Relation between perceived effort and the electromyographic signal in localized low-effort activities

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Hand-based human–machine interfaces are complex tasks that involve repetitive or sustained movements and postures of the hands that can lead to overuse syndromes of the musculoskeletal system. Consequently, it is important to minimize the physical effort that occurs at these interfaces. The evaluation of physical effort can be performed either by subjective evaluation of the relative perceived effort (e.g., Borg scale) or by objective physiological measurements (e.g., electromyography – EMG). However, the relation between these two measures has not been sufficiently studied for localized low-effort activities. This study investigated the relation between EMG and Borg ratings, as well as the issue of gender differences during low-effort activity of forearm muscles. Nine females and nine males performed eight different hand gestures (localized low-effort activity), during which EMG signals were recorded from six forearm muscles and Borg ratings were obtained. On average, the female subjects rated the gestures as less effortful than the male subjects, and also demonstrated a higher positive correlation between the EMG and Borg ratings. Furthermore, the linear model that was fitted for predicting the Borg ratings based on gender and the combined activity of muscles provided an R-squared value of approximately 0.3.

INTRODUCTION

Human–machine interfaces (HMI) allow users to control, manipulate and communicate with electromechanical systems, e.g., computers, vehicles, robots, etc. Many of these interfaces, such as keyboards, joysticks, touchscreens and hand gesture recognition interfaces, are based on the use of the hands, whether it is a handheld device or a remote, hand gesture based control device.

Hand-based interfaces involve different positions and movements of the fingers, hand, wrist and arm, as well as the activation of various hand muscles. Some interfaces involve awkward, repetitive movements and postures that can cause muscle or tendon strain which, in turn, may lead to cumulative trauma disorders such as carpal tunnel syndrome (Williams & Westmorland, 1994), tenosynovitis of the dorsal wrist extensor compartments and flexor tendons of the wrist, trigger finger (Verdon, 1996) and De Quervain's tenosynovitis (Chin & Jones, 2002). Since all these clinical syndromes are often use-related, it is important to minimize the physical effort of the musculoskeletal system in order to reduce the risk of overuse syndromes, by designing or using interfaces that are as comfortable as possible during prolonged use.

When evaluating physical effort, two approaches are commonly used: (a) subjective evaluation of relative perceived effort (RPE) by the user (e.g., Borg scale, Likert scale) and (b) objective physiological measurements, e.g., metabolic power, heart rate (HR) and electromyography (EMG). Objective measurements such as metabolic power and HR are typically used for measurement of whole body activities. However, when interested in measuring more localized effort, it is more common to use EMG signals for investigating the level of muscular effort during physical activities.

Skotte et al. (2002) used the peak root mean square (RMS) of surface EMG (SEMG, i.e., placing the electrode non-invasively on the skin surface) signals obtained from the lower back muscles of healthcare workers, when examining their physical load during different patient handling tasks. Mork and Westgaard (2006) used the RMS of the SEMG signals to investigate the relation between low amplitude trapezius muscle activity and shoulder and neck pain during work and leisure activities. Agarabi et al. (2004) used SEMG to assess computer mouse design by comparing four different types of mice during three different grasps. During each grasp, SEMG signals from eight forearm muscles were recorded, and EMG RMS values for different types of mice were compared in order to determine preferable mouse design. Several studies also used peak RMS values of finger flexors and extensors to investigate the effect of keyboard stiffness on finger effort level and fatigue during typing (Radwin & Ruffalo, 1999; Rempel et al., 1997). In other studies, EMG median frequency and RMS amplitude have been applied to investigate muscle fatigue (De Luca, 1985; Oddsson & De Luca, 2003), and together with the Borg scale these have been used to study the level of overall fatigue during physical activities (Chan et al., 2000; Oberg et al., 1994; Yassierli & Nussbaum, 2007).

Other studies found a strong positive correlation between RPE (Borg scale) and the objective measures of muscle exerted force (EMG RMS) in isometric contractions of the upper trapezius muscle (Troiano et al., 2008), as well as between RPE ratings and muscle activity (integrated EMG) during bench press exercises (Lagally et al., 2004). Tiggemann et al. (2010) found a strong positive correlation between Borg scale ratings and the intensity levels of strength exercises, during leg and bench press exercises.

The above studies focus on various muscles of the body and the relationship between the activity of specific muscles and the level of effort. However, to the best of our knowledge, there are no studies that investigated the effect of the combined activity of several muscles on the level of physical effort, even though most physical activities are complex tasks that involve activating more than one muscle. This would seem to suggest that the perceived effort will be related to the combined effect of the active muscles and not just to the activity of individual muscles.

Several of the studies mentioned above also investigated the relation between subjective and objective approaches for evaluating physical effort. These studies, however, mostly focused on medium to high levels of effort, and not on low-effort activities such as occur in human-machine interactions.

Another interesting issue is the comparison of perceived effort in men and in women during various physical activities. Previous studies present contradictory findings about gender differences regarding perceived effort during physical activity. Demura et al. (2008) found no gender difference in subjective muscle fatigue sensation during sustained static gripping. Laforest et al. (1990) reported that there were no gender differences in muscle endurance during a cycle of 50 maximal contractions of knee extensors and flexors, performed using an isokinetic dynamometer. On the other hand, O'Connor et al. (2002) found that women rate eccentric exercises of the same relative intensity level as less effortful compared with men. Koltyn et al. (1991) compared the perception of effort in female and male competitive swimmers during submaximal swimming (90% of maximal velocity), and discovered that the RPE was lower in females despite their greater objective strain (mean HR). As can be seen from these studies, the issue of gender difference in perceived effort of physical activity is unclear, and may depend on the nature of the specific activity.

The main purpose of the present study was to investigate the relation between muscle activity (EMG) and the Borg scale of RPE during low-effort activities of the relatively small forearm muscles, as well as the combined effect of these muscles on the perceived effort. An additional aim was to examine if there is a gender difference in perceived effort in these kinds of physical activities.

METHOD

Participants

Eighteen healthy students (nine males, nine females; age range 22-29) were recruited for this study. The subjects, all right-handed, reported no musculoskeletal disorders in the right forearm or hand at the time of the study. After receiving comprehensive oral and written explanations about the experiment, all subjects provided their full and informed consent prior to taking part in the study.

Evaluation of perceived effort

The Borg CR-10 scale for rating localized exertions was used to assess the subjective effort as perceived by the subjects during the study. The scale ranges from 0 to 10, with 0 representing "no effort" (at rest) and 10 indicating the maximum possible effort (Borg, 1982). All numerical ratings were anchored by appropriate verbal expressions. The scale was explained to the subjects verbally as well as by written explanations. When rating the effort level, subjects were instructed to start by looking at the Borg scale's written expressions and then to choose a number that corresponded to the written expression.

Hand gestures

To simulate localized low-effort activity, eight hand gestures (Figure 1) were used. The hand gestures were selected from a set of gestures that were identified as good hand gestures for human-machine interactions (gestures 1-6) (Stern et al., 2008) and from a set of difficult gestures (gestures 7 and 8). The eight specific gestures were selected in order to attain a wide and diverse range of hand movements and difficulty levels that would encompass the range of possible hand postures during human-machine interactions.

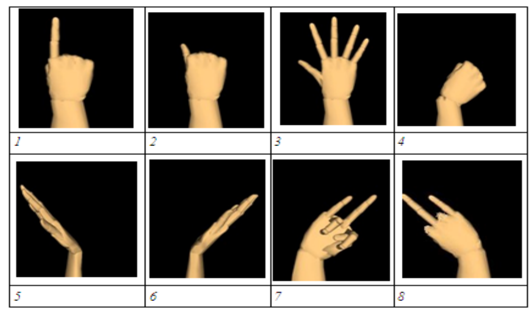

Figure 1. Hand gestures that were used in this study

Testing procedure

The subjects sat comfortably on a chair. Their right elbow, forearm and hand were situated on a soft sponge covered table, the hand was open and its palm was facing down (we refer to this position as the “base posture”). The Borg scale and the hand gesture illustrations were placed in front of the subjects. The subjects were instructed to relax their muscles as much as possible when in the base posture.

Each subject performed eight different hand gestures. Each gesture was performed as follows. The subject held his or her hand in the base posture. Then, after receiving an oral command, the subject performed the required hand gesture by slightly lifting his/her right hand and forearm from the table and performing the desired gesture. The right elbow remained motionless on the table. The subject had to hold this position for 15 seconds, and then return to the base posture for 15 seconds of rest. This cycle was repeated three times for each of the hand gestures before moving to the next gesture. Additional 30-second rest periods were given between the different hand gestures. The Borg score for each gesture was obtained during the rest period between the repetitions (each gesture was rated three times). To ensure that the sequence of performing the gestures would not affect the results of the study, four different sequences of the eight gestures were used. These sequences were randomly assigned to the subjects.

After completing the hand gesture session, each subject performed a set of maximal isometric voluntary contraction (MVIC) tests for each of the six measured forearm muscles (as described under the EMG section). The tests were performed using the muscle testing technique for isolating specific muscles (this is done by performing a unique movement in a joint in order to isolate a specific muscle from other muscles that are responsible for the movement of this joint). Each isometric contraction lasted for six seconds, with a two-minute rest period between the contractions to allow the muscles to recover (De Luca, 1997).

EMG

EMG measurement. During the experiment, SEMG signals were recorded for each of the hand gestures and the MVICs. The signals were recorded from six superficial forearm muscles: (1) pronator teres (p.t), (2) flexor carpi radialis (f.c.r), (3) flexor carpi ulnaris (f.c.u), (4) extensor carpi radialis brevis and longus (e.c.r), (5) extensor carpi ulnaris (e.c.u) and (6) extensor digitorum (e.d).

These muscles where chosen based on the predicted contribution of each muscle to the performance of different hand gestures and on our ability to measure them using SEMG. The SEMG signals were recorded using six wireless EMG sensors (Trigno Wireless System, Delsys, Boston, MA). After cleaning the skin with alcohol, each EMG sensor was placed on the skin over the underlying muscle belly and parallel to the muscle fibers. The location of the muscle's belly was found using a muscle testing technique (as described in the testing procedure section). The EMG sensors where attached to the skin by adhesive interfaces (Adhesive Interfaces for Trigno Sensors, Delsys, Boston, MA), and were fixed to the skin using surgical tape (Medipore Surgical Tape, 3M, St.Paul, MN) in order to provide extra assurance that the sensors would not move during the experiments. After placing the sensors on the skin, prior to the testing procedure, EMG signals were reviewed (for details, see below) during the isolation of each muscle to verify the absence of crosstalk between adjacent muscles.

Signal acquisition and processing. The EMG signals from the six muscles were collected at a sampling rate of 2000 Hz and band pass filtered (20-450 Hz). To verify the integrity of the EMG signals, the collected data was reviewed on-line on a computer using a graphical acquisition program (EMGWorks 4.1.1 acquisition, Delsys, Boston, MA).

At the end of the data acquisition, a moving RMS of the raw EMG signals was calculated (both for the gestures and for the MVIC parts) using a time window of 0.125 seconds and an overlap of 0.0625 seconds. For each muscle, an average RMS value was calculated for the time periods of each repetition. These periods were defined as beginning with the start of the subject's hand movement and terminating with the end of movement, just before the return to the base posture. Then, an average RMS value for each gesture was calculated (an average of three repetitions). In order to allow comparison of the results between and within participants, these average values (a total of eight values per muscle) were normalized by dividing them by the maximal RMS value for each muscle as obtained during the MVIC part of the experiment.

The data processing was performed off-line using our own programming code in MATLAB R2010b software (MathWorks, Natick, MA).

Data analysis

Since all data (normalized RMS values and Borg scale ratings) complied with the principal assumptions of quantitative models, parametric statistic methods were used for the data analysis.

Pearson product-moment correlation was applied to determine the relationship between the activity of subject's forearm muscles (normalized RMS - NRMS) and their perceived effort, as represented by the Borg scale ratings. This process was performed for each of the six muscles as well as for the average and maximum values of the six muscles per gesture. The logic for choosing the maximum values of the NRMS of six muscles is based on the weakest-link concept. Within the framework of this concept, we assumed that the perceived effort would be affected mostly by the muscle that has the highest tension (SEMG correlates to muscle force). Therefore, the closer the muscle is to its maximum capability (i.e., higher NRMS value), the higher the level of perceived effort. The average value of the NRMS of all the muscles was also used as a parameter representing the overall level of muscle activity, since we assumed that activation of additional muscles would be reflected in higher RPE ratings.

To improve our ability to predict the Borg scale ratings based on muscle activity, generalized linear mixed models (GLMM) analysis was used to fit a general linear model:

$$Borg_{est} = Gender + \sum (w_i \times NRMS_i) + \varepsilon \quad (1)$$

where $Borg_{est}$ is the model estimated Borg scale rating; Gender is subject's gender; $NRMS_i$ is the NRMS value of one of the six muscles and w_i is its relative weight (estimate); and ε is the error due to unexplained factors (as explained below). For the maximum and average models, the sum operator contains only a single variable.

This model takes into account the relative influence of the forearm muscles and the subject's gender (i.e., fixed effects), as well as the influence of random effects of the subjects (between-subjects variance) and gestures. The logic for defining the influence of subjects and gestures as random was our desire to generalize this model for various types of subjects and low-effort activities, regardless of the specific subject or gesture. This analysis was performed for the combination of six single muscles as well as for the maximum and average values, as mentioned above. The goodness of fit for the models was evaluated using the R-squared coefficient that was calculated by:

$$R^2 = 1 - SS_{res} / SS_{tot} = 1 - (n_1+n_2+n_3) / (m_1+m_2+m_3) \quad (2)$$

where SS_{res} is the sum of squared residuals (i.e., the measure of the discrepancy between the data and the model) and SS_{tot} is the total sum of squares, which is proportional to the sample variance. The parameters n_1, n_2 and n_3 are the unexplained variations of the model due to random factors, between-gestures variances and between-subjects variances, respectively. The parameters m_1, m_2 and m_3 represent the corresponding unexplained variations of the intercept model (no fixed effects).

To evaluate gender differences, a two-tailed Student's t-test for independent samples was used to compare NRMS values and Borg scale ratings for male and female subjects. All data analyses were conducted at a 0.05 significance level, using the MATLAB R2010b software and statistical analysis program (SPSS Statistics 18, IBM, Armonk, NY).

RESULTS

The average NRMS values (average of six muscles) ranged between 0.016 and 0.141 for different subjects, with an average of 0.058 (i.e., 5.8 %MVIC; SE=0.027). The average Borg rating value was 1.757 (SE=1.118), and the maximal value was 5.67 (out of 10). About 90% of the Borg rating values were 3 or below.

Normalized RMS and Borg scale correlation

The Pearson correlation coefficients (R^2) between the NRMS values and the Borg scale ratings were calculated for each of the six muscles, and for the maximum (max) and average (avg) NRMS values (Table 1).
When examining all subjects or the female subjects only, the correlations are significant for most of the muscles as well as for the maximum and average values. Yet, when examining the male subjects, the correlations are significant only for the extensor digitorum muscle and for the maximum and average values. The R-squared values are higher in women for all of the cases below, i.e., there is a stronger correlation for female subjects.

Table 1. Pearson correlation coefficients between NRMS and Borg ratings

	All subj.		Male subj.		Female subj.	
	R^2	Sig.	R^2	Sig.	R^2	Sig.
p.t	0.016	0.134	0.001	0.780	0.298	0.000
f.c.r	0.009	0.259	0.002	0.681	0.053	0.052
f.c.u	0.066	0.002	0.003	0.631	0.308	0.000
e.c.r	0.059	0.003	0.028	0.160	0.063	0.034
e.c.u	0.064	0.002	0.031	0.140	0.129	0.002
e.d	0.154	0.000	0.122	0.003	0.145	0.001
Max	0.115	0.000	0.055	0.047	0.170	0.000
Avg	0.183	0.000	0.101	0.006	0.319	0.000

General linear model

To predict the Borg scale ratings based on muscle activity and gender, we used generalized linear mixed model (GLMM) analysis, in order to obtain the fixed effects for three linear models: (1) gender and combination of six muscles, (2) gender and maximum values, and (3) gender and average values. For all three models, the gender effect was significant. In the six-muscle model, only three muscles (pronator teres, flexor carpi ulnaris and extensor digitorum) had a significant effect, and the R-squared value for the three-muscle model was R^2=0.295. Both the maximum and average main effects were significant, with R-squared values of 0.196 and 0.278 for the corresponding models, respectively (Table 2). None of the interactions (between the muscles and gender) were significant.
We also calculated the maximum R-squared values that can be achieved when the influences of subjects and gestures are regarded as fixed effects (i.e., knowing the specific subject and gesture), thus eliminating unexplained variations due to between-gestures and between-subjects variances (i.e., removing n_2 and n_3 in Eq. 2). The corresponding R-squared values for the models are 0.730, 0.651 and 0.706, for three-muscle, maximum and average values models, respectively.
All models were tested on the dataset of the test subjects.

Table 2. Linear models for muscles and gender

Fixed Effects	Linear model	R^2
Gender + 3 muscles	Borg = 0.945 X Gender* + 14.737 X p.t*** + 4.467 X f.c.u** + 6.464 X e.d***	0.295
Gender + maximum	Borg = 0.738 X Gender* + 4.444 X Max***	0.196
Gender + average	Borg = 0.786 X Gender* + 20.187 X Avg***	0.278

Gender : 1 for male, 0 for female. (* p<0.05, ** p<0.01, *** p<0.001)

Gender difference

A significant difference ($p < 0.001$) between the perceived effort ratings of men and women (average Borg scale ratings of 2.162 and 1.352, respectively) was revealed using the two-tailed Student's t-test for independent samples. On the other hand, the differences of NRMS values between men and women showed no consistent tendency across all the muscles; significant differences were detected for pronator teres ($p < 0.001$), where women had higher average NRMS values than men (0.039 vs 0.025), and for the extensor carpi radialis ($p < 0.05$), where the average NRMS values where higher in men (0.067 vs 0.051). No significant differences between genders were detected for the rest of the muscles or for the maximum and average values.

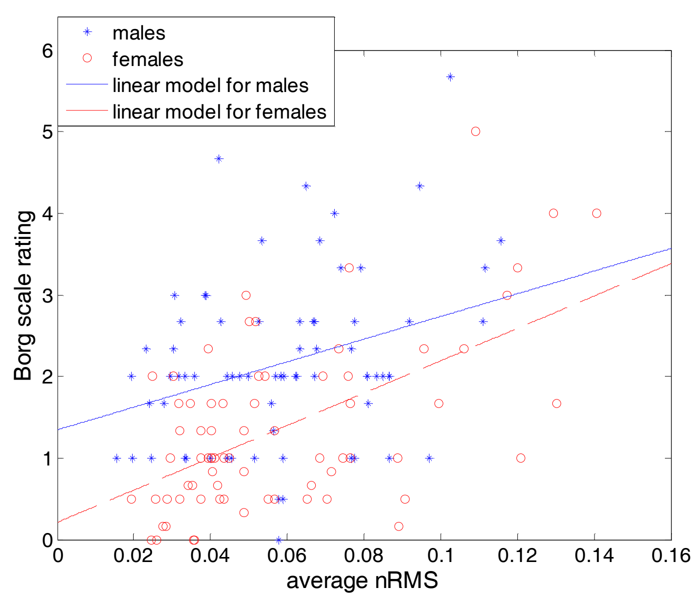

Figure 2. Relation between Borg scale ratings and average NRMS for male and female subjects

The relation between the Borg scale ratings and the average NRMS values for men and for women is shown in Figure 2. It can be seen that the fitted linear model for men is consistently higher than the one for women. Furthermore, the difference between the two models decreases as we move towards higher NRMS values (i.e., as the effort level increases).

DISCUSSION

The main purpose of the present study was to investigate the relation between muscle activity (i.e., EMG) and localized perceived effort ratings (i.e., Borg CR-10) during localized low-effort activities. The average NRMS values (i.e., objective measurement) of subjects range from 1.6% to 14% of the MVIC; approximately 90% of the Borg ratings (i.e., subjective evaluation) are three and under (i.e., moderate effort or lower). These findings support the choice of hand gestures for a localized low-effort activity in this study. Results show that for low-effort activities such as hand gestures, it is difficult to predict the perceived level of effort based on the activity of individual muscles only (low R^2). Better prediction (higher R^2) is achieved when taking into account both the gender and the combined effect of active forearm muscles. The three-muscle model (and gender) achieves a slightly higher R-squared value than the average values model (0.295 vs 0.278). Both models achieve much higher R-squared values than the maximum values model (R^2=0.196). This suggests that our weakest-link theory is not suitable for these types of activities, and that combined activity of muscles is a better predictor. Furthermore, we believe that the average values model might be more appropriate for general use, since it does not require finding a specific combination of muscles. However, this assumption requires further investigation. We also examined how well we can predict the perceived level of effort when also knowing the specific subject and gesture (i.e., the type of physical activity). In that case we can explain approximately 70% ($R^2 \approx 0.7$) of the variation in the response variable (i.e., the estimated Borg rating). Yet, this requires individual adjustment of the model for each subject and gesture, and reduces our ability to generalize the model for other subjects and low-effort activities.

As for the gender differences, our results show that the perceived effort ratings of the female subjects are lower than those of the male subjects. This may be due to differences in the relative effort level of men and women during this study (i.e., higher muscle activity in men) or to gender difference in the perception of physical effort. Since there is no consistent difference between the NRMS values (i.e., muscle activity) of men and women, we suggest that women perceive low-effort activities of the same relative intensity level (i.e., same muscle activity) as less effortful compared with men. Furthermore, our analysis of linear fitted models (Figure 2) shows that for low level of effort, there is a relatively large difference in the relation between EMG and the perceived effort for men and women, while for higher NRMS values (i.e., as the effort level increases) this difference diminishes. Future work should evaluate this issue at medium to high levels of effort of the forearm muscles to obtain a fuller and more accurate picture.

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