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Effect of arm position on spatial distribution of upper trapezius muscle activity during simulated car driving

Kohei Watanabe and Takahiro Yoshida

Laboratory of Neuromuscular Biomechanics, School of Health and Sport Sciences and School of International Liberal Studies, Chukyo University, Japan

ABSTRACT

The present study aimed to investigate the upper trapezius muscle activity during simulated car driving while adopting three different arm positions. Ten participants were instructed to maintain the following positions: hands on the steering wheel (Hands-On), hands not on the steering wheel (Hands-Off) and hands not on the steering wheel but arms on armrests (Armrests). During the tasks, multi-channel surface electromyography (EMG) was recorded from the upper trapezius muscle with 64 two-dimensionally distributed electrodes. Amplitudes of surface EMG in Armrests were lower than in Hands-On ($p = 0.004$). The spatial distribution of surface EMG changed with time in Hands-Off and Armrests ($p < 0.05$), but not in Hands-On ($p > 0.05$). These findings suggest that being freed from steering leads to the recruitment of various muscle fibers/motor units within the upper trapezius muscle and the use of armrests may help reduce the physiological burden loaded on the muscle of drivers.

KEYWORDS

automated driving system; steering; surface electromyography; car driving

1. Introduction

Automated driving systems have been developing and will become widely available in the near future. Levels of driving automation are defined in terms of executioner, monitoring or driving modes by the Society of Automotive Engineers International (SAE) (J3016_201806) [1]. The contribution of human drivers is decreasing with an increase in the SAE level. Thus, progression of automation would reduce human drivers' physiological and psychological burdens while driving. One of the most marked changes on transitioning from normal driving to automated driving is being freed from steering. This would lead to many advantages due to freeing of the arms and hands [2,3]. Also, this change in driving style would be directly associated with physiological burdens, since the arm position, whether the hands are on the steering wheel, changes the activations and postures of neck and shoulder muscles [4], and so neuromuscular fatigue of upper limbs during driving will be influenced. Human drivers need to perform all steering at SAE level 0, partly perform steering at SAE level 1 and do not need to perform steering at all at SAE levels 2–5 [1]. Therefore, the physiological burden is considered lower with an increase in the SAE level, and progression of the automated driving level has advantages in terms of physiological aspects.

There have been many studies assessing neuromuscular fatigue using surface electromyography (EMG) during certain motor tasks. Surface EMG is a classic method to measure the action potentials of muscles from the skin surface, being considered to reflect physiological responses of the neuromuscular system, such as motor unit recruitment and its firing pattern [5,6]. However, the detected surface EMG signal provides information on a very small portion of the muscle, since a pair of small electrodes is generally used to record surface EMG from the muscle of interest. Recently, a multi-channel surface EMG technique that can record surface EMG from a large area of muscle using multiple two-dimensionally oriented electrodes has been developed as a methodology to estimate motor unit activation or provide more detailed physiological information [6]. In particular, region-specific activation has been reported in relatively large muscles such as the trapezius [7–10]. Therefore, the multi-channel surface EMG technique would be useful to fully understand the neuromuscular function and/or fatigue condition in relatively large muscles.

The aim of the present study was to investigate the effect of arm positions on the spatial distribution of upper trapezius muscle activity during simulated car driving. We simulated three different situations: hands on the steering wheel (Hands-On), hands not on the steering wheel without any supports (Hands-Off) and hands not on the steering wheel but arms supported on armrests (Armrests). The distal ends of upper limbs were supported by the steering wheel or armrests during Hands-on and Armrest but were unsupported during Hands-off. Also, different arm positions induce alterations in biomechanical conditions of the upper extremities, and this modifies force production strategies of the neck and shoulders. We thus hypothesized that neuromuscular activation, which is an indicator of the physiological burden of neck muscles, is greater in Hands-Off than in Hands-On and Armrests, and that different spatial distributions of upper trapezius muscle activity are observed in Hands-On compared with Armrests and Hands-Off.

2. Methods

2.1. Participants

The participants in this experiment comprised 10 healthy young men (age 21.1 ± 1.0 years, height 170.1 ± 5.5 cm, body mass 59.3 ± 6.6 kg). All subjects were healthy with no history of any musculoskeletal or neurological disorders. They gave

CONTACT Kohei Watanabe wkohei@lets.chukyo-u.ac.jp

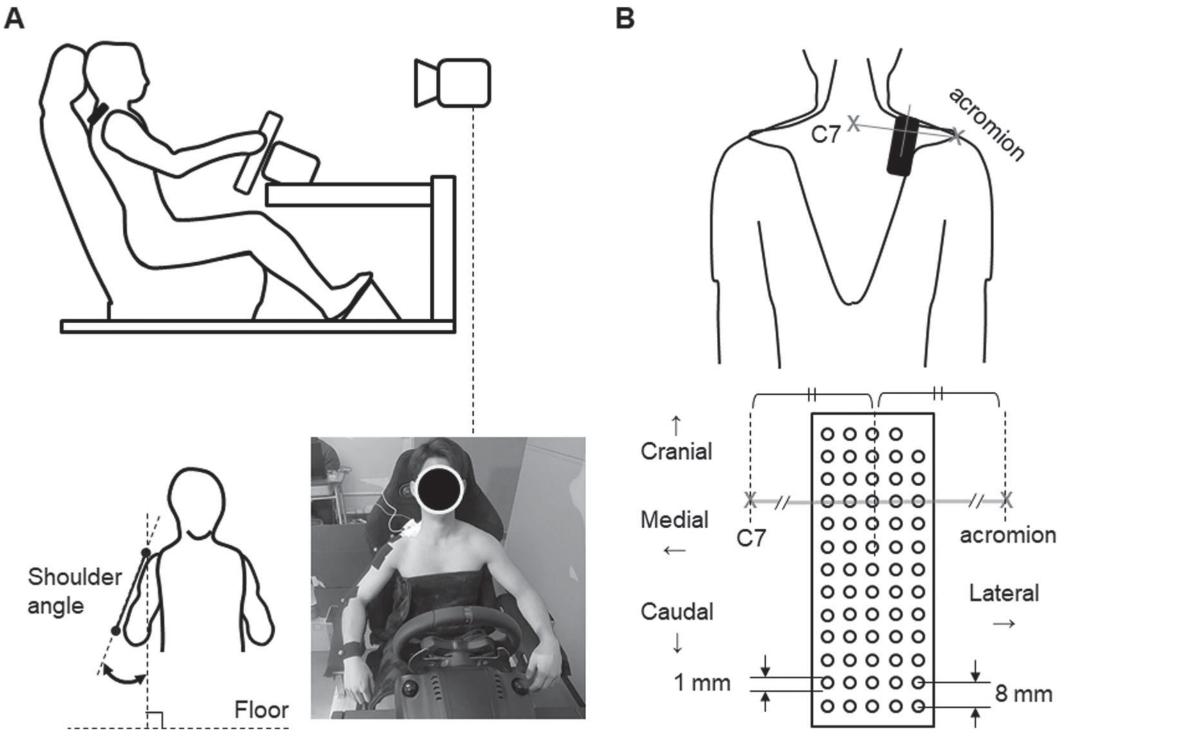

Figure 1. Experimental setting and definitions of the shoulder joint angle (A), and the electrode location and schematic representation of the electrode grid (B). Note: C7 = seventh cervical vertebra.

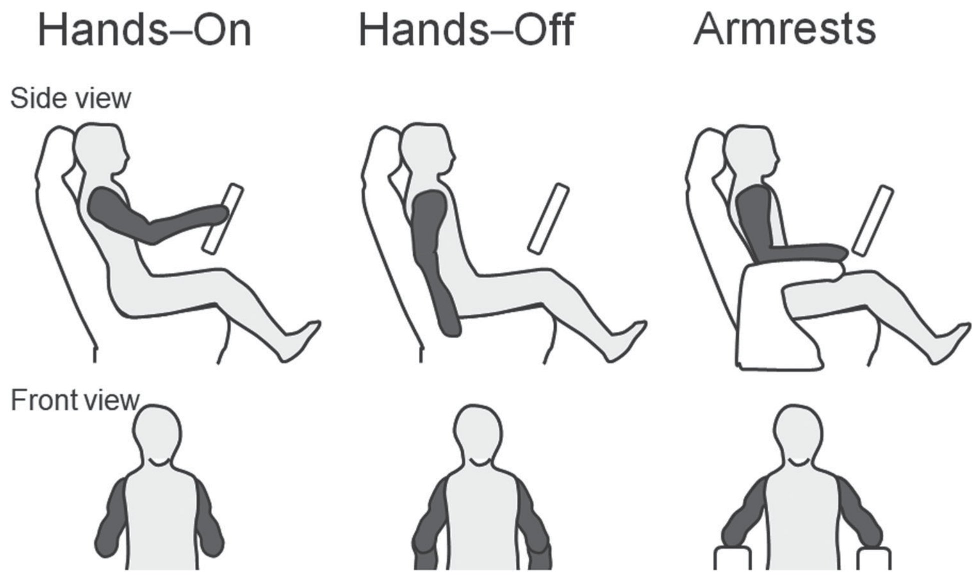

Figure 2. Side and front views of the instructed arm positions for Hands-On, Hands-Off and Armrests.

Note: Armrests = hands not on the steering wheel but arms on armrests; Hands-Off = hands not on the steering wheel; Hands-On = hands on the steering wheel.

informed consent for the study after receiving a detailed explanation of the purposes, potential benefits and risks associated with participation. All procedures used in this study were conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of Chukyo University (2019-057).

2.2. Experimental design

Participants chose the preferred steering wheel and seat positions in the car driving simulator (Costick Co., Ltd., Japan) with a controller (Logicool Co., Ltd., Japan) and performed the given tasks (Figure 1A). Participants were instructed to maintain the three different arm positions for 10 min each. The order of the three arm positions was randomized and rest intervals between the different arm position tasks were set at 10 min. During the tasks, multi-channel surface EMG was recorded from the upper trapezius muscle, and the shoulder position in the frontal plane was measured by video camera.

We used three arm positions: Hands-On, Hands-Off and Armrests. Instructions were to grip the sides of the steering wheel but not use the wheel to support the weight of their arms or upper body for Hands-On, not to grip anything and relax their arms at their sides for Hands-Off and to place their forearms on armrests for Armrests (Figure 2). The height of the armrests was adjusted for each participant's body size.

The shoulder angle in the frontal plane was calculated based on reflective markers on the acromion and lateral humeral epicondyle, which were captured by a video camera (GoPro Inc., USA) at 30 fps during the tasks. Horizontal and vertical coordinates of the markers were detected using a video analysis system (4 assist, Japan), and the line between these markers was identified as the upper arm. The interior angle between the upper arm and vertical line was calculated as the shoulder joint angle in the frontal plane (Figure 1A).

2.3. Multi-channel surface EMG

Multi-channel surface EMG signals were recorded from the upper trapezius muscle of the right shoulder with a semi-disposable adhesive grid of 64 electrodes (OT Bioelectronica, Italy). The grid comprises 13 rows and five columns of electrodes (1-mm diameter, 8-mm inter-electrode distance in both directions) with one missing electrode in the upper-left corner (Figure 1B). Prior to attaching the electrode grid, the skin was cleaned with alcohol. Conductive gels were inserted into the cavities of the grid electrode to ensure appropriate electrode contact with the skin. Within the electrode grid, we determined the reference point as the proximal fourth electrode on the longer side of the grid and the middle point on the shorter side of the grid. The reference point of the electrode grid was placed at 50% of the distance between the acromion and seventh cervical vertebra (C7) (Figure 1B). This position was defined based on the procedures in a previous study [7] with a minor change in this study in order to cover the participant's upper trapezius muscle with our electrode grid. A reference electrode was placed at around C7.

Monopolar surface EMG signals were amplified by a factor of 256, sampled at 2000 Hz and converted to digital form by a 16-bit analog-to-digital converter with a band-pass filter between 10 and 500 Hz (OT Bioelectronica, Italy). Recorded monopolar surface EMG signals were transferred to MathWorks (R2017b) and differentiated along the reference line (estimated muscle fiber directions). Differentiated EMG signals from 0–1, 4–5 and 9–10 min were chosen for further analysis. The average rectified value (ARV) and the median frequency (MDF) were calculated for each channel and mean values across the channels were used for analysis.

To characterize changes in the spatial surface EMG potential distribution during the given tasks and its differences among the three different arm positions, we also calculated the centroid of the ARV in the electrode grid along the medial–lateral axis (*x* coordinate of the center of gravity [CoG]) and the cranial–caudal axis (*y* coordinate of the CoG) [8,10,11] in order to detect changes in the spatial distribution pattern during tasks and differences in this pattern among the tasks. The location of the CoG was defined as the distance from the blank electrode position that is the most cranial and the lateral position of the electrode grid (Figure 1B).

Table 1. Shoulder joint angles in the frontal plane during the given tasks for the three different arm positions.

		Shoulder joint angle (°)		
Task	Time (min)	Median	Interquartile range	*p*
Hands-On	0–1	14.7	12.0–16.7	0.001*
	4–5	14.2	10.1–16.5	0.001*
	9–10	14.1	9.9–15.7	0.001*
Hands-Off	0–1	18.3	15.5–19.4	0.007*
	4–5	18.5	13.4–20.2	0.007*
	9–10	18.8	13.6–21.0	0.007*
Armrests	0–1	34.4	32.6–35.5	–
	4–5	34.3	31.3–34.5	–
	9–10	34.2	30.9–34.5	–

*$p < 0.0125$ vs Armrests.
Note: Armrests = hands not on the steering wheel but arms on armrests; Hands-Off = hands not on the steering wheel; Hands-On = hands on the steering wheel.

2.4. Statistics

All data are shown as the median and interquartile range. Non-parametric tests were used in this study since the sample size was limited ($n = 10$) and the distribution of data was partly non-Gaussian. The ARV, MDF, *x* and *y* coordinates of the CoG and shoulder angles were compared at 0–1, 4–5 and 9–10 min among the three different tasks and time periods for each task by the Friedman test, with Dunn's test as a post-hoc test.

The level of significance was set at 0.05 for the Friedmann test and modified by Bonferroni correction, i.e., $\alpha = 0.05$ / number of compared pairs, for the post-hoc test. Statistical analyses were performed using SPSS Version is 21.0.

3. Results

There were no significant changes in shoulder joint angles with time during the given tasks in any of the three arm positions ($p > 0.05$) (Table 1). Shoulder joint angles in Hands-On and Hands-Off were significantly smaller than in Armrests ($p = 0.001$ for Hands-On and $p = 0.007$ for Hands-Off).

Representative ARVs illustrated as color maps are shown in Figure 3. The ARVs in Armrests were lower than in Hands-On and Hands-Off. Spatial distribution patterns of the ARVs tended to differ among the three arm positions.

The ARV and the MDF were not significantly changed over time in any of the three arm positions ($p > 0.05$) (Figure 4A and B). The ARV in Hands-On was significantly higher than in

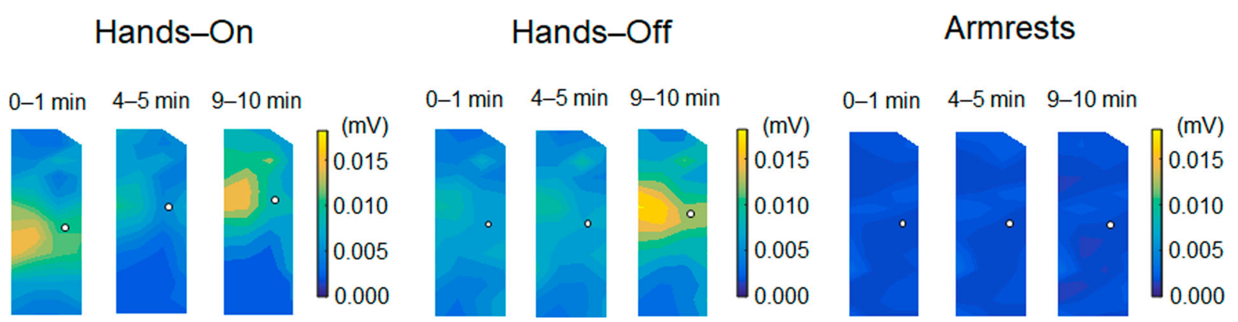

Figure 3. Representative surface electromyography amplitude within the electrode grid shown as color-scale maps and location of the center of gravity of the surface electromyography amplitude (CoG) (white dots) during the given tasks for the three different arm positions.

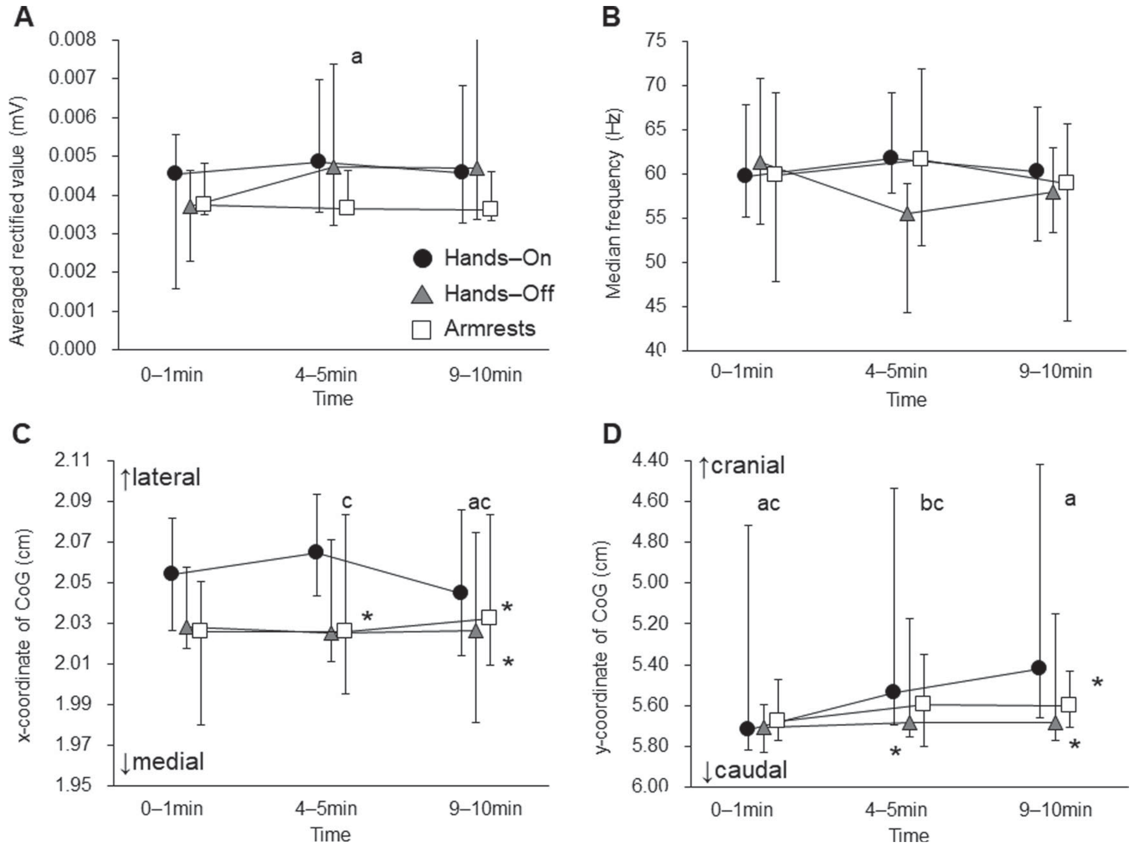

Figure 4. Averaged rectified value (A), median frequency (B), *x* coordinate of the center of surface electromyography amplitude (CoG) (C) and *y* coordinate of the CoG (D) during the given tasks for the three different arm positions. *, a, b and c indicate a significant difference from 0–1 min ($p < 0.025$), significant difference between Hands-On and Armrests ($p < 0.0125$), significant difference between Hands-Off and Armrests ($p < 0.0125$) and significant difference between Hands-On and Hands-Off ($p < 0.0125$), respectively.

Note: Armrests = hands not on the steering wheel but arms on armrests; Hands-Off = hands not on the steering wheel; Hands-On = hands on the steering wheel.

Armrests at 4–5 min ($p = 0.004$) (Figure 4A). The CoG was significantly changed along the medial–lateral axis (*x* coordinate) and the cranial–caudal axis (*y* coordinate) with time in Hands-Off and Armrests ($p < 0.05$), but not in Hands-On ($p > 0.05$) (Figure 4C and D). The CoG in Hands-On was located in a significantly more lateral region when compared with Hands-Off ($p = 0.004$ at 4–5 min and $p = 0.001$ at 9–10 min) and Armrests ($p = 0.004$ at 9–10 min) (Figure 4C). The CoG in Hands-On was located in a significantly more cranial region when compared with Hands-Off ($p = 0.001$ at 0–1 min and $p = 0.002$ at 4–5 min) (Figure 4D). The CoG in Hands-On was located in significantly more cranial and caudal regions when compared with Armrests, respectively ($p = 0.007$ at 0–1 min and $p = 0.002$ at 9–10 min) (Figure 4D). The CoG in Armrests was located in a significantly more cranial region when compared with Hands-Off ($p = 0.001$ at 4–5 min) (Figure 4D).

4. Discussion

The present study compared the spatial distribution of upper trapezius muscle activity during simulated car driving among three different arm positions that simulate different levels of automated car driving. We found that neuromuscular activation in Armrests was weaker than in Hands-On, the spatial distribution of muscle activity changed with time in Hands-Off and Armrests but not in Hands-On, and Hands-On showed a different spatial distribution of muscle activity compared with Hands-Off and Armrests. These findings do not support the hypothesis that neuromuscular activation is greater in Hands-Off than Hands-On and Armrests, but support another hypothesis that different spatial distributions of upper trapezius muscle activity are observed in Hands-On compared with Armrests and Hands-Off.

The present study did not detect significant changes in the MDF with time in any of the three arm positions ($p > 0.05$) (Figure 4B). Smaller shifts in frequency components of surface EMG during fatiguing contractions were reported in many previous studies as indicators of neuromuscular fatigue [8,12–14], and physiological mechanisms leading to a decline of MDF during sustained contraction have been clarified [5,15]. A decrease in the conduction velocity of muscle fiber action potentials, induced by an alteration in membrane properties of muscle fibers [15–17], is considered to mainly reflect a decline of MDF during sustained contraction. The lack of significant changes in MDF in the present study suggests that the given tasks did not induce detectable neuromuscular fatigue. While the previous studies applied loaded or resisted contractions [7–10], our motor tasks simply involved participants holding their arms in the instructed positions with the assistive devices of steering wheels and armrests. The lack of marked neuromuscular fatigue may be reasonable, and the given tasks in the present study during simulated driving may impose a relatively weaker physiological burden.

A significantly greater ARV in Hands-On when compared with that in Armrests was detected in the present study ($p < 0.0125$) (Figure 4A). On the other hand, we did not detect significant differences in the ARV between Hands-On and Hands-Off ($p > 0.0125$) (Figure 4A). Since variables associated with surface EMG amplitude such as the ARV mainly reflect the number of recruited motor units and their firing rate [16,18], we interpret them as indicators of neuromuscular activation in the muscle of interest. Therefore, it can be considered that neuromuscular activation during Hands-On is greater than that during Armrests, but not than that during Hands-Off, and that the use of armrests may contribute to reducing the physiological burden loaded on the neck muscles of drivers. However, surface EMG variables are also strongly influenced by joint angles when surface EMG is recorded since changes in joint positions alter the muscle geometry under the electrodes and the distance between the innervation zone and electrodes, and this leads to different EMG responses [19]. We thus need to interpret them while considering these non-physiological factors. Changes in shoulder joint angles among the three arm positions used in the present study mainly occurred in the sagittal and frontal planes. Considering the origin and insertion of the upper trapezius muscle fibers [20], the muscle geometry should be altered when the shoulder joint angle is changed in the frontal plane, rather than in the sagittal plane. In the present study, the shoulder joint angle in the frontal plane in Armrests was different from Hands-On and Hands-Off, as presented in Table 1. We should note that the significantly greater neuromuscular activation in Hands-On than in Armrests may involve non-physiological factors since the shoulder angle in the frontal plane is significantly different between these two arm positions ($p = 0.001$) (Table 1). This is also reflected as a significant difference in the spatial distribution of muscle activation between Hands-On and Armrests (Figure 4C and D). As there were no significant differences in the shoulder joint angle between Hands-On and Hands-Off (Table 1), non-physiological factors may not be critical when considering the ARV results on comparing Hands-On and Hands-Off (Figure 4A).

Previous studies showed a cranial shift of the CoG on surface EMG within the upper trapezius muscle during sustained contractions [7–10]. We also noted a cranial shift of the CoG on surface EMG within the upper trapezius muscle during Hands-Off and Armrests (Figure 4C), while no significant change in CoG with time was noted during Hands-On (Figure 4D). These results indicate that spatial distributions of neuromuscular activation were changed in Hands-Off and Armrests, but not in Hands-On. Since muscle fibers innervated by different motoneurons are distributed non-uniformly within a muscle [21,22], changes in the spatial distribution of surface EMG have been interpreted as recruitment/de-recruitment of motor units [23]. Farina et al. [8] reported a positive correlation between the magnitude of the CoG shift in the spatial distribution of surface EMG within the upper trapezius muscle and endurance time of sustained shoulder abduction. Madeleine et al. [10] showed experimental pain-induced changes in the spatial distribution of surface EMG within the upper trapezius muscle during sustained shoulder abduction. From these findings, changes in the spatial distribution of neuromuscular activation during sustained contraction are considered to comprise a physiological strategy to prolong the given task, minimize neuromuscular fatigue or avoid recruitments of fatigued or impaired muscle fibers/motor units [7,8,24]. We therefore considered that Hands-Off and Armrests lead to the recruitment/de-recruitment of various muscle fibers and/or motor units, and that neuromuscular fatigue may be suppressed when compared with Hands-On. This neuromuscular strategy during Hands-Off and Armrests may also contribute to reduce the physiological burden loaded on the neck muscles of drivers.

The CoG of the spatial distribution of surface EMG within the upper trapezius muscle in Hands-On at 4–5 and 9–10 min was located in more lateral and cranial regions than in Hands-Off and Armrests (Figure 4C and D). Recruitment of cranial regions of the upper trapezius muscle was noted when the performed force was increased and neuromuscular fatigue was marked [7–10]. The motor units recruited with an increase of exerted force or following fatigue should have higher recruitment thresholds and innervate muscle fibers contributing to higher force productions, such as fast-twitch fibers, and these types of motor units or muscle fibers could show weaker fatigue resistance than motor units with lower recruitment thresholds [25]. So, we considered that the cranial region is composed of fatigable motor units or muscle fibers, and during Hands-On we selectively recruit them and do not have reserve motor units to compensate for fatigued motor units. In fact, a histochemical study showed that muscle fibers near the clavicle, corresponding to the cranial regions of the electrode grids used in the present study, have a relatively higher percentage of fatigable muscle fibers when compared with descending regions, which correspond to caudal regions of the electrode grids used in the present study [26]. For medial and lateral directions, previous studies showed no marked shift in the spatial distribution of surface EMG during sustained contractions [7–10]. However, when experimentally induced pain was applied to the center of muscle, a shift of the CoG to a lateral region and the lack of cranial shift of the CoG were noted during sustained contraction [10,27]. Although it is difficult to directly compare our study to the study applying experimentally induced pain, we estimated that similar physiological conditions may occur during Hands-On in the present study with the condition of experimentally induced pain. For example, shoulder flexion to maintain the arms on the steering wheel may activate limited motor units or muscle fibers located in cranial regions, and this should lead to regional increases in intramuscular pressure. An increase in intramuscular pressure restricts blood flow in contracted muscle or parts of muscle [28–30], and this induces energy depletion, metabolite accumulation, a decreased membrane potential and intramuscular acidosis [30–34]. These chemical changes interfere with excitation–contraction coupling and result in a decrease in the force developed and increased neuromuscular fatigue [35,36]. In fact, marked variability of intramuscular pressure within a muscle was reported in the gastrocnemius muscle of the toad [37], and region-specific developments in neuromuscular fatigue were reported in the upper trapezius muscle [7–10], rectus femoris muscle [14] and medial gastrocnemius muscle [12] in humans. This discussion is speculative, but it can be considered that different physiological conditions within the upper trapezius muscle occur when drivers adopt the arm position for Hands-On as compared with Hands-Off and Armrests, and this would be related to regional activation within the upper trapezius muscle due to the arm position in Hands-On. However, we should note that this study was performed with a small sample size. Further studies with a larger sample size would be needed to apply our results to practical conditions such as actual car driving.

In conclusion, we investigated the spatial distribution of upper trapezius muscle activity during simulated car driving among three different arm positions. Our main findings were that neuromuscular activation in Armrests was weaker than in Hands-On, the spatial distribution of muscle activity changed with time in Hands-Off and Armrests, but not in Hands-On, and Hands-On showed a different spatial distribution of muscle activity compared with Hands-Off and Armrests. These results suggest that the use of armrests may help reduce the physiological burden loaded on the upper trapezius muscle of drivers, Hands-Off and Armrests recruit or rotate various muscle fibers/motor units within the upper trapezius muscle and Hands-On activates limited muscle fibers/motor units within the upper trapezius muscle. One of the major advantages of automated driving systems would be allowing the occupants to be 'hands-free', giving them the freedom to use their hands and arms during car driving. From comparisons between the arm positions when hands are on (Hands-On) and off (Hands-Off and Armrests) the steering wheel, we conclude that relief from steering, from SAE levels 0–1 to SAE levels 2–5, provides physiological advantages to minimize the neuromuscular burden or fatigue, and the use of armrests has a greater effect on reducing the neuromuscular burden.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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