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Neuromuscular fatigue profiles depends on seat feature during long duration driving on a static simulator

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Abstract:

Prolonged driving may induce neuromuscular fatigue and discomfort since drivers have little opportunity to change position. However, better car seat design could play a major role in limiting these effects. This study compared the effect of two different seats (S - soft and F - firm) on neuromuscular fatigue and driver's perceived discomfort during prolonged driving, also assessing the effect of different road types on neuromuscular activity. Twenty participants performed two three-hour driving sessions, one for each seat, on a static simulator. Every twenty minutes, participants self-evaluated their level of whole-body and individual body-area discomfort. Surface electromyography (sEMG) was recorded for eight muscles including Trapezius descendens (TD), Erector spinae longissimus (ESL), Multifidus (MF), Vastus lateralis (VL) and Tibialis anterior (TA) throughout the driving sessions. Moreover, an endurance static test (EST) was performed prior to and after each driving session. Whole-body discomfort increased with time with both seats, but no difference in discomfort scores was observed between seats throughout the driving sessions. The highest discomfort scores were for neck and lower back areas with both seats. Neuromuscular fatigue was revealed by a shorter endurance time in post-driving EST for both seats. EMG recordings showed different neuromuscular fatigue profiles for the two seats, with earlier onset of fatigue for S. Despite the lack of difference in perceived discomfort, the softness of S induces greater activity of the lower back muscles than F, thereby increasing support for the lower back.

Keywords: seat design, prolonged driving, neuromuscular fatigue, discomfort

1. Introduction:

Increasing amounts of time are spent in a sitting position due to the changing requirements of work, leisure, and transport in our societies. Driving could be an important risk factor for lower back pain, in particular where long journeys are involved. Porter and Gyi (2002) reported that 36% of drivers seated in their cars for more than 20 hours per week experienced lower back pain for more than 8 days per year, as compared to only 16% of people who sat in an office chair for the same amount of time. The driver's position is constrained by the need to control the steering wheel and pedals and to keep looking at the road environment (Van Veen & Vink, 2016). To maintain the driving position, therefore, muscles involved in the maintenance of the neck, the stabilization of the trunk, and the movement of upper and lower limbs are constantly solicited (Winkel & Westgaard, 1992; Kruizinga et al., 1998). With time, these sustained submaximal contractions could induce a high level of discomfort associated with neuromuscular fatigue (Hosea et al. 1986; Jorgensen et al., 1988; El Falou et al. 2003; Baucher & Leborgne, 2006).

Neuromuscular fatigue can be defined as “any reduction of the subject's capacity to produce a force / speed / power, whether the task is maintained or not, and reversible during a recovery period” (Barry & Enoka, 2007). It should be considered as a multidimensional concept involving almost four dimensions: task dependency, muscle capacity to maintain a task, neural strategy used to prolong the task, and perception of effort potentially related to motivation. This complexity is captured by different profiles of neuromuscular fatigue, task-dependent and characterized by specific forms of adaptation to the task. Commonly, surface electromyography (sEMG) is used to assess the effect of driving on neuromuscular fatigue through objective measurement of muscle activity. The sEMG signals are determined by several factors such as the number and size of motor units recruited, the discharge frequency of motor units, the electrical properties of the tissues and the rate of motor units' synchronization (Hamilton et al., 2004). This objective measure is frequently compared to subjective self-evaluation of comfort/discomfort, which remains controversial.

Most studies treat comfort/discomfort as a single variable on one continuous scale, suggesting that the feeling of comfort signals an absence of discomfort. However, some studies have demonstrated that comfort is more of an emotional state associated with relaxation and well-being, while discomfort is more of a physical state associated with biomechanical factors inducing pain and soreness (Zhang 1996; Helander & Zhang, 1997; Helander, 2003). De Looze et al., (2003) introduced a comprehensive model, highlighting the non-linear relationship between comfort and discomfort and emphasizing the dominance of

discomfort in overall feeling, based on three main influencers: the human, the product, and the environment.

Concerning muscle activity, consensus is rendered difficult by the great variability of experimental protocols in terms of nature and number of studied muscles, car seats tested, driving conditions (real or virtual environment / with or without vibrations) and driving time. For instance, on a dynamic simulator, El Falou et al., (2003) studied the effects of two different seats, used for 150 minutes with and without vibrations, on neuromuscular fatigue and discomfort. Despite a significant increase in perceived discomfort, EMG analysis did not reveal any significant modification of the activity of cervical erector spinae and oblique muscles for all conditions. In contrast, Hostens and Ramon, (2005) found that after 1 hour of track driving, half of their participants reported trapezius and deltoid muscle stiffness. In a study including six 15-minute driving sessions on a static simulator, Maradei et al., (2015) observed an increase in erector spinae muscle activity during the first three sessions, followed by a decrease. Changes in muscle activity may be a sign of neuromuscular fatigue as motor units are recruited differently to maintain the force required by the task. However, Gyi and Porter, (1999) suggested that a minimum of two hours is required to clearly assess seat comfort and subsequent neuromuscular fatigue. Moreover, in their review, De Looze et al., (2003) reported that the three factors determining driver's physical fatigue are pressure distribution, muscle activity, and vertebral column curvature.

Seat design characteristics may influence these parameters. Depending on their shape and on the firmness of the foam, car seats could modify contact pressure, body maintenance, and therefore the neuromuscular activity necessary to maintain the driving position. To investigate car seats' impact on these parameters, the present study compared the effect of two different seats (one soft = S and one firm = F) on neuromuscular fatigue and perceived discomfort during prolonged driving on a static simulator. The device provided a controlled environment (without car vibrations or longitudinal and lateral accelerations, at stable temperature and under controlled weather conditions) that enabled us to characterize the different profiles of neuromuscular fatigue directly related to seat features. Using these profiles, a further study should be able to investigate the effect of seat features on neuromuscular fatigue under real-life prolonged driving conditions. The long-term objective is to identify seat features that could reduce neuromuscular fatigue.

2. Materials & Methods:

2.1. Sampling:

Twenty participants (10 men and 10 women), whose mean age, height and weight were 27.8 ± 5.6 years, 1.7 ± 0.1 meters 69.9 ± 14.4 kg respectively, were recruited through the university network and volunteered to take part in this study. Conditions for inclusion in the study were having no relevant signs of musculoskeletal problems or back pain and at least two years of driving experience. Prior to the experiment, all participants gave their written informed consent. All experimental procedures were performed at the “Centre de Réalité Virtuelle de la Méditerranée” (CRVM) which enjoys ethical committee approval for human research (Regional Health Agency - DOS-0515-3092-D).

2.2. Seats tested:

For this experiment, two serial seats provided by Peugeot and Citroën were used. A firmer seat (F) in a mixture of fabric and artificial leather and a softer seat (S) made entirely of standard car upholstery fabric. Prior to the experiment, a study was performed by a Spanish automotive technology center, CTAG (Centre Technologique de l'Automobile de Galice, Spain), to assess the height under weight (HUW) of both seats. This is the gold standard technique for measuring overall seat behavior (polyurethane foam, leather or fabric trim, metallic frame and metal-plastic suspension map; *Figure 1*). Briefly, a robotic arm applied a conformator successively to the backrest and the cushion of each seat. Continuously increasing force was applied on the foam until a maximum of 1050 N was reached, and the maximum foam displacement was measured for each condition (*Figure 2*). The degree of backrest foam displacement was similar for both seats (23 and 24 mm). However, the cushion of the first seat revealed higher displacement (55 mm – considered softer; S) than the second seat (41mm – considered firmer; F).

2.3. Experimental synopsis:

To overcome the effect of circadian rhythmicity, each experiment started at the same time of day (1:00 pm). Each participant wore identical sportswear, shorts and a T-shirt, provided by the experimenters to avoid any clothing effect on discomfort perception. The sEMG electrodes were attached to participants, and sEMG signals were tested for each muscle being assessed. Then, participants performed the first endurance static test (EST) (described in the “Endurance static test” section hereunder) to assess their initial physical capacity prior to the driving session. After the EST, participants climbed into the cockpit and

self-adjusted the car seat to the most comfortable position possible, following which a calibration recording of sEMG signals was performed. Then the driving scenario was launched and new sEMG signals were recorded throughout the 3-hour driving task. Finally, at the end of the driving session, the participants performed a second EST. Each participant performed two driving sessions, one for each seat tested, at least one week apart. The order of tested seats was randomly attributed.

2.4. Simulator features and driving sessions:

Experimental driving sessions were performed on a static driving simulator (Compact simulator, A.V Simulation, France). Before the experimental protocol began, experimenters carried out structural modifications to the simulator to reproduce the normal seating position in the cockpit for both seats. The 3-hour driving scenario was programmed with Scanner[®] software (Scanner Studio version 1.6, A.V Simulation, France) and consisted of several types of roads: city (Ci), highway (H), country (Co), and mountain (M). The chronological order of the sections was organized as shown in *Figure 3*. Traffic density was designed to be as realistic as possible, unpredictable and random.

Following a calibration recording, the driving scenario was launched. Participants had to drive in the most natural way possible, respecting the French speed limits and driving regulations as if in real vehicles. The gearbox was automatic and participants had to keep their hands on the steering wheel as long as possible throughout the driving session. A programmed GPS allowed each participant to follow the same itinerary.

2.5. sEMG positioning:

To assess the effects of a prolonged driving task on neuromuscular fatigue, neuromuscular activity was monitored by sEMG (Biopac[®], Cerom, France) of the following eight muscles: right and left trapezius descendens (TD) (involved in the stabilization of the head and the movements of the arms), right and left Erector spinae longissimus (ESL) and right and left Multifidus (MF) (which ensure the maintenance of the spinal column), right Vastus Lateralis (VL) and Tibialis anterior (TA) (involved in pedal control). For all these muscles, the surface of the skin was shaved if necessary and cleaned with an alcohol swab. Then, EMG electrodes were positioned according to international recommendations ([Hermens et al., 2000](#)), i.e. on the midline of belly muscle, perpendicular to the length of muscle fibers, spaced 2 cm apart and fixed with adhesive tape.

2.6. Endurance static tests:

Participants performed an endurance static test just before (ESTb) and immediately after (ESTa) the driving task. The test consisted in maintaining a weight bar at pectoral level as long as possible, as described in *Figure 4*. Prior to the evaluation, the load of the weight bar was progressively adjusted to the physical capacity of each participant, starting from 8 kg. If the participant succeeded easily, the weight was increased to 14 kg; if the first attempt at 8 kg was too difficult for the participant, the weight was reduced to 4kg. When the first attempt was challenging enough, the weight of 8kg was maintained for ESTb. The load remained unchanged for ESTa, so that subjects were tested as their own controls. Overall, three adjusted weights were used (4kg, 8kg and 14kg), and endurance time was measured for each EST.

2.7. Neuromuscular activity during driving:

Prior to the driving task, when participants had adjusted their seat, they were asked to maintain their hands on the steering wheel and their right foot on the throttle pedal and to stay in this position for two minutes. During this short period, a first recording of sEMG signals was carried out. This recording of basal neuromuscular activity related solely to seat setting and driver's position was used for calibration. Then, the driving scenario and a new sEMG recording were launched synchronously with the beginning of the driving task. For the purposes of data analysis, a homemade MATLAB[®] program was used to filter raw signals (10 – 500 Hz) and to exclude electrocardiogram signals when necessary. For each participant, each road section and each muscle, the same program provided ten RMS values calculated according to neuromuscular activity during each successive 10% of the total time spent in each road section. These data were normalized twice: (i) according to the corresponding RMS values obtained during calibration and, (ii) according to the first RMS data obtained from the driving task (i.e., the RMS recorded during the first 10% of the time spent in the first road section). The mean and the variation of normalized RMS values were analyzed further.

2.8. Perceived discomfort:

During the driving session, participants regularly self-evaluated their level of discomfort, as commonly done in discomfort studies (Borg, 1982; Kruizinga et al., 1998; Hiemstra-van Mastrigt et al., 2015; Varela et al., 2019). A visual analog scale (VAS) was used to evaluate participants' whole-body discomfort. The side of the device shown to participants included only one sliding cursor running from left (no discomfort) to right (very

uncomfortable). The other side, only visible to the experimenter, had a graduated scale precisely quantifying the degree of discomfort with continuous values (from 0 to 100 mm). To assess the evolution of whole-body discomfort during the driving session, the average of each of the ten VAS evaluations was calculated for both seats tested.

In addition, to distinguish the most uncomfortable body areas, an adaptation of the local perceived discomfort (LPD) method was used (Van der Grinten and Smitt, 1992). Briefly, following each VAS evaluation, participants were asked to verbally give a discomfort score of between 0 and 100 for thirteen body parts (i.e. neck; upper and lower back; and right and left arm, buttock, thigh, leg and foot), where 0 represented the minimum imaginable discomfort and 100 represented the maximum imaginable discomfort. This method afforded reliable assessment of the discomfort perceived over time without excessively disturbing participants during the driving task. Corresponding data were expressed as a percentage of the maximum value observed for each subject throughout the driving session (highest discomfort score of the ten VAS evaluations) and data for all participants were averaged for each of the ten VAS evaluations.

2.9. Statistical analysis:

Data were expressed as the mean \pm standard deviation. All statistical analysis was performed with STATISTICA[®] software (version 6.0). EST results were compared using a paired t-test (before vs after driving for each tested seat). A two-way ANOVA (2 seats x 10 discomfort scores) was performed to compare whole-body discomfort data. Comparative analysis covered: (i) whole-body discomfort scores at each assessment interval against the initial whole-body score for each seat (time effect) and (ii) at each assessment interval, the whole-body discomfort scores for seat S against seat F (seat effect). A Tukey-Kramer post-hoc test was performed when a significant effect was observed. The same methodology was used to analyze the evolution of perceived discomfort for each body area. To compare the effects of driving time and road sections on neuromuscular activity, normalized RMS values were compared using a two-way ANOVA (2 seats x 13 road sectors). A Bonferroni post-hoc test was applied when a significant effect was observed. All statistical differences were considered as significant at $p < 0.05$.

3. Results:

3.1. Endurance static test:

Endurance time for ESTa was significantly shorter than for ESTb for both seats ($p < 0.01$ for S and $p < 0.05$ for F) (*Figure 5*). Mean endurance time was 26 seconds shorter for S and 34 seconds shorter for F after the driving sessions. However, the ESTb/ESTa ratio did not significantly differ between seats. Statistical analysis of RMS and mean frequency of both TD muscles did not reveal any significant difference.

3.2. Discomfort:

For both seats, the level of whole-body discomfort began to be significant (compared to the initial discomfort scores) after 43 min and continued to increase until the end of the driving session (*Figure 6*). However, perceived whole-body discomfort did not significantly differ between seats throughout the driving task.

Likewise, no difference between seats was observed in the mean discomfort level for any body parts. *Figure 7* represents the body mapping of local perceived discomfort (LPD). Data are expressed as a color gradient representing the discomfort percentage mean for each body part and for both seats.

3.3. Neuromuscular activity during driving:

Figure 8 displays the normalized RMS values for TD, ESL and MF muscles by road section for each seat tested. Standard deviation of normalized RMS by road section is presented in *Table 1*.

With the softer seat (S), lower RMS values were recorded for both TD muscles in City 3 (Ci3) than in Ci1 (Right TD: $p < 0.001$; left TD: $p < 0.05$) and Ci2 (right TD: $p < 0.001$; left TD: $p < 0.01$). With the firmer seat (F), the neuromuscular activity of left TD was higher in Highway 3 (H3) than in H1 ($p < 0.01$) and higher in Country 3 (Co3) than in Co1 and Co2 ($p < 0.001$ for both).

Turning to the muscles involved in the stabilization of the spinal column (i.e. ESL and MF), the neuromuscular activity of right ESL decreased significantly in the last road section (i.e. Co3) for both seats compared to the first two country road sections. Seat S had significantly lower RMS for right ESL in Ci3 than in Ci1 ($p < 0.001$), and in Co3 compared to Co1 ($p < 0.05$). Seat F had lower RMS values for right ESL in Mountain 2 (M2) than in M1 ($p < 0.001$), and in Co3 compared to Co1 and Co2 ($p < 0.01$ and $p < 0.05$, respectively).

Interestingly, the neuromuscular activity of left ESL was lower in the last road section with F, whereas it increased significantly from H3 on with S. This increase was associated with higher variability in the corresponding sections. More precisely, with F, the neuromuscular activity of left ESL yielded significantly lower RMS values in Ci3 than in Ci1, and in Co3 compared to Co1 and Co2 ($p < 0.001$ for all). In addition, with S, RMS values were significantly higher in H3 than in H1 and H2 ($p < 0.001$ for both).

Regarding right MF, no significant difference was observed with S within the same road types regardless of sections, while several differences were observed with F. RMS values of right MF with F were significantly higher in H3 than in H1 and H2 ($p < 0.001$ and $p < 0.01$, respectively). Moreover, RMS values in H2 were also significantly higher than in H1 ($p < 0.001$). RMS values of right MF were also higher in Co3 than in Co1 ($p < 0.001$) and Co2 ($p < 0.05$). Regarding left MF, RMS values with S were significantly higher in Ci3 than in Ci1; but also in H3 compared to H1 and in Co3 compared to Co1 and Co2 ($p < 0.001$ for all). In contrast, the only difference found with F was higher RMS values in H3 than in H1 ($p < 0.01$).

Concerning differences between seats, in Co3, the normalized RMS values with F were even higher in comparison with S for both trapezius descendens ($p < 0.01$ for both TD). For the first mountain section (M1), F induced higher right ESL neuromuscular activity than S ($p < 0.001$), while left ESL showed significantly lower RMS values with F than with S ($p < 0.05$). Moreover, left ESL RMS values were significantly higher in H3 and Co3 with S than with F ($p < 0.001$ for both).

Finally, for differences between seats on a single road section, S induced significantly higher left MF RMS values than F in Ci2 ($p < 0.05$) and in Co3 ($p < 0.001$). In contrast, right MF RMS values were higher with F than with S in H3 and Co3 ($p < 0.001$ and $p < 0.01$, respectively). Results for TA and VL are not shown, as no difference was observed for these muscles.

4. Discussion:

Seeking to improve drivers' well-being and comfort, automotive companies have focused their research over the past decades on human-machine interactions ([Romelfanger & Kolich; 2019](#); [Varela et al., 2019](#)). Several studies have highlighted a deleterious effect of driving on comfort and neuromuscular fatigue ([Kolich & Taboun, 2002](#) ; [Hostens & Ramon, 2005](#)). Numerous factors are involved, including driver's physical capacity, driving time, road

type, car vibrations, and car seat design (Jagannath and Balasubramanian, 2014). However, due to the wide variability of experimental protocols, there is still no consensus regarding the best strategy for car seat design.

In the present study, based on a reproducible protocol, the impact of two different seats (softer and firmer) on perceived discomfort and neuromuscular fatigue was assessed during three hours of driving on a static simulator. Over time, whole-body discomfort increased in the same way regardless of the type of seat, which is consistent with findings from previous studies (Smith et al., 2015; Sammonds et al., 2017). The highest discomfort scores were observed for neck and lower back areas, for both seats. Neuromuscular fatigue was revealed by shorter endurance time scores after than before the driving task, for both seats. Despite the absence of any significant difference between the two seats in subjective assessments of discomfort, muscle activity recordings showed different profiles of neuromuscular fatigue. Thus, it appears that the firmer the seat, the greater the body support and the lower the muscle activity required for the driving task. Conversely, the softer the seat, the greater the muscle solicitations required to improve stabilization.

4.1. Perceived discomfort:

In their model, Ebe and Griffin (2000a, b) described static and dynamic factors that could influence drivers' perceived discomfort. The "static" factors are the overall design of the seat including stiffness, shape, and related pressure distribution, while vibrations and longitudinal/lateral accelerations belong to the "dynamic" factors. In the present study, as a first step, we considered solely static factors to determine how different seats (different shapes and foams) may influence perceived discomfort in prolonged driving. For both seats (soft and firm), the level of whole-body discomfort began to be significant from forty-three minutes of driving, and continued to increase until the end of the driving session (*Figure 4*). This result is in accordance with several studies investigating level of discomfort during prolonged driving (El Falou et al., 2003; Porter et al., 2003; De Carvalho & Callaghan, 2011). In terms of whole-body discomfort, no difference was observed between the two seats; however, differences were observed in individual body-area discomfort. Interestingly, the highest discomfort levels experienced were in the neck and the lower back, predominantly in the neck area for S and in the lower back area for F. The firmer foam affords better support for the body and induces higher contact pressure on the lower back area. De Carvalho & Callaghan et al. (2011) demonstrated that participants using a firm seat experienced passive lumbar spine stiffness after two hours of simulated driving. With time, this could induce lower back

injuries. In the present study, perceived arm discomfort was also quite high for both seats, but this is probably due to the driving instructions: participants had to keep their hands on the steering wheel throughout the driving sessions. Perceived lower limb discomfort was relatively low for both seats, but greater on the right side than on the left side. This could be due to the action of the right leg on the pedals; the left leg was inactive, as the gearbox was automatic.

4.2. Effect of seat on neuromuscular fatigue:

The effect of prolonged driving on neuromuscular fatigue was attested by a shorter endurance time in ESTa than in ESTb for both seats. This result suggests that participants' physical capacity was lower after the three-hour driving task. While no difference was observed between seats in this respect, our monitoring of neuromuscular activity during driving reveals a different profile of neuromuscular fatigue for each seat. Importantly, our results suggest that a two-hour driving task may be insufficient to induce major neuromuscular fatigue: most of the significant differences here appeared after 2 hours and 30 minutes of driving. This finding supports the previous finding by Gyi and Porter ([Gyi & Porter, 1999](#)) that a long period is required to clearly evaluate the effectiveness of a seat.

In terms of neuromuscular fatigue for each muscle, normalized RMS values for both TD were higher at the end of the driving task with F than with S. However, this only concerned road section Co3. The first differences in both TDs' neuromuscular activity with S appeared in Ci3, where RMS values were lower than in the previous city sectors. Moreover, the left trapezius neuromuscular activity with S was higher in H3 than in the first two highway sections. Another interesting finding is that for the highway sections, the variability of trapezius neuromuscular activity was greater for S than for F. This could be explained by the S-induced need to differently recruit trapezius muscles to modify body position. These results show that trapezius muscle neuromuscular fatigue appeared sooner with S than F. It is likely that the softness of the foam means the trapezius has to work harder to maintain the steering wheel and to counteract the body's sinking into the S seat. Moreover, the highly static posture of drivers on highways engenders constant recruitment of all the muscles involved in the driving task without allowing any relaxing movements, which increases neuromuscular fatigue ([Chen et al., 2014](#)).

Concerning the muscles involved in the stabilization of the spinal column (i.e., ESL and MF), right ESL remained quite stable almost throughout the driving task, RMS values only decreasing towards the end, on the last road section: the normalized RMS in Co3 was

lower than in the previous country road sections for both seats. Interestingly, the neuromuscular activity of left ESL was lower on the last road section with F, whereas it increased significantly from H3 on with S. This increase was associated with greater variability in the corresponding road sections, which could suggest that the softer seat did not generate relaxation in left ESL. These different profiles lead necessarily to different repositioning strategy, which is in agreement with Isawa et al., (2005). Indeed the later demonstrated that ESL fatigue alter trunk repositioning accuracy in both forward and lateral flexion.

MF muscular activity evolved similarly to that of ESL. Neuromuscular activity of right MF was higher with F on the two last highway sections and on the last country road, while left MF showed higher neuromuscular activity with S on Ci3 and the two last sections (H3 and Co3). Variability of normalized RMS values was higher for these sections. This could be attributed to a possible change in muscle recruitment due to neuromuscular fatigue and discomfort. The fact that MF neuromuscular activity outcomes were similar to those of ESL muscles is not surprising, as these muscles have a synergistic action, in particular for back stabilization and motion. Moreover, these muscles have to compensate for the action of the right leg, which is involved in operating pedals. The outcomes are probably due to the different types of foam used in the two seats tested. The softer foam of S compelled drivers to increase their muscle recruitment to maintain their posture. In contrast, the firmer F backrest kept the body position steadier and less contralateral neuromuscular compensation was required to maintain a suitable and comfortable driving position. Seat F generated lower back neuromuscular compensation for right leg actions solely on the right side. Interestingly, Tian et al (2008) reported that after eight hours, unsymmetrical fatigue in bilateral dorsal muscles was observed for taxi drivers.

These results illustrate the capacity of the neuromuscular system to deploy various strategies, here leading to two compensatory profiles that differed according to the softness of the seats. Naturally, the musculoskeletal system reacts to counteract any inappropriate curvature of the spine induced by a driver's position. Thus, during the driving task, the level of neuromuscular contraction was constantly adjusted to reduce the biomechanical constraints in each joint involved in the perceived discomfort (Baucher & Leborgne, 2006). Overall, the neuromuscular activity of the right leg remained relatively stable throughout the session, which could be interpreted as indicating an absence of neuromuscular fatigue in this body area. Given our protocol, this could be due to a compensatory effect from the back muscles, or simply the fact that the right leg was not involved in maintaining the driving position.

4.3. Effect of road type on neuromuscular activity:

As previously specified, the degree of muscle solicitation differed according to road type. There was very little muscle solicitation on highways and country roads, which do not require many movements from drivers. Jammes et al., demonstrated that driving at constant elevated speed, as is common on highways, reduces the myotatic reflex and the recruitment of motor units of TA muscle (Jammes et al., 2016). Contrastingly, city and mountain roads, with their numerous turns and successive accelerations/brakings, induce higher muscle solicitation. In our study, most of the significant differences appeared on country and city roads and on highways, especially towards the end of the driving session. Furthermore, muscle activity remained relatively steady in all mountain areas for both seats, except for right ESL for F and left ESL for S: RMS values were quite high on M1, but these differences disappeared on M2. The high level of solicitation on mountain roads distorted the analysis of neuromuscular fatigue in these sections. However, repeated muscle solicitation obviously contributes to neuromuscular fatigue.

4.4. Methodological considerations:

The results of the present study should be interpreted in the light of some methodological limitations. Driving sessions were performed on a static simulator; thus, contrary to real driving conditions, drivers were not exposed to car vibrations, lateral/longitudinal accelerations, temperature and weather condition variations. The impact of these factors on muscle activity should not be overlooked. In addition, the levels of mental workload and stress related to crash risks and environmental stimuli are higher in real driving conditions than on a static simulator (Philip et al., 2005). This is a substantial issue, since such factors are known to strengthen musculoskeletal system solicitation, especially in the case of a monotonous task involving sustained low-intensity contractions, such as driving (Bongers et al., 2002; Van Galen et al., 2002; Zuzewicz et al., 2013). However, as a first step, we sought here to characterize neuromuscular fatigue profiles induced by prolonged driving (a very complex task) in a controlled environment. Our aim was first to assess how, even without all the normal environmental and psychological factors involved in driving, different seat features might affect drivers' perceived comfort and neuromuscular fatigue. Based on these first results, a further study will be performed under real driving conditions.

5. Conclusion:

For both seats, neuromuscular fatigue appeared after prolonged driving, but generally sooner with **S** than with **F**. It is likely that the relative softness of **S** induced greater muscle activity of the lower back muscles through contralateral compensation, thereby offering better support for the lower back.

The presence of neuromuscular fatigue was confirmed by shorter endurance times in post-driving EST. Despite increased body discomfort (mainly in the lower back and neck) throughout the driving session, participants did not seem able to distinguish between the neuromuscular fatigue profiles induced by each seat. This suggests that levels of neuromuscular fatigue and perceived discomfort may not be directly related.

Moreover, compared to maximum voluntary contractions, the contraction levels observed in our study were relatively low. Thus, neuromuscular fatigue did not stem from muscle exhaustion but from a prolonged repetition of submaximal contractions due to a relatively static position. Although this position may be affected by different types of seat, it appears that subjective measures like perceived discomfort are not sensitive enough to distinguish between different neuromuscular fatigue profiles.

These findings suggest first that automotive companies need to bear in mind that the seat perceived as the most comfortable is not necessarily the least tiring. A second message is that attempts to improve seat comfort or the seat's ability to reduce neuromuscular fatigue should be based on objective measures such as muscle activity assessments, for more accurate analysis of seat features. Further studies should be directed at identifying the perfect car seat design compromise between a high level of comfort and optimal reduction of neuromuscular fatigue, to improve the well-being of drivers during as well as after driving.

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Figures:

Figure 1: Schematic representation of the different components of a seat. The main components that determine overall seat features are metallic frame, suspension map, foam and trim.

Figure 2: Column 1 shows both firm (1a) and soft (1b) seats. Column 2 illustrates the setup for the CTAG's tests assessing the height under weight for the cushion (2a) and the backrest (2b) of each seat. Corresponding results are shown in the force versus displacement graphics of column 3. At the same force, cushion displacement (3a) is greater in the soft seat than in the firm seat; for the backrest, there is almost no difference in force versus displacement curve (3b) between seats.

Figure 3: Chronological order of road sections in driving scenario. Each participant followed the same itinerary, which included city (Ci), highway (H), country (Co) and mountain (M) roads.

Figure 4: Illustration of endurance static test (EST) performed before and after driving session. EMG electrodes were used to record trapezius neuromuscular activity during the test.

Figure 5: Endurance time mean (in seconds) for EST before and after driving session for both seats. Significant differences between endurance time measured before and after driving session are illustrated by * ($p < 0.001$).

Figure 6: Evolution of whole-body discomfort during driving session. Significant levels of discomfort compared to initial values are represented by * (**: $p < 0.01$; ***: $p < 0.001$).

Figure 7: Mean of discomfort scores expressed as a percentage of maximum values for each body part for both seats.

Figure 8: Mean of normalized RMS values for each road section for both seats. *: significant differences between sections for the same road type (sections showing significant differences are mentioned above *); §: significant differences between seats for the same road section.

Table 1: Variability of normalized RMS values on each road section for driving sessions with S and F seats. Green, yellow, and red cells indicate that the corresponding road section was respectively at the beginning, the middle and the end of the driving session.

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