SURFACE ELECTROMYOGRAPHY AS A TOOL TO COMPARE VEHICLE RESPONSES TO LATERAL ACCELERATIONS

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Abstract: The purpose of this study was to objectively assess the response of car passengers to lateral accelerations. Three vehicles were tested. Surface EMG signals were collected bilaterally from the cervical erector spinae (CES), latissimus dorsi (LD), erector spinae (ES), external oblique (EO), and vastus lateralis muscles of 10 subjects. Lateral acceleration was also recorded. Recorded SEMG signals were often contaminated by noise, and were therefore denoised using Expectation-Maximization (EM) technique and autoregressive modeling (AR). The RMS of extracted EMG segments was used as an indication of muscle activity. Muscle activation of VL and ES were significantly affected by the vehicle tested ($p < 0.05$). Such a finding implies that SEMG can be used as a tool to compare vehicle responses to lateral accelerations.

Introduction

In the automotive world, comfort has become an important criterion for user choice. The automotive industry places a big emphasis on ergonomic works in order to satisfy user demands such as security and comfort. In this context, comfort means not only air conditioning or shock absorption, but also the minimal perception of accelerations transmitted through the seats. Comfort assessment remains complex and has generally consisted of two methods: subjective methods based on subjects' responses to questions about the comfort of different seats while driving, and mechanical methods using sensors, in particular accelerometers, mounted on seats or other parts of the vehicle. Previous studies used both methods to derive a better representation of comfort [1]. There have been few objective methods developed in order to assess dynamic comfort. Andersson et al. [2] used surface electromyography (SEMG) to analyze muscle activation levels, while Cholewicki et al. [3] used the Center of Pressure (CoP) to quantify postural control in lumbar muscles. Some studies combined several methods to evaluate comfort. For instance, Grabish et al. [4] demonstrated that fuzzy measures and integrals provided a powerful methodology to model complex (multidimensional) subjective sensations. Kolich and Taboun [5] demonstrated that seat comfort could be assessed using SEMG data as well as subjective responses for long duration trials. Other studies combined acceleration and SEMG measurements [6]. Therefore, SEMG has been widely used for comfort assessment.

In ergonomics, SEMG is a non-invasive method that can be used to provide information on muscle activity. Some examples of ergonomic applications of SEMG include the response of the trunk muscles to postural perturbations in sitting subjects [7], the assessment of head rest comfort in cars [8], or the comparison of muscle activity between different car seats due to changing backrest inclination, lumbar support position and seat inclination [2,9].

Although SEMG is a useful tool for objective comfort evaluation, there are a number of problems associated with SEMG recordings in ergonomic settings that make data analysis difficult. The recording environment introduces additional noise that alters EMG characterization and the extraction of relevant parameters. For instance, El Falou et al. [10] showed that classical signal processing methods were unable to identify muscular fatigue in SEMG recordings despite the presence of subject discomfort, whereas a specific process of elimination of non-postural EMG segments performed on the same data enabled the identification of muscular fatigue [11].

The aim of this paper is to objectively assess the response of car passengers to lateral accelerations on a 5-km circuit (similar to a state highway), with an average velocity of 110 km/h. The following section is reserved for recording and denoising EMG signals. In the results section, vehicles are compared by means of muscle activity. Results are then discussed before conclusion.

Materials and Methods

Eighteen male subjects participated in the study. Subjects' mean age, height and mass were 43 ± 8 y, 180 ± 7 cm and 83 ± 14 kg, respectively. All subjects were passengers during the trials.

Surface EMG signals were recorded bilaterally from five muscles using a bipolar electrode configuration. The muscles chosen, after pilot testing, were external oblique (EO), latissimus dorsi (LD), erector spinae iliocostalis (ES), cervical erector spinae (CES) and vastus lateralis (VL). When an additional letter L or R is

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used for the abbreviation, it refers to the left hand side or right hand side of the body, respectively (i.e. EOL denotes the external oblique recorded on the left hand side). Due to recording constraints, nine channels were available for SEMG recordings. All muscles were recorded bilaterally with the exception of VL, which was recorded on the right hand side only, as turns to the left were more pronounced than turns to the right. Red Dot 2330 electrodes were used (3M Health Care, St Paul, MN, USA) for LD and ES muscles, owing to their thin shape, which made them ideal for recording dorsal muscle activity as the thinness of the electrode made for a more comfortable contact with the backrest of the seat. A connection technique using press-studs guaranteed an electrically solid contact between electrodes and cables, while minimizing the thickness of the electrode-cable connection. Circular Red Dot 2238 electrodes were used for the remaining muscles due to their good electrode-skin contact. Electrode placements were in accordance with the SENIAM recommendations for SEMG data collections [12].

In order to facilitate subsequent elimination of the QRS cardiac complex of the ECG signal, it was necessary to record the ECG signal. To this end, an ECG signal was recorded using two Red Dot 2238 electrodes positioned over the second right intercostal space and over the sternum.

The lateral accelerations typically recorded while driving on a highway are usually of the order of ± 0.1g [13]. Such a low signal level needs to be recorded with an accelerometer having a low sensitivity against mechanical vibrations. To this end, an Endevco 7290A variable capacitance accelerometer (ENDEVCO Corporation, San Juan Capistrano, CA, USA) was used. This 1-axis accelerometer, with a sensitivity of 1V/g at 100 Hz was aligned with the transversal axis.

All testing was performed at the Renault Centre Technique d'Aubevoye (CTA). The circuit used for the study was similar to a state highway and had six turns, three veering right and three veering left (figure 1). Three vehicles were tested and were denoted by A, B and C. Experts reported that vehicle A was the least comfortable while turning, and that vehicles B and C were not well differentiated in turning. For reasons of commercial sensitivity, the models can not be disclosed.

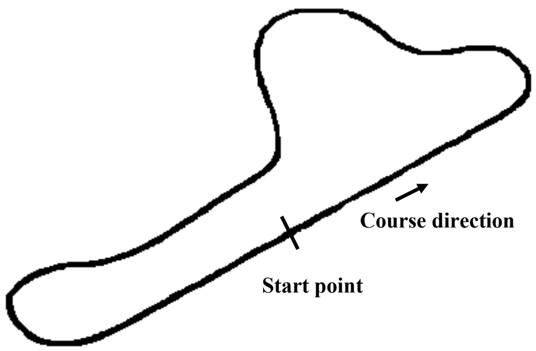

Figure 1: The circuit used for the experimentation

In order to identify the effect of vehicles, subjects were tested once in each car. Each test consisted of one lap of the circuit, corresponding to a duration of approximately 3 minutes. All subjects were passengers and were asked to remain seated while looking straight ahead, without using the armrest. Each subject was tested in each of the three vehicles in a random order. The time between each test was 15 min, which was the time required to transfer the recording equipment between vehicles. Drivers were instructed to take each turn at a velocity between 90 and 110 km/h, which corresponds to the speed on state highways in France.

Data acquisition was performed using a 6036E NIDAQ card (National Instruments, Austin, TX, USA) and a laptop computer. A proprietary software program written in Labview (Version 6.0, National Instruments, Austin, TX, USA) was used for data acquisition.

Sixteen signals were recorded: nine channels for SEMG, one for ECG, one for lateral acceleration and five for other mechanical data (not used in the current analysis). SEMG data were amplified using the gBSAMP (Guger Technology, Graz, Austria), a stand-alone biosignal amplifier system that guarantees a linear amplification until ± 5 Volts for an output voltage of ± 10 Volts. The system Common Mode Rejection Ratio (CMRR) was greater than 110 dB with a frequency range between 0.01 Hz and 50 KHz. All data were sampled at 2000 Hz and pre-amplified by 1000. The band-pass filtering range was (20 – 500) Hz for SEMG signals and (0.5 – 100) Hz for ECG. Acceleration was directly collected by the acquisition system without any amplification.

Signal processing was performed using Matlab (The MathWorks Inc. Natick, MA, USA). Acceleration was averaged every 200 points, a period that corresponded to 0.1 s, before being normalized with respect to the direction of the turn. Negative accelerations occurred when turning right, while positive accelerations occurred when turning left. Due to the experimental conditions, SEMG signals were contaminated by high amplitude artifacts (HAA), white noise, and low frequency noise. In order to denoise the signals, signal processing algorithms were performed and were based on known statistical and classification methods [14].

Firstly, QRS peaks were detected in the ECG recording. The corresponding periods of 100 ms around the detected peaks, which were expected to include the whole QRS complex, were removed from the EMG signals, with values for these parts of the signals left at zero. Each recorded signal was then considered as a mixture of phasic activity (PA) and background activity (BA) contaminated by high amplitude artifacts (HAA), where such artifacts existed. Because of the equality of the means, signals were segmented with respect to energy to avoid class overlapping. Therefore, all classes belong to a centered chi-square distribution. Providing that $x_i \sim N(0,\sigma^2)$, then $y = \sum_{i=1}^{n} x_i^2$ belongs to a chi-

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square distribution with probability density function $f(y) = \frac{1}{(2\sigma^2)^{\frac{n}{2}-1}\Gamma(\frac{n}{2})} y^{\frac{n}{2}-1} e^{-\frac{y}{2\sigma^2}}$.

The Classification Expectation-Maximization (CEM) algorithm was applied in order to estimate the unknown parameter σ for each of the three classes. For more information about the CEM technique and its adaptability to the segmentation of SEMG signals, refer to [14]. After a successful decomposition of recorded SEMG signals into HAA, PA and BA classes, white noise and low frequency components were eliminated from PA segments using Daubechies5 orthogonal wavelets. Some of the denoised PA segments did not have an EMG spectrum and needed, therefore, to be eliminated. An additional classification process involving an autoregressive (AR) spectral modeling of PA segments was applied for residual noise segment elimination. It was found that the pole of highest module corresponded to a frequency between 30 and 80 Hz for all recorded muscles, with the module higher than 0.7 and eventually less than 1.

The root mean square (RMS) parameter was the most suitable for this study, as no fatigue induction was expected from the protocol used in the study. RMS values were estimated for all EMG segments, as a reflection of muscle activation. RMS values for the corresponding acceleration were calculated. Parameters were calculated separately for each of the six turns on the circuit, with the mean value of all EMG segments contained within a given turn used in all subsequent analyses.

SEMG amplitude changed considerably from one subject to another. Normalization was therefore necessary before pooling subjects' data. EMG data were normalized for each subject and each muscle with respect to the mean value.

Statistical analyses were performed with the Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA). Measures of skewness and kurtosis were used to check for normality. When data were separated with respect to the turn direction (i.e. using the acceleration sign), normal distributions of the EMG activity were observed. Analysis of variance was used to test for the effect of configuration, with EMG activity as the dependent variable and acceleration as the independent variable. Analysis of contrasts were undertaken to identify differences between configurations, with Bonferroni adjustments used to reduce type I error rates. Alpha level was set at $p<0.05$.

Results

High amplitude artifacts (HAA) segments were eliminated with a good detection rate of 95%, and 96.25% of BA activities were detected. The remaining PA segments were then classified using AR modeling. Ninety six percent of EMG segments were detected with a false alarm rate of 8%. Figure 2 shows the decomposition of a randomly chosen GDR muscle into three classes: the recorded SEMG signal is represented in bold. PA refers to phasic activity, BA to background activity and HAA to high amplitude artifacts.

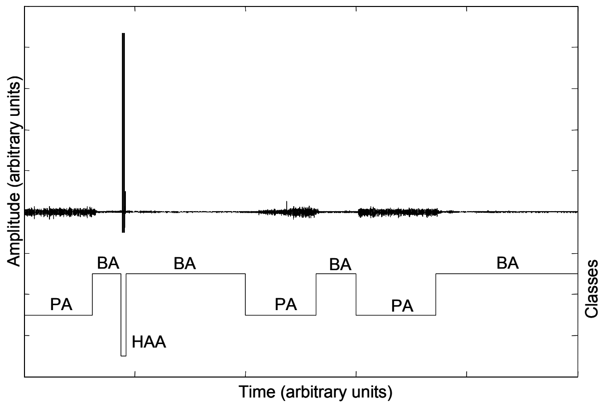

Figure 2: A successful decomposition of a recorded SEMG signal into three classes.

All segments classified as EMG activity were found to be induced by lateral accelerations. When cars were in the straight sections of road on the testing circuit, no phasic EMG segments were detected. Muscle activity was significantly correlated with acceleration for all muscles, with higher accelerations inducing greater muscle activation ($p<0.05$).

Muscles could be divided into three groups, as follows: muscles that were more active during negative accelerations; muscles that were more active during positive accelerations; and muscles that were equally active for both acceleration directions. Muscle activities of the first group were significantly higher when turning right than when turning left; CESR, LDL and ESR muscles belonged to this group. The second group consisted of muscles significantly more activated when turning left than when turning right; CESL, LDR and ESL were in this group, which means that reciprocal phasic activities were observed for CES, LD and ES muscles. Finally, the activities of muscles belonging to the third group were not significantly affected by the acceleration direction; this finding was observed for EOR, EOL and VER muscles. An example of the typical acceleration and muscle activation traces for muscles belonging to each of the three groups can be seen in Figure 3.

In respect to differences in muscle activity between configurations, ESR, ESL, and VER were significantly affected by the chassis-seat configuration ($p<0.05$). Analysis of contrast for ES and VE muscles showed greater muscle activity during turns for the A vehicle than for both B and C vehicles ($p<0.05$, refer to figure 4). In contrast, there were no significant differences in muscle activity levels for CES, LD and EO muscles for both right and left hand sides.

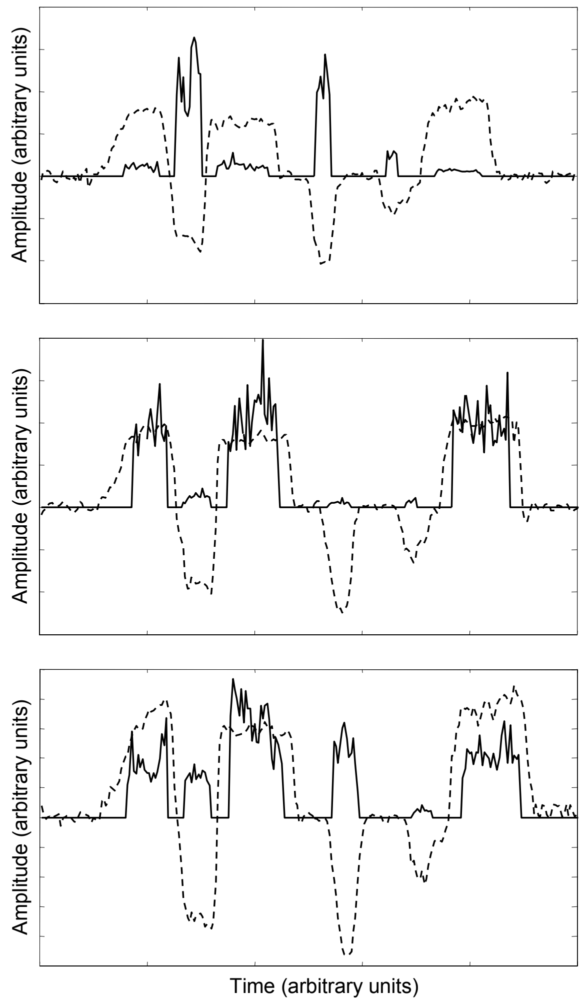

Figure 3: Typical muscle activation and acceleration results: a) LDL muscle activated while turning right; b) ESL muscle activated while turning left; c) EOR muscle activated for both turning directions. Negative acceleration values correspond to right turns, whereas positive values correspond to left turns.

Discussion

The experimental protocol used in the present study proved to be reliable. Given that the study did not aim to evaluate the effect of fatigue, a three-minute circuit with six turns was sufficient to detect significant differences between the vehicles. The use of passengers as subjects, who were required to maintain a pre-imposed position, enabled differences in activation levels required to maintain a steady position to be identified. Such an experimental constraint was chosen in order to minimize the bias introduced by voluntary muscle activity if subjects had been passengers without constraints, or drivers.

The choice of the muscles was based on pilot testing, in which CES, ES, LD, EO and VL muscles had been seen to be activated during a similar experimental protocol. This choice of muscles was valid, certainly in terms of ES and VL muscles, which were able to successfully discriminate between different configurations.

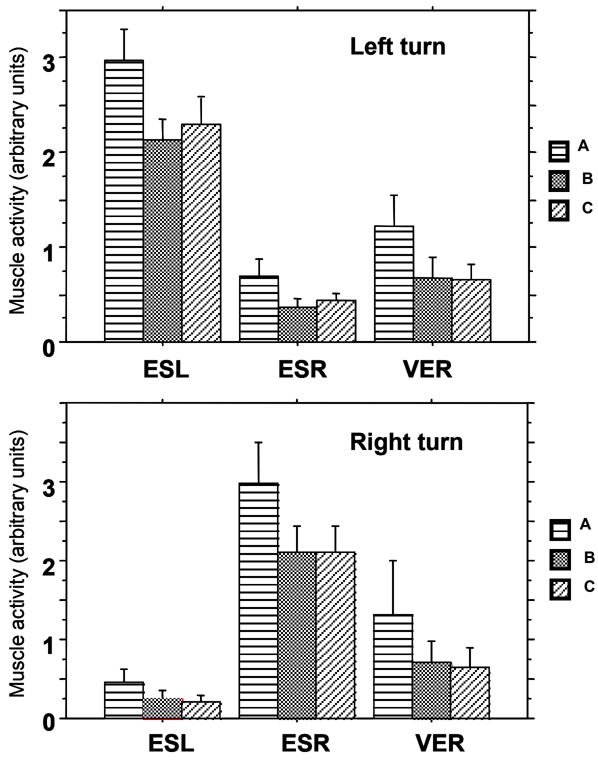

Figure 4: Classification of vehicles in terms of muscle activation level for ESL, ESR and VER muscles for left and right turns.

The choice of electrodes was influenced by the recording environment. The poor signal to noise ratio (SNR) was due to the presence of low frequency vibrations, high amplitude artifacts (the interface between the backrest and the electrode and cable movement), low frequency components and white noise, as well as the QRS complex of ECG signals. One possibility would have been to use active electrodes, in order to improve the SNR [15]. However, the need to record dorsal muscle activity when subjects were in contact with the backrest of the seat precluded their use owing to the size and fragility of this type of electrode. The solution chosen was to use thin Red Dot 2330 electrodes with in-house press-stud connections. The electrode-cable part of the recording system was sufficiently small so as to be easily tolerated by the subjects. Furthermore, the use of the denoising techniques described in part I enabled SEMG signals to be successfully extracted from the recorded signals, despite the presence of a low SNR.

Muscle activity was affected by the turning direction. When vehicles turned to the left, passengers were forced to the right due to the lateral accelerations induced. In order to counteract this acceleration, subjects activated CESL, to maintain their head position, and ESL to stabilize their lower back. Finally, the activation of LDR permitted the torso to remain stable. When vehicles turned to the right, reciprocal phasic activities were observed, with increased activity for CESR, ESR and LDL. In contrast, muscle activity in

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EOR, EOL and VER were not affected by the turning direction.

The differences observed between CES, ES and LD muscles with respect to the turning direction may be interpreted as a bust torsion, which seems to be the reaction of car passengers to lateral accelerations. In addition, the right thigh was similarly activated for right and left turning directions, which may be considered as the result of the pre-imposed position where subjects were not able to use the armrest. This position, although not realistic in terms of the typical activity of car passengers, was the most suitable for this study, as previously discussed.

In respect to differences between configurations, both ES and VE muscles had different activation levels according to the vehicle tested. The A vehicle required greater activity levels for these muscles than for both B and C vehicles. This means that passengers were required to exert more effort in order to remain seated. This finding could be interpreted as a lack of lateral support for the A vehicle.

The presence of lower levels of muscle activation during car turning was thought more comfortable for passengers, although comfort is not only related to muscular activity. In the present study, it could be argued that the higher the activity, the less comfortable the vehicle since it involves a lack of lateral support. As explained previously in the methods section, experts reported that vehicle A was the least comfortable while turning. Comparing findings with the experts' reports, it can be concluded that greater muscle activity results in a decrease in comfort as shown for vehicle A.

Conclusions

The present study was able to identify differences in lateral support between different vehicles using SEMG recordings. Muscle activity was found to be highly correlated with lateral acceleration and significant differences were observed with respect to the acceleration direction. Patterns of muscle activation indicated that passengers counteracted lateral accelerations by using a bust torsion, at the same time as an activation of their quadriceps. It could be concluded that higher muscle activity results in less comfortable vehicles. In addition, the detection of significant differences between configurations using only SEMG activity indicates that SEMG could be used as an objective tool for comparison of vehicles undergoing lateral acceleration.

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