34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Novel Method for Quantitative Assessment of Physical Workload of Healthcare Workers by a Tetherless Ergonomics Workstation

Warren D. Smith, *Member, IEEE*, Kamal A. Alharbi, Jeremy B. Dixon, and Hind Reggad

Abstract—**Healthcare workers are at risk of physical injury. Our laboratory has developed a tetherless ergonomics workstation that is suitable for studying physicians' and nurses' physical workloads in clinical settings. The workstation uses wearable sensors to record multiple channels of body orientation and muscle activity and wirelessly transmits them to a base station laptop computer for display, storage, and analysis. The ergonomics workstation generates long records of multi-channel data, so it is desired that the workstation automatically process these records and provide graphical and quantitative summaries of the physical workloads experienced by the healthcare workers. This paper describes a novel method of automated quantitative assessment of physical workload, termed joint cumulative amplitude-duration (JCAD) analysis, that has advantages over previous methods and illustrates its use in a comparison of the physical workloads of robotically-assisted surgery versus manual video-endoscopic surgery.**

I. INTRODUCTION

HEALTHCARE personnel are at physical risk when they are at work in clinical settings. For example, the physical demands imposed on surgeons put them at risk of neuromuscular injury, and the effects on their workload of modern technologies such as video-endoscopic and robotically-assisted surgery need to be assessed [1]. Likewise, nurses risk injury in tasks such as moving bedridden patients [2], [3]. Integrated systems that include multi-camera video motion analysis coordinated with force platforms, electromyogram (EMG) signals, and other inputs have been developed for studies in a laboratory setting of physical exposure to work-related musculoskeletal risks [4]. Previous work at California State University, Sacramento, produced a tetherless ergonomics workstation that has allowed us to move studies of the physical workloads of surgeons and nurses out of the laboratory and into clinical settings [5], [6]. The workstation generates long, multi-channel records of body orientation and muscle activity. It is highly desirable for the workstation to automatically process these records and provide graphical and quantitative summaries of subject workloads that are meaningful, even to the non-expert, and useful for statistical analysis. This paper presents and illustrates the use of a novel processing algorithm for this purpose that provides useful advantages over previously-available methods.

II. ALGORITHM DEVELOPMENT

Numerous methods for assessment of physical workload have been developed [4], [7]–[10]. Direct methods of sensing muscle activity and posture, as performed by our tetherless ergonomics workstation, are more accurate than methods involving subject self-reporting or observation, but direct methods pose the challenge of having to process large volumes of data. To meet this challenge, a number of methods for automated analysis of such data have been developed. In assessing physical workload, the characteristics of interest are the amplitude or level of effort or exposure and the uninterrupted duration of effort. Endurance and risk are functions of uninterrupted duration, as well as amplitude, because during muscle contraction, blood is squeezed from the veins toward the heart, and the inflow of blood to the muscle is reduced [11]. Contraction duration affects metabolic energy cost and fatigue in skeletal muscle [11], and rest periods help increase muscle endurance time [12].

Some automated processing methods, such as cumulative probability distribution of force (CPDF) analysis [13], or the more general amplitude probability distribution function (APDF) analysis [14], have focused on amplitude. The APDF curve provides a compact overview of level of effort, and the shape of the curve reflects task complexity. The curve also provides useful summary statistics, such as the P_{10}, P_{50}, and P_{90} percentiles, representing respectively "static," "median," and "peak" levels of effort [13]. However, the curve has the drawback of not showing durations of uninterrupted effort. Other methods, such as contraction frequency analysis (CFA) [15], successfully summarize the repetitiveness aspects of muscle performance but fail to reflect amplitude levels or changes in duty cycle.

Automated processing methods also have been developed to capture the combination of amplitude and frequency characteristics of effort. The widely-used method of power spectrum analysis for showing the distribution of amplitude

---

Manuscript received March 26, 2011. This work was supported in part by ALPHA Fund.

W. D. Smith is a professor in Electrical and Electronic Engineering, Department, California State University, Sacramento, Sacramento, CA 95819 USA (916-278-6458; fax: 916-278-7215; e-mail: smithwd@csus.edu).

K. A. Alharbi is a graduate student in the Electrical and Electronic Engineering Department, California State University, Sacramento, Sacramento, CA 95819 USA (e-mail: kamal.alharbi@gmail.com).

J. B. Dixon is a graduate student in the Electrical and Electronic Engineering Department, California State University, Sacramento, Sacramento, CA 95819 USA (e-mail: dixonj@ecs.csus.edu).

H. Reggad is a graduate student in the Electrical and Electronic Engineering Department, California State University, Sacramento, CA 95819 USA (email: hreggad@gmail.com).

978-1-4577-1787-1/12/$26.00 ©2012 IEEE

versus frequency for a time recording has been applied to physical workload assessment [16], [17]. A frequency spectrum analysis, however, does not reflect the important relation between the level of effort and the uninterrupted duration of such effort.

The method of exposure variation analysis (EVA) was developed in order to capture the distributions of both amplitude and uninterrupted durations during physical activity [18]. In this method, thresholds of level of effort or exposure and thresholds of uninterrupted duration of effort are established that define bins of exposure and bins of duration, and then the percent of working time is accumulated for each set of exposure and duration bins. This method has the drawbacks that the resulting "density" pattern of percent working time versus amplitude and duration is complex and not convenient for statistical summaries and comparisons. Moreover, the pattern undesirably undergoes significant changes in appearance with changes in amplitude and duration bin widths and even sampling frequency [19]. One approach to reducing the drawbacks of EVA is clustered exposure variation analysis (CEVA) [20], in which the number of exposure bins is collapsed to three (Low, Moderate, and High) and the number of duration bins is collapsed to two (Short and Prolonged). The reduced number of amplitude-duration bins simplifies statistical analysis.

Another approach to improving EVA, developed at California State University, Sacramento, is modified exposure variation analysis (MEVA) [19]. The difference between MEVA and EVA is that, in MEVA, efforts are accumulated that occur above each amplitude threshold rather than that occur between the thresholds defining amplitude bins. The motivation for MEVA was to replace the undesirable "density" characteristics of EVA with the more robust "distribution" characteristics for amplitude exhibited by the APDF. As desired, with this change, MEVA presents a meaningful graphical summary of amplitudes and durations that preserves its appearance in the face of changes in the spacings of amplitude and duration thresholds and changes in sampling frequency. Also, like the APDF, MEVA provides simple statistics that are convenient for summary and comparison purposes. The MEVA method was implemented in LabVIEW (National Instruments, Austin, TX) in a portable ergonomics workstation and used to study physical workload in surgeons. The study showed that the effort experienced by surgeons performing video-endoscopic surgery is significantly greater than that during traditional direct-view open surgery [21].

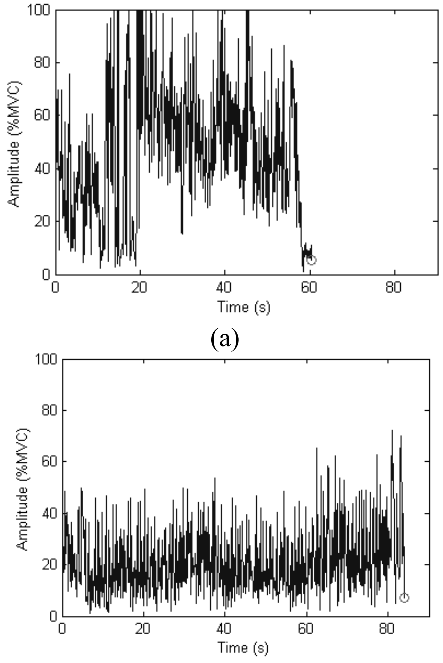
The novel processing method presented here, termed joint cumulative amplitude-duration (JCAD) analysis, goes a step beyond MEVA, in that a "distribution" rather than a "density" approach is taken for uninterrupted duration, as well as for amplitude. That is, uninterrupted durations are accumulated that occur above each duration threshold, rather than that occur between the thresholds defining duration bins. This modification allows JCAD to provide novel and more useful graphical and statistical summaries of long records of physical workload data such as those generated by our tetherless ergonomics workstation. The characteristics of JCAD analysis now are illustrated on surgeon workload data.

III. APPLICATION OF JCAD ANALYSIS

With IRB approval, 10 volunteer surgeon subjects (8 male and 2 female) each performed a suturing (knot-tying) task using manual video-endoscopic surgery techniques and a robotically-assisted surgery system in random order. To work manually, the subject stood at a traditional video-endoscopic station and laparoscopic trainer box (Karl Storz Endoscopy – America, Culver City, CA). To perform robotically-assisted surgery, the subject sat at the console of a ZEUS Robotic Surgical System (Computer Motion, Inc., Goleta, CA) with a MicroWrist interface and three-dimensional video display. The suture task consisted of driving a suture needle through the finger of a stretched rubber glove and tying three knots. During the task, a skin surface electromyogram (EMG) signal was recorded from the surgeon's right thumb (thenar compartment). The amplified EMG signal was rectified and smoothed using analog circuitry, then digitally sampled at 10 Hz and stored to a laptop hard drive by a LabVIEW-based tetherless ergonomics workstation [5]. The EMG amplitude was normalized by the amplitude measured when the subject exerted the thumb muscle maximally and is expressed as percent maximum voluntary contraction (%MVC).

Fig. 1 shows recordings versus time of thumb EMG amplitude from one of the surgeon subjects for the suturing task performed (a) manually and (b) robotically-assisted. Figs. 2 and 3 show the results of JCAD analysis for the two time recordings in Fig. 1 in the form of JCAD-I and JCAD-II plots, respectively. For this JCAD analysis, amplitude thresholds were established with a spacing of 1 %MVC, uninterrupted duration thresholds were established with a spacing of 0.1 s (the sampling interval), and accumulated worktime thresholds were established with a spacing of 1 s.

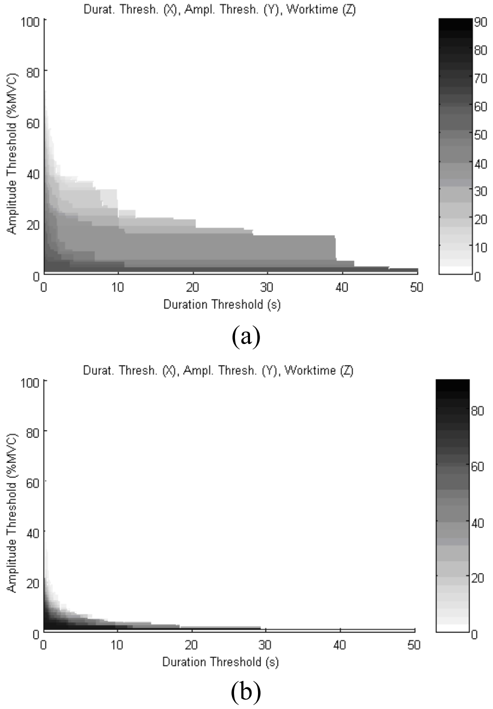
In the JCAD-I plots in Fig. 2, the x-axis shows uninterrupted duration threshold values, the y-axis shows amplitude threshold values, and the z-axis uses a grayscale to show accumulated worktime (s) for amplitudes and uninterrupted durations at or above the given thresholds. If desired, the z-axis can be scaled to show percent of total worktime, but that was not done here in order to preserve the differences in task times between the suturing task performed manually and robotically-assisted. The x-axis could have been made logarithmic as suggested by [18], but linear scales were used here to make it easier to compare the uninterrupted duration values in Fig. 2 with the original time recordings in Fig. 1. The axes in a JCAD-I plot correspond to those used for an EVA plot, and the two plots show the same information but in different ways. The difference, again, is that a JCAD-I plot shows a joint cumulative "distribution" of accumulated worktime or percent worktime versus amplitude and uninterrupted duration, whereas an EVA plot provides a “density” presentation of this information. Like an MEVA plot, the JCAD-I plot has the advantage of preserving its overall appearance as amplitude and duration threshold level spacings are changed, whereas changes in threshold level spacings greatly affect the appearance of the EVA plot. A JCAD-I plot provides a meaningful data summary. For example, the plots in Fig. 2 show that the subject spent more worktime exerting higher levels of effort for longer uninterrupted durations when performing the task manually (a) than with robotic assistance (b). However, the JCAD analysis results can be presented even more meaningfully by means of a JCAD-II plot, as shown in Fig. 3.



(a)

(b)

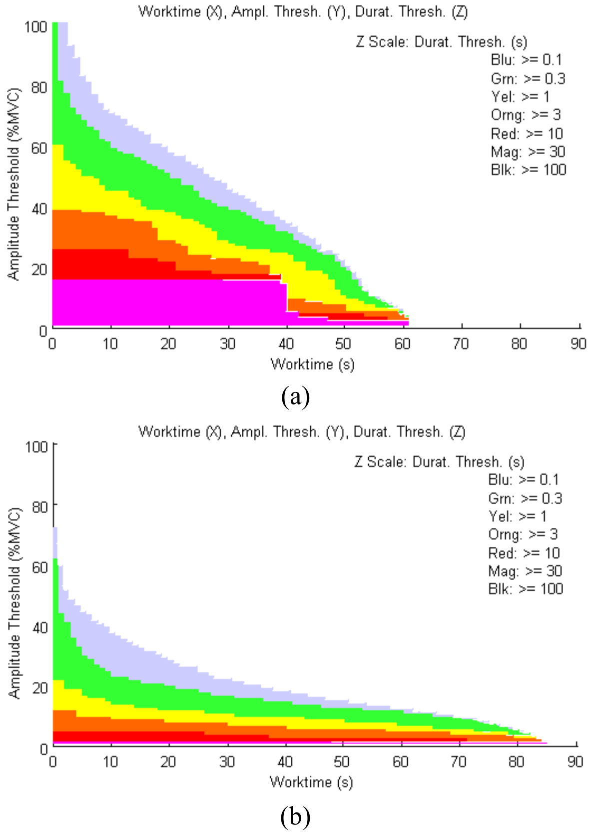
Fig. 1. Thumb EMG amplitude versus time from the same subject for the suture task performed (a) manually and (b) robotically.



(a)

(b)

Fig. 2. JCAD-I plots, showing accumulated worktime (z-axis) versus uninterrupted duration threshold values (x-axis) and amplitude threshold values (y-axis), of the recordings in Fig. 1 for the suture task performed (a) manually and (b) robotically-assisted.



(a)

(b)

Fig. 3. JCAD-II plots, showing uninterrupted duration threshold values (z-axis) versus accumulated worktime (x-axis) and amplitude threshold values (y-axis) of the recordings in Fig. 1 for the suture task performed (a) manually and (b) robotically-assisted.

The JCAD-II plots in Fig. 3 show the same results as in Fig. 2, but in a JCAD-II plot, the x-axis shows accumulated worktime (s), the y-axis shows amplitude threshold values, and the z-axis shows uninterrupted duration threshold values. In Fig. 3, the z-axis displays duration logarithmically, with threshold values of 0.1 s, 0.3 s, 1 s, 3 s, 10 s, 30 s, and 100 s. If desired, the x-axis can be scaled to show percent worktime, but, again, that is not done here so that the difference in accumulated worktimes to perform the task (a) manually and (b) with robotic assistance is shown clearly.

An advantage of the JCAD-II plot is that it is a straightforward extension of the APDF. In fact, when the x-axis is scaled to percent worktime, the outermost profile of a JCAD-II plot – that is, using the lowest duration threshold value (0.1 s) – is a flipped version of the APDF. Thus, like the APDF, the JCAD-II plot provides useful statistics such as the P_{10}, P_{50}, and P_{90} percentiles. For example, in the JCAD-II plot, the P_{90} percentile for amplitude, meaning the level of effort that is not exceeded 90 percent of the time (or is exceeded 10 percent of the time), is the amplitude value on the y-axis corresponding to the 10-percent accumulated worktime point along the x-axis. In Fig. 3, the P_{90} value for the task done manually is 85 %MVC, whereas the P_{90} value for the task with robotic assistance is only 43 %MVC. Moreover, when the x-axis is accumulated worktime, the area under the overall JCAD-II plot is the commonly-used summary statistic, integrated effort. The JCAD-II plot goes beyond the APDF, however, in that it provides uninterrupted duration, as well as amplitude, information. Each z-axis uninterrupted duration threshold in the JCAD-II plot generates its own APDF-like curve, with its own percentiles and integrated effort value. Thus, for example, Fig. 3 shows that, for the task performed manually, the overall P_{50} value is 48 %MVC, and the $P_{50(3s)}$ value for uninterrupted durations of at least 3 s (shown as orange in the figure) is 25 %MVC. In contrast, for the task performed with robotic assistance, the overall P_{50} value is only 20 %MVC, and the $P_{50(3s)}$ value for is only 8 %MVC. A comparison of these percentile values supports the conclusion that the workload for robotically-assisted surgery is less than for manual surgery.

IV. DISCUSSION

We presently are using JCAD analysis to complete our study of the physical workload of manual versus robotically-assisted surgery. An advantage of JCAD analysis is that it can provide a display of workload status along a time axis while it is computing its summary results. We are investigating alternative methods of graphical and numerical presentation of both the real-time and summary information. In this regard, we are carrying out human subjects testing to identify JCAD analysis features that best correlate with workload. We are starting with force recordings obtained during handgrip maneuvers, together with subject self-assessment of level of fatigue. Our goal is to identify JCAD real-time and summary features that best allow healthcare workers to optimize their efforts and minimize their risks while they perform clinical tasks.

V. CONCLUSIONS

A new method, joint cumulative amplitude-duration (JCAD) analysis, has been developed for automatically processing the long recordings that are generated by direct measurements of muscle activity and posture as performed by our tetherless ergonomics workstation. The JCAD method has advantages over the previously-developed methods of APDF, CFA, power spectral density, EVA, and MEVA that will facilitate quantitative assessment of the physical workload of healthcare workers in clinical settings.

REFERENCES

[1] R. Berguer, "Surgery and ergonomics," *Arch. Surg.*, vol. 134, pp. 1011–1016, 1999.

[2] L. Hui, G. Y. Ng, S. S. Yeung, and C. W. Hui-Chan, "Evaluation of physiological work demands and low back neuromuscular fatigue on nurses working in geriatric wards," *Appl. Ergon.*, vol. 32, pp. 479–483, 2001.

[3] W. S. Marras, K. G. Davis, B. C. Kirking, and P. K. Bertsche, "A comprehensive analysis of low-back disorder risk and spinal loading during the transferring and repositioning of patients using different techniques," *Ergonomics*, vol. 42, pp. 904–926, 1999.

[4] G. Li and P. Buckle, "Current techniques for assessing physical exposure to work-related musculoskeletal risks, with emphasis on posture-based methods," *Ergonomics*, vol. 42, pp. 674–695, 1999.

[5] W. D. Smith, R. Berguer, and J. C. Rosser, "Wireless virtual instrument measurement of surgeons' physical and mental workloads for robotic versus manual minimally invasive surgery," *Studies in Health Technology and Informatics*, vol. 94, pp. 318–324, 2003.

[6] W. D. Smith, M. E. Nave, and A. Hreljac, "Tetherless ergonomics workstation to assess nurses' physical workload in a clinical setting," *Proc. 33rd Annual International IEEE EMBS Conference*, Boston, 2011, pp. 5633–5636.

[7] E.-P. Takala, I. Pehkonen, M. Forsman, G.-Å. Hansson, S.E. Mathiassen, W. P. Neumann, G. Sjøgaard, K. B. Veiersted, R. H. Westgaard, and J. Winkel, "Systematic evaluation of observational methods assessing biomechanical exposures at work," *Scand. J. Work Environ. Health*, vol. 36, pp. 3–24, 2010.

[8] G. C. David, "Ergonomic methods for assessing exposure to risk factors for work-related musculoskeletal disorders," *Occupational Medicine*, vol. 55, pp. 190–199, 2005.

[9] A. J. van der Beek and M. H. W. Frings-Dresden, "Assessment of mechanical exposure in ergonomic epidemiology," *Occup. Environ. Med.*, vol. 55, pp. 291–299, 1998.

[10] J. Winkel and S. E. Mathiassen, "Assessment of physical work load considerations," *Ergonomics*, vol. 37, pp. 979–988, 1994.

[11] M. C. Hogan, E. Ingham, and S. S. Kurdak, "Contraction duration affects metabolic energy cost and fatigue in skeletal muscle," *American Journal of Physiology*, vol. 37, pp. E397–E402, 1998.

[12] B. Jonsson, "The static load component in muscle work," *European Journal of Applied Physiology*, vol. 57, pp. 305–310, 1988.

[13] H. Iridiastadi and M. A. Nussbaum, "An evaluation of cumulative probability distribution of force (CPDF) as an exposure assessment method during isometric non-isotonic shoulder abductions," *International Journal of Industrial Ergonomics*, vol. 36, pp. 37–43, 2006.

[14] M. Hagberg, "The amplitude distribution of surface EMG in static and intermittent static muscular performance," *European Journal of Applied Physiology*, vol. 40, pp. 265–272, 1979.

[15] J. Winkel and T. Bendix, "A method for electromyographic analysis of muscular contraction frequencies," *European Journal of Applied Physiology*, vol. 53, pp. 112–117, 1984.

[16] C. Lu and N. J. Ferrier, "Automated analysis of repetitive joint motion," *IEEE Transactions on Information Technology in Biomedicine*, vol. 7, pp. 263–273, 2003.

[17] R. Radwin and M. Lin, "An analytical method for characterizing repetitive motion and postural stress using spectral analysis," *Ergonomics*, vol. 36, pp. 379–389, 1993.

[18] S. E. Mathiassen and J. Winkel, "Quantifying variation in physical load using exposure-vs-time data," *Ergonomics*, vol. 34, pp. 1455–1468, 1991.

[19] C.-Y. J. Chen, "Modified exposure variation analysis to study the surgeon's muscle effort during video-endoscopic and direct view surgery," M.S. thesis, Biomedical Engineering Program, California State University, Sacramento, Sacramento, CA, 1998.

[20] D. Anton, T. M. Cook, J. C. Rosecrance, and L. A. Merlino, "Method for quantitatively assessing physical risk factors during variable noncyclic work," *Scand. J. Work Environ. Health*, vol. 29, pp. 354–362, 2003.

[21] R. Berguer, C.-Y. Chen, and W. D. Smith, "A virtual instrument ergonomics workstation to measure surgeons' physical stress," *Studies in Health Technology and Informatics*, vol. 62, pp. 49–54, 1999.