A Potential Whiplash Mechanism for Cerebral Concussion

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I. INTRODUCTION

The clinical presentations of concussion and whiplash injury have considerable overlap [1], although the mechanisms for these two injuries are different. Concussion is generally attributed to a relatively short-duration, high-acceleration impact to the head, whereas whiplash injury is generally attributed to inertial loading of neck tissues by the head mass—often in concert with a relatively long-duration, low-acceleration head impact with the head restraint. Despite these differences, the head's angular velocity change during some rear-end impacts [2] is similar to that observed in some reconstructed concussive head impacts [3]. This similarity raises the possibility of concussion during rear-end impacts typically associated with whiplash injuries. Here we sought to compare the brain tissue deformation that develops during football-related head impacts and rear-end crashes to better understand the relative potential for concussion during these two exposures.

II. METHODS

Linear and angular head kinematics were taken from two previously published experiments of rear-end crashes [2] and football helmet impacts [4]. For the rear-end crashes, 19 different vehicles (13 cars, three SUVs, three pickups) were towed into a rigid barrier at speeds from 6-12 km/h. A 50th percentile male BioRID II dummy was in the driver seat with a snug lap/shoulder seatbelt (Figure 1a top). For vehicles that underwent multiple tests (n=5 vehicles), the adjustable head restraints were varied between the full-up and full-down positions. A total of 35 crash tests were performed (24 at 8 km/h, six at 6 km/h, four at 10 km/h, and one at 12 km/h). Head linear accelerations in the sagittal plane and angular velocity about the mediolateral axis were measured, and horizontal linear velocity and angular acceleration were then calculated from these measurements.

Football helmet impacts were performed using a horizontal linear impactor (m=14 kg) that struck a modified Hybrid III head and neck fitted to a sliding table (m=23.5 kg). A large Riddell Revolution Speed helmet (m=2.1 kg) was fitted to the headform and secured snugly with a chinstrap. Six degree-of-freedom head kinematics were measured with a 3-2-2-2 array of linear accelerometers, and velocities were calculated by integrating the accelerations. Four impact tests were used for this analysis: two impact speeds (5.5 and 9.3 m/s) in two impact locations (low rear: head flexed 9.7°; high rear: head extended 15.1°; Figure 1a middle and bottom).

The Simulated Injury Monitor (SIMon v4.0, [5]) finite element model of the brain was used to predict brain tissue strain from the time-varying head kinematic data of each rear-end crash and football helmet impact (Figure 1b). The maximum principal strain (MPS) within each element of the model over the test duration was extracted and then the average and 90th percentile MPS over the whole brain was calculated for each test. The relationships between strain and peak kinematics were assessed using linear regression analyses.

III. INITIAL FINDINGS

The vehicles in the crash tests experienced speed changes between 9.3 and 17.6 km/h. The dummy's head struck the head restraint in all but one vehicle (a pickup), wherein it struck the rear window (see grey points in Figure 1c). Head impact durations varied from 45-79 ms (63 ± 9 ms) for the 34 head restraint impacts, 21 ms for the rear window impact, and 13-17 ms for the four low and high rear football helmet impacts. The average MPS was 6.9 ± 2.1% (4.3-14.0%) in the crash tests, 8.2% and 10.6% in the 5.5 m/s helmet impacts, and 14.6% and 16.1% in the 9.3 m/s helmet impacts. The 90th percentile MPS was 10.7 ± 3.2% (6.7-22.0%) in the crash tests, 12.9% and 13.7% in the 5.5 m/s helmet impacts, and 23.4% and 25.7% in the 9.3 m/s helmet impacts.

The linear regressions of the average and 90th percentile brain strains behaved similarly. The regressions

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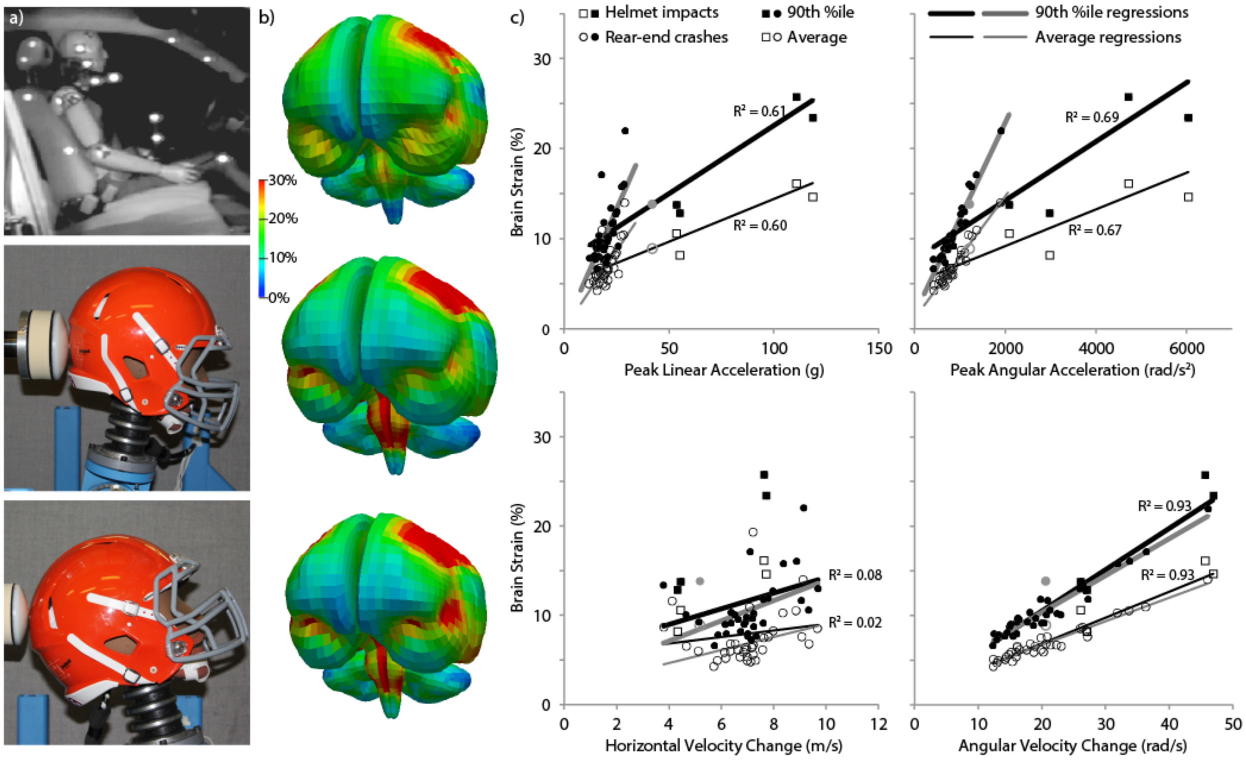

Figure 1. a) Three photographs showing the rear-end crash test setup, and the low rear and high rear helmet impact locations; b) surface MPS maps corresponding to the rear-end crash with the highest brain strains (ΔV=15 km/h, head restraint full-down) and the 9.3 m/s low-rear and high-rear helmet impacts; and c) plots showing how average (open markers) and 90th percentile (closed markers) maximum principal strain vary with peak linear acceleration (top left), peak angular acceleration (top right), horizontal velocity change (bottom left) and angular velocity change (bottom right). The grey lines show regressions against the rear-end crash tests only; the black lines show regressions against the combined crash and helmet data. The coefficients of determination are for the combined data.

against peak linear and angular accelerations were moderately strong (R^2 = 0.60 to 0.69), but the regressions against only the crash data (grey lines, Figure 1c) did not align with the regressions against the combined data (black lines, Figure 1c). The regressions against horizontal velocity change were nominally similar for the crash-only and combined data, but weak (R^2 = 0.02 to 0.08). In contrast, the regressions against angular velocity change for the crash-only and combined data were both strong (R^2 = 0.93) and had similar slopes.

IV. DISCUSSION

One rear-end crash generated average and 90th percentile maximum principal strains in the brain that were similar to those generated in a 9.3 m/s helmet impact (Figure 1b and c), which itself yielded larger linear and angular velocity changes than the two concussive rear impacts amongst the 25 previously reconstructed football concussions [3]. This rear-end crash involved the dummy's head wrapping onto the top of a full-down head restraint during a 15 km/h speed change and generated a head angular velocity change of 46.1 rad/s. Our average and 90th percentile maximum principal strains correlated best with head angular velocity change, even though the durations of the head-to-head-restraint impacts were about four times longer than typical football helmet impacts. This finding supports prior studies showing a correlation between brain strain and head angular velocity change [5-6], and extends this correlation to longer duration rear head impacts. These findings are preliminary and must be interpreted cautiously within the limitations of the experiments and the computational model. Nevertheless, our results indicate that brain strain amplitudes similar to those predicted for the reconstructed football concussions can occur under some specific conditions in rear-end impacts.

V. REFERENCES

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