Muscular and Kinematic Responses to Rear-End and Oblique Collisions in a Bumper Car-Based Whiplash Model

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I. INTRODUCTION

Automotive accidents and whiplash-associated disorders are frequently reported outcomes of low-speed rear-end collisions. However, the biomechanical mechanisms underlying these injuries remain debated and poorly understood, particularly in scenarios involving oblique impacts, rotated head postures, unbraced collisions, and sex-based variability [1–4]. Bumper cars have emerged as a cost-effective and low-risk platform for studying low-speed collisions with human participants [5–11]. Their design permits repeatable impacts without vehicle damage, while occupants remain in an upright seated posture that closely mimics automotive conditions, including a high potential for neck hyperextension due to the absence of a head restraint. Prior studies have validated the biomechanical relevance of bumper car impacts, demonstrating comparable delta-V and acceleration values to low-speed vehicle crashes [5][7][8]. Prior research has provided valuable insights into vehicle and occupant kinematics during rear-end and lateral impacts involving forward-facing, pre-positioned participants who were aware of the impending collision [10][12].

The present study addresses previously untested combinations of loading direction, head posture, and collision anticipation, with the added consideration of sex-based differences in cervical muscle responses. To achieve this, we integrated surface electromyography (EMG), 3D motion capture, and inertial sensors to evaluate cervical muscle activity and head/neck kinematics during bumper car collisions involving complex loading scenarios. Participants experienced rear-end, oblique, and head-turned impacts, as well as unanticipated free-driving collisions designed to simulate real-world uncertainty and multi-impact events. This multi-modal dataset provides a novel foundation to investigate how posture, impact direction, anticipation, and sex may influence muscular responses and kinematic behavior in low-speed impacts.

II. METHODS

This study investigated cervical muscle responses across four primary bumper car impact configurations using a large volunteer cohort. Thirty-four healthy adults (19 males, 15 females; aged 18–35) with no history of neck pain/injury were recruited. Each participant underwent three structured collision conditions and one unstructured free-driving session designed to simulate spontaneous, real-world impacts. All tests were conducted using the same set of bumper cars, which lacked headrests and featured minimal padding to replicate common real-world vulnerabilities.

Prior to participant testing, a series of mechanical calibration trials were performed to determine the coefficient of restitution and assess the maximum achievable vehicle speeds under standard operating conditions. These tests yielded peak velocities of 8.96, 10.51, 11.43, and 12.67 km/h for operating modes 1 through 4, respectively. Based on these results, operating modes 2 and 3 were selected for experimental trials due to their representative speeds and repeatability. The study protocol was reviewed and approved by the Ethics Committee of Comillas Pontifical University. All participants provided written informed consent prior to participation.

Figure 1a-b: (top) Bumper-car vehicle set-up with VICON markers attached to vehicle and on-board GoPro camera. (bottom) Example test of volunteer rotating head approximately 45° to the right for a rear-end impact.

Instrumentation

Surface EMG electrodes were placed bilaterally over the sternocleidomastoid (SCM), upper trapezius (UT), and semispinalis capitis (SSC) muscles. Maximal voluntary isometric contractions (MVCs) were recorded once per participant prior to the testing session, using a standardized series of resisted head and shoulder movements to normalize EMG amplitude across conditions. This procedure was designed to elicit maximal activation while minimizing variability due to fatigue or improper technique. EMG signals were sampled at 1000 Hz, bandpass

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filtered using a fourth-order Butterworth filter (20–450 Hz), and smoothed using a 250 ms moving root-mean-square window [13].

Cervical and cranial kinematics were recorded using eight infrared VICON cameras (1000 Hz), which tracked reflective markers placed on the head, neck, face, and limb joints. Head and vehicle accelerations were measured using six-degree-of-freedom inertial sensors (6DX, Diversified Technical Systems). A forward-facing on-board GoPro camera was used to verify impact timing and identify any anticipatory or bracing behavior exhibited by participants during each trial.

Experimental Testing

Each volunteer was subjected to four distinct collision conditions: 1) rear-end impact with the head in a neutral position, 2) rear-end impact with head rotated approximately 45% to the right, 3) oblique impact with a head in a neutral position, and 4) unstructured free-driving impacts to simulate unanticipated multi-directional collisions. Vehicle velocity was controlled by enforcing a fixed travel distance prior to impact, allowing the bumper car to reach a consistent speed specific to each operating mode. Adjustments were made as needed to account for large mass discrepancies between occupants of the target and bullet vehicles, ensuring comparable kinetic energy transfer across participants. Following testing, volunteers completed a follow-up symptom questionnaire at 24 hours, 72 hours, and one-month post-collision.

III. INITIAL FINDINGS

Preliminary data indicate that female participants exhibited higher normalized cervical muscle activation than males across all test conditions. In oblique impacts, right SSC activity in females reached 280.2 ± 62.6% MVC, versus 92.1 ± 12.5% in males, with a similar pattern in the left SSC (131.4 ± 16.7% vs. 70.7 ± 9.7%). In head-turned impacts, bilateral SSC activation in females exceeded 220% MVC (left: 220.5 ± 27.3%, right: 222.8 ± 40.7%), more than twice that of males (80.9 ± 10.6% and 69.0 ± 6.8%, respectively). Rear-end collisions elicited the highest responses, with females reaching 309.9 ± 39.5% MVC on the right and 155.4 ± 19.1% on the left, while male values remained below 80%. SCM and trapezius muscles showed smaller sex differences but followed the same trend. Overall, females demonstrated higher peak activation and greater variability, particularly in extension-related muscles like the SSC.

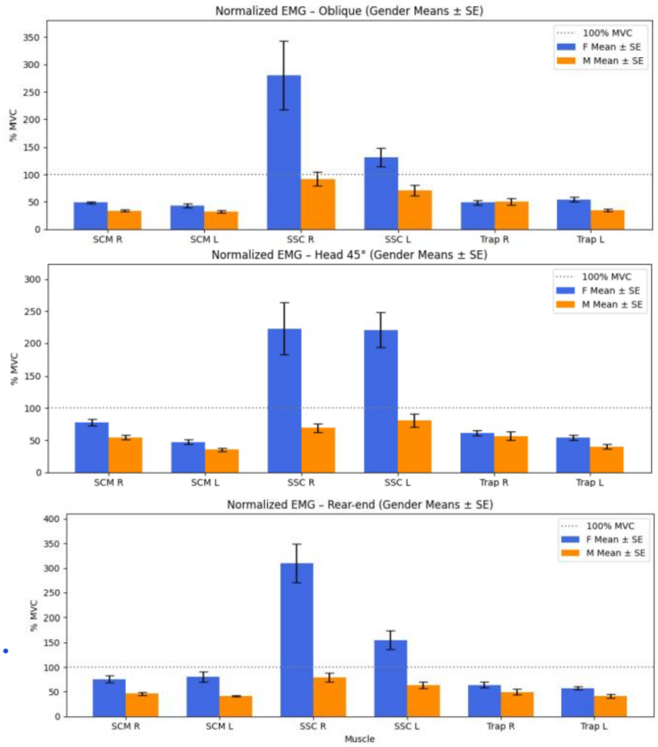

Figure 2a-c: Electromyographic (EMG) readings for 3 collision conditions: a) oblique (from the right rear), b) rear-end with the head turned to the right at 45 degrees, and c) rear-end with the head in a neutral position. EMG signals were normalized by the maximum voluntary contraction (MVC) calibration values. EMG electrodes were placed bilaterally on the sternocleidomastoid (SCM), semispinalis capitis (SSC), and upper trapezius (UT)

IV. DISCUSSION

These preliminary findings should be interpreted with caution, as the full dataset has not yet been controlled for potential confounding factors such as muscle mass, neck morphology, or variations in target vehicle acceleration. Notably, substantial variability was observed, particularly among female participants, with some SSC values exceeding 300% of MVC. Plausible explanations for values surpassing 100% MVC include motion artifacts, high-velocity dynamic contractions, eccentric loading during rapid extension–flexion movements, and the inherent difficulty of eliciting true maximal voluntary contractions in cervical muscles. The increased variability in female responses may also reflect differences in posture, muscle tone, or motor control.

Despite these limitations, the current data suggest sex-specific muscular responses to low-speed impacts, with females exhibiting both higher peak activation and greater variability across all test conditions. This heightened response—especially in the SSC muscles—may indicate differences in muscle recruitment or control strategies, particularly under non-inline loading. The elevated activation observed in females during oblique and rear-end impacts may have implications for understanding sex-related differences in whiplash injury risk and cervical kinematics. Continued analysis of the full dataset, including synchronized EMG, kinematic, and inertial data, will be essential to elucidate the underlying mechanisms and assess the broader clinical significance of these findings.

V. REFERENCES

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