mousing task, the presence of a forearm support device may offer additional advantages.

Forearm extensor muscle activity was high for the standing drilling simulation task (with and without forearm support), indicating that this task is likely to lead to fatigue over extended periods of time. Many participants reported feeling severe forearm fatigue after 2 min of performing this task. High loads to the extensor carpi radialis muscle were required to keep the drill pointed up during this task. To reduce this high muscle activity, support would be better offered at the tool itself, rather than at the forearm, in order to reduce the large moment about the wrist that is caused by the weight of the drill. While other studies have measured and demonstrated high loads on the forearm extensors during various tasks, few have documented statistically significant load reductions for them from forearm support (Feng *et al.* 1997, 1999).

The effects of suspended arm support (10–15 N) on the supraspinatus during simulated assembly and welding tasks were previously explored in another study by Jarvholm *et al.* (1991). The output measures of that study were intramuscular pressure (IMP) and EMG measurements for the supraspinatus. Good correlation (r = 0.96) was found between IMP and EMG readings, indicating that EMG measurements represent a robust measure of muscle load for the supraspinatus. Statistically significant reductions of roughly 20% were found in both IMP and EMG readings for both tasks with arm support. These findings reinforce the supraspinatus findings of the present study – forearm support can reduce supraspinatus activity for some tasks.

The primary limitation of the present study was the short duration for which each task was examined. Participants spent approximately 10 min performing each task and data

were collected for 1 min for each activity. However, short cycle times and reasonable rest periods between tasks were provided to minimize the influence of fatigue from prior tasks. The other problem with short task duration was that the participants may not have achieved steady-state performance in the short time frame. To mitigate this risk, EMG data collection was not initiated until the task was observed to be performed consistently and smoothly. Finally, while data collection times were short, they were designed to be long enough to capture data over many task cycles (40 cycles for most dynamic tasks), to ensure representative cycle sampling.

Other potential study limitations included the fact that tasks were presented in a fixed order. The fixed study order had the potential to introduce learning or fatigue effects. However, this potential was reduced by making comparisons only within tasks and by randomizing conditions within tasks. Also, this study involved a small sample size (n = 11). So, while a number of outcome measures showed trends toward benefit from using forearm support, few of them were significant.

Experimental observations yielded some feedback about the design of the forearm support device. This feedback is applicable to a broad range of dynamic support devices and therefore may be useful in the design of future forearm support devices.

1. Device inertia and static friction should be low in forearm-tracking support devices to improve usability and reduce task-induced loads. Inertia and static friction increase the forces required to move the device and, therefore, the forces required to perform a given task while using the device. Device inertia and friction will influence dynamic tasks but not tasks that are relatively static.
2. Good forearm coupling is required for tasks that require rapid motions, particularly in the presence of high support device inertia or friction. Otherwise, the support device may not properly follow the user's forearm motions. Coupling can be improved with larger forearm contact area and surfaces with high friction. Coupling is more difficult for motions in the vertical direction and there may be a trade-off between secure coupling and user comfort.
3. The forearm support length should be adjustable to accommodate different forearm lengths. Design details of the device should be based on the anthropometry of the expected users.

5. Conclusions

A spring-loaded articulated forearm support can reduce static muscle loads on upper extremity muscles for hand-intensive tasks that involve horizontal motions of the arms. The device provided little reduction in muscle load for tasks involving rapid or vertical arm motions. Subjective preferences for the device generally matched the EMG findings. The internal inertia and friction of the support device may limit its benefit, especially with tasks that involve rapid forearm motions or forearm movements.

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