Applied Ergonomics 45 (2014) 261–269

Contents lists available at SciVerse ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Evaluation of multiple muscle loads through multi-objective optimization with prediction of subjective satisfaction level: Illustration by an application to handrail position for standing

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A R T I C L E I N F O

Article history:
Received 26 August 2011
Accepted 8 April 2013

Keywords:
Electromyography
Multi-objective optimization
Design engineering

A B S T R A C T

Proposed here is an evaluation of multiple muscle loads and a procedure for determining optimum solutions to ergonomic design problems. The simultaneous muscle load evaluation is formulated as a multi-objective optimization problem, and optimum solutions are obtained for each participant. In addition, one optimum solution for all participants, which is defined as the compromise solution, is also obtained. Moreover, the proposed method provides both objective and subjective information to support the decision making of designers. The proposed method was applied to the problem of designing the handrail position for the sit-to-stand movement. The height and distance of the handrails were the design variables, and surface electromyograms of four muscles were measured. The optimization results suggest that the proposed evaluation represents the impressions of participants more completely than an independent use of muscle loads. In addition, the compromise solution is determined, and the benefits of the proposed method are examined.

1. Introduction

Since the marketplaces of many products have reached maturity, decisions taken by consumers while they are purchasing products are affected by key factors such as product usability and design novelty in addition to rudimentary factors such as functionality, performance, and economy. Therefore, it is increasingly important for manufacturers to design products that provide comfort and satisfaction to consumers in addition to the rudimentary benefits (Jordan, 1998). Ergonomics or human factor methodologies are applied to product design in order to consider the satisfaction levels of consumers (Hägg, 2003). Bioinstrumentation measurements such as the electromyogram (EMG), electroencephalogram (EEG), and electrocardiogram (ECG) are employed in ergonomic design to evaluate the usability of products quantitatively (Chaffin et al., 1999; Tsang and Vidulich, 2006). Among these, the surface EMG is frequently used for evaluating physical stress and fatigue because of the noninvasive nature and ease of its measurement (U.S. Department of Health and Human Services, 1992). In general, surface EMGs of multiple muscles are measured when product usability and work fatigue are evaluated; however, often each surface EMG is evaluated independently.

For example, Kothiyal and Kayis (2001) measured surface EMGs of the biceps brachii, triceps brachii, anterior deltoid, posterior deltoid, and middle deltoid when moving weights, so as to determine the effects of varying load magnitude and work rate on the muscular load in seated manual handling tasks performed with one hand. They concluded that each muscle load was dependent on the direction of movement and that it was difficult to identify the preferred movement direction for all muscles. Herring and Hallbeck (2007) measured the flexor digitorum profundus, triceps brachii, biceps brachii, anterior deltoid, and posterior deltoid when pushing or pulling a shift lever, in order to determine the best location for the shift lever in a pushing and pulling task such as operating a manual transmission. From the results of measurements for pulling trials, a trade-off was found between the activity of the posterior deltoid and flexor digitorum profundus. These studies did not investigate a method for simultaneously evaluating multiple muscle loads.

Eksioglu (2004) used the sum of multiple muscle loads as the indicator of comprehensive muscle load so as to determine the optimum grip span for a power grip exertion. However, it is possible that a particular muscle load dominates perceived total discomfort (hereafter referred to as the human satisfaction, or

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http://dx.doi.org/10.1016/j.apergo.2013.04.006

simply the satisfaction). In addition, the muscle load which dominates the satisfaction may be different for each consumer. Also, the weighted sum with different amplitude of weight may affect the satisfaction. Therefore, the sum of multiple muscle loads may not always represent human satisfaction with muscle loads; thus it might not be suitable in the comprehensive evaluation of muscle loads. Ben-Gal and Bukchin (2002) and Nussbaum et al. (2009) combined multiple objectives (i.e., economic measures and ergonomic measures) into one objective. However, in these studies, multiple objectives were combined arbitrarily. Objective functions have been applied to estimate muscle loads with biomechanical models because an excessive number of muscles exists in relation to the mechanical degrees of freedom at the joints (Alexander, 2003; Erdemir et al., 2007; Herzog, 1996; Prilutsky and Zatsiorsky, 2002). The two common criteria are minimization of the sum of squared muscle-force divided by maximum muscle-force (Pedotti et al., 1978) or minimization of the sum of cubed muscle-force divided by cross-sectional muscle-area (Crowninshield and Brand, 1981). These objective functions are defined for evaluating the strategy of a muscle activity, not for assessing the comfort of a human motion. Therefore, the objective functions already proposed for estimating muscle force are perhaps not appropriate for direct application to evaluating the burden that users feel.

In previous studies (Chihara and Seo, 2011; Chihara et al., 2011), we proposed a simultaneous evaluation method for multiple muscle loads by applying the methodology of multi-objective optimization. Multiple muscle loads were defined as objective functions that should be minimized, and the simultaneous muscle load evaluation of each consumer was formulated as a multi-objective optimization problem (MOOP). That is, the MOOPs were formulated for each consumer. The each consumer's MOOP was solved and the optimum solution for each consumer was obtained. In general, optimum solutions for consumers do not correspond with each other; but we need to determine the only one design variable vector. We, therefore, introduced the concept of "regret" (Yu, 1973; Yu and Leitmann, 1974). The regret is defined as the difference from the optimum function value of the optimum solution. Hence, if design variable vector corresponds to the optimum solution, the regret equals to zero; and the more the distance from design variable vector to the optimum solution increases, the more the regret increases. Obviously the regrets of consumers do not always correspond to zero when the one design variable vector is determined for all consumers. Then, the design problem to determine one optimum solution for all consumers (hereafter referred to as the compromise solution) was formulated as the minimization of the maximum regret of consumers. The min–max problem indicates that the optimization of the problem makes objective function values for all consumers as close as possible to the objective function value of their each optimum solution.

However, in previous studies, we considered only the muscle loads and did not confirm the degree of subjective satisfaction. That is, the relationship between the objective muscle loads and the subjective satisfaction levels was not clear. Thus, it is essential to develop the proposed method to evaluate the relationship between muscle loads and satisfaction levels. Therefore, the objective of the present study was to reveal the relationship between objective muscle load and subjective satisfaction levels. In this study, we derive an evaluation function of subjective satisfaction and evaluate the satisfaction levels of participants. The proposed method will provide designers both subjective and objective information for ergonomic design problem, and help the decision making of designers. Design of a handrail position for the sit-to-stand movement is undertaken as the case study and confirms the benefits of the proposed method.

2. Evaluation of multiple muscle loads for ergonomic design

2.1. Overview of proposed method

First, multiple objective indicators are measured while participants use a product or perform a task. Next, the response surfaces are predicted for objective indicators that are significantly changed by design variable changes. In addition, the consistency between objective indicators and subjective satisfaction levels is evaluated, and the response surface of satisfaction scores is predicted as the satisfaction level function. Then, the simultaneous evaluation of objective indicators for each participant is formulated as a MOOP, and the optimum design solution for each participant is obtained. Finally, a compromise solution for all participants is obtained by considering the regrets of participants. Moreover, the satisfaction level at the obtained compromise solution is also calculated to support the decision making of designers. The proposed method will be described in greater detail in the following subsections. In addition, the muscle load is taken as the example of the objective indicator in the following description, because muscle load (or, EMG) is used in the application.

2.2. Measurement of surface EMGs

Design variables x_i ($i = 1, 2, \ldots, nDES$), which are unknown parameter to decide the design, are selected that possibly affect either the usability of an intended product or the work load of an intended task. It is noted that usability is defined as "the extent to which a product can be used by specific users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use" (ISO 9241-11, 1998). In other words, usability is the ease of use of a product; thus, physical effort is one of components that affect usability. Here, *nDES* represents the number of design variables. Then, multiple levels are set for each design variable. In addition, multiple muscles are selected that might contract while using the product or performing the task. The EMGs of the selected muscles are measured under all experimental conditions. Moreover, the subjective satisfaction scores for each condition are collected.

2.3. Approximation of EMG response surfaces

Among the measured EMGs, those that exhibit significant changes in response to design variable changes are selected. Here, *nEMG* represents the number of selected EMGs. The response surfaces of the selected EMGs are approximated as follows:

$$\widehat{M}_{j,k} = f_{j,k}(\boldsymbol{x}) = f_{j,k}(x_1, x_2, \ldots, x_{nDES}) \quad (j = 1, 2, \ldots, nEMG; \; k = 1, 2, \ldots, nPAR) \tag{1}$$

where $\widehat{M}_{j,k}$ denotes the approximate value of the j-th EMG of the k-th participant and *nPAR* denotes the number of participants. Moreover, $f_{j,k}$ represents the response surface predicted by the radial basis function network (RBFN) (Orr, 1996). The RBFN performs well in terms of accuracy and robustness, irrespective of the degree of nonlinearity. Additionally, it is robust against experimental errors or noise (Jin et al., 2001). Thus, we consider the RBFN to be a dependable method for approximating the EMGs because the degree of nonlinearity in the EMGs is difficult to predict, and measured EMGs unavoidably contain experimental errors and noise. In this study, the parameters proposed for the RBFN by Kitayama and Yamazaki (2011) are adopted.