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Experimental evaluation of child restraint systems structural integrity and biomechanical response following repeated frontal impacts

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Abstract-

Objectives

Post-crash replacement of child restraint systems (CRS) is widely recommended, yet experimental evidence quantifying potential degradation in protective performance after repeated crash exposures remains limited. This study aimed to (1) characterize recurrent structural damage patterns in CRS following dynamic testing to inform the development of a structured visual inspection (VI) protocol, and (2) experimentally evaluate whether repeated frontal impacts produce measurable changes in injury-related biomechanical response.

Methods

A two-phase exploratory study was conducted. Phase 1 included structured visual inspection of 218 CRS previously subjected to frontal offset deformable barrier (ODB) or mobile deformable barrier (MDB) dynamic tests within a consumer information program. Phase 2 consisted of controlled sled testing of three CRS configurations (rearward-facing ISOFIX with support leg; forward-facing ISOFIX with top tether; forward-facing seatbelt installation). For each model, one sample underwent repeated loading consisting of two UN Regulation No. 129 (UN R129) frontal pulses (ΔV = 50 km/h) followed by a higher-severity pulse derived from a Latin NCAP frontal impact test (ΔV = 64 km/h), while a second sample was tested once under the higher-severity condition. Injury metrics were recorded using a Q3 anthropomorphic test device.

Results

Among the 218 CRS inspected with all identified damage considered as grounds for rejection from potential continued use, the most frequent damage modes were rotation mechanism damage (12.4%), ISOFIX guide deformation (10.1%), and shell cracks (4.1%). No damage was observed in harness webbing, buckles, or belt-routing components. All CRS tested under the UN R129 pulse remained below the evaluated biomechanical injury criteria thresholds. Under the higher-severity pulse, differences between repeated and single samples remained below 7.4% for head resultant acceleration (3 ms clip) and below 11.5% for upper neck compression across configurations. No consistent trend of increasing injury metrics following repeated loading was observed, and visual inspection after repeated impacts revealed no crack propagation, structural fracture, or functional impairment. Qualitative high-speed video review also showed comparable head excursion patterns between similar test conditions,

without evidence of altered head kinematics following repeated loading.

Conclusions
Within the tested configurations and severity range, repeated frontal impacts were not associated with consistent increases in injury-related biomechanical metrics as measured with the Q3 dummy. Qualitative video assessment also did not indicate increased head excursion or abnormal dummy kinematics following repeated loading. These exploratory findings provide preliminary experimental evidence supporting further research on structured post-impact CRS inspection criteria and evidence-based discussion of CRS replacement practices. The results should not be interpreted as supporting unrestricted reuse of CRS after real-world crashes.

Index Terms- Child restraint systems; crash testing; child occupant protection; post-crash inspection; injury biomechanics; road safety

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