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# The Ability of American Football Helmets to Manage Linear Acceleration With Repeated High-Energy Impacts

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***Context:*** Football players can receive up to 1400 head impacts per season, averaging 6.3 impacts per practice and 14.3 impacts per game. A decrease in the capacity of a helmet to manage linear acceleration with multiple impacts could increase the risk of traumatic brain injury.

***Objective:*** To investigate the ability of football helmets to manage linear acceleration with multiple high-energy impacts.

***Design:*** Descriptive laboratory study.

***Setting:*** Laboratory.

***Main Outcome Measure(s):*** We collected linear-acceleration data for 100 impacts at 6 locations on 4 helmets of different models currently used in football. Impacts 11 to 20 were compared with impacts 91 to 100 for each of the 6 locations.

***Results:*** Linear acceleration was greater after multiple impacts (91–100) than after the first few impacts (11–20) for the front, front-boss, rear, and top locations. However, these differences are not clinically relevant as they do not affect the risk for head injury.

***Conclusions:*** American football helmet performance deteriorated with multiple impacts, but this is unlikely to be a factor in head-injury causation during a game or over a season.

***Key Words:*** head injuries, material fatigue, education

**Key Point**

- Linear acceleration was greater after impacts 91–100 than after impacts 11–20 for the front, front-boss, rear, and top helmet locations. However, these differences in linear acceleration do not affect the risk for head injury.

Repeated head impacts are a common part of football, and their consequences can be severe if not properly managed. On average, football players receive 6.3 head impacts per practice and as many as 14.3 head impacts per game.[1] The number of head impacts over the course of a season can reach 1400.[1] Although the vast majority of impacts are low energy,[2,3] 1 in every 70 impacts incurred by football players is high energy.[4] Ideally, football helmets should be made of material capable of attenuating the energy of an impact or multiple impacts without being permanently deformed or fracturing. Repeated applications of stresses or strains on a material can lead to a change in the material's energy absorption, a phenomenon known as *material fatigue*.[5] Football helmets are subject to standards regarding their capacity to absorb energy, which are assessed in terms of the ability to manage linear acceleration, a known predictor of head injuries such as skull fractures and traumatic brain injuries.[6,7] Considering the number of head impacts a football player experiences in a season, it is not unreasonable to think that the materials used in the helmet might exhibit a decreased ability to manage linear acceleration, which would increase the risk of head injuries. The current standard requires 3 to 5 impacts per location.[8] Hence, it does not represent the many impacts a football helmet sustains over a season and, consequently, does not reflect the ability of the helmet to maintain its protective

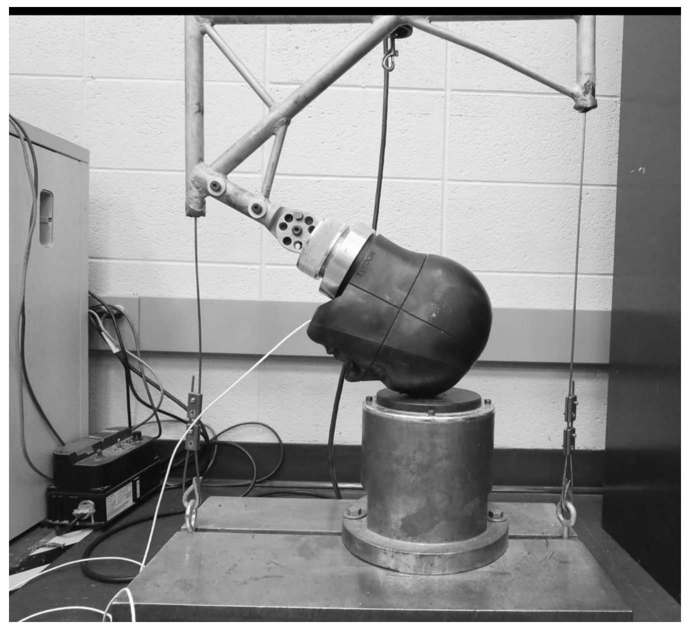

**Figure 1. National Operating Committee on Standards for Athletic Equipment twin-wire–guided drop rig with medium headform (Overland Park, KS).**

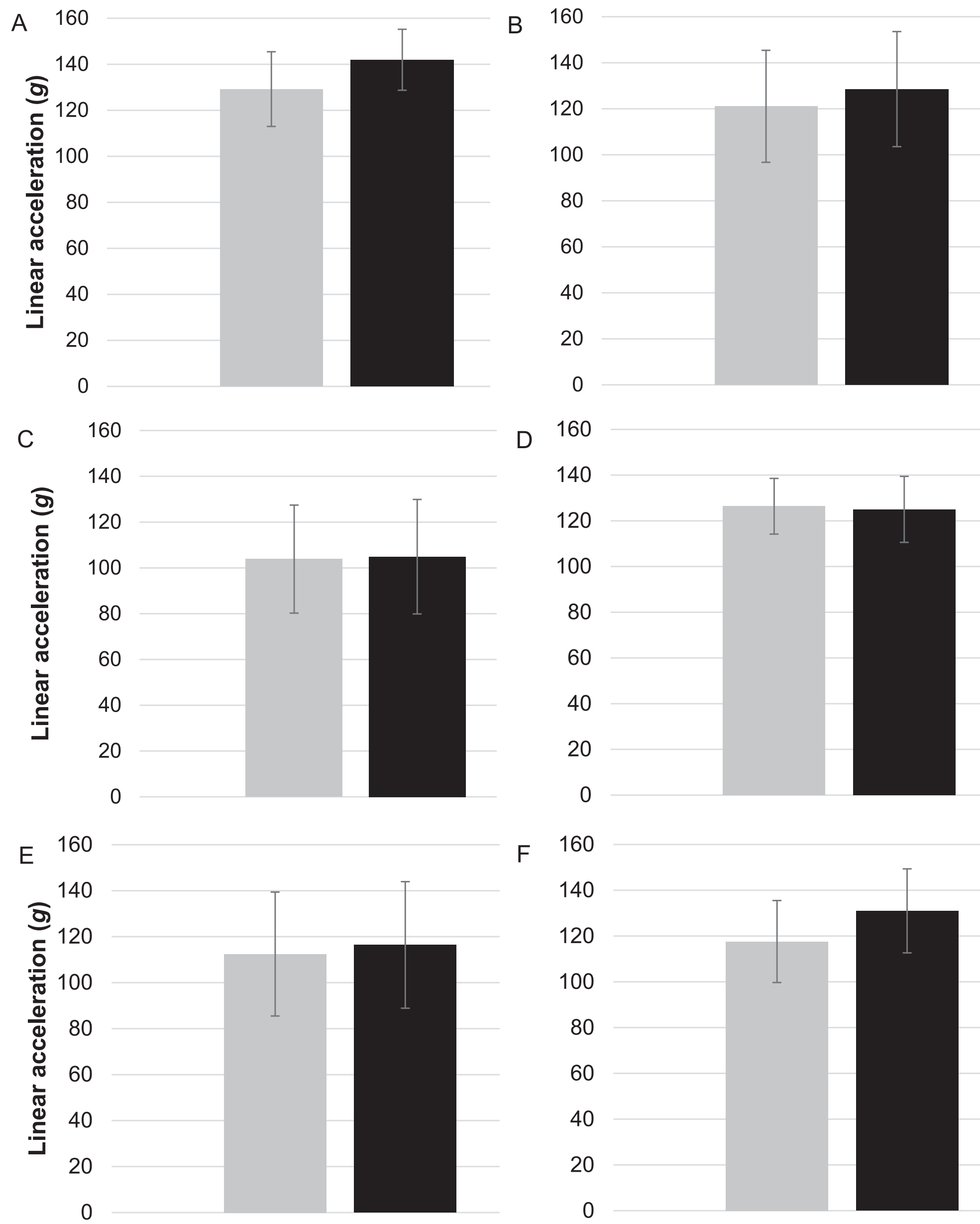


**Figure 2. Linear acceleration (mean ± SD) for impacts 11 to 20 (gray bar) and 91 to 100 (black bar) for the 6 National Operating Committee on Standards for Athletic Equipment impact locations.[8] A, Front. B, Front boss. C, Side. D, Rear boss. E, Rear. F, Top.**

capability. Therefore, the goal of our study was to see if football helmets are still protective against severe brain injuries after multiple impacts.

## METHODS

### Equipment

We used the National Operating Committee on Standards for Athletic Equipment ([NOCSAE] Overland Park, KS) certified twin-wire drop rig, NOCSAE-certified Hodgson WSU headform, and KME computer (model 200; KME Systems, Lake Forest, CA).[8] The NOCSAE drop rig consisted of 2 wires affixed to a steel anvil at the base and to a plate at the top. The length of the wires allowed for a free-fall drop of approximately 8 ft (2.4 m). A drop carriage was attached to both wires using Teflon bushings (The Chemours Company, Wilmington, DE) to reduce the effect of frictional drag upon release of the headform and carriage system. Attached to the top plate was an electric winch that allowed the carriage to move to the appropriate drop height. A mechanical release lever attached to the wire leading to the electric winch managed the release of the headform and carriage. The impact surface was a calibrated 0.5-in (1.27-cm)–thick, 6-in (15.24-cm)–diameter mono-elastomer programmer, the standard impact surface for NOCSAE football-helmet testing.[8]

We used a medium NOCSAE headform (Figure 1) attached to the drop carriage by a mechanical coupler that allowed the headform to be positioned in accordance with NOCSAE standard impact locations.[8] We calibrated the headform according to NOCSAE document ND001-04m05[8] and instrumented it with 3 single-axis accelerometers (model 354M37; PCB Piezotronics, Depew, NY) that were sampled at 20 kHz. The KME computer collected the

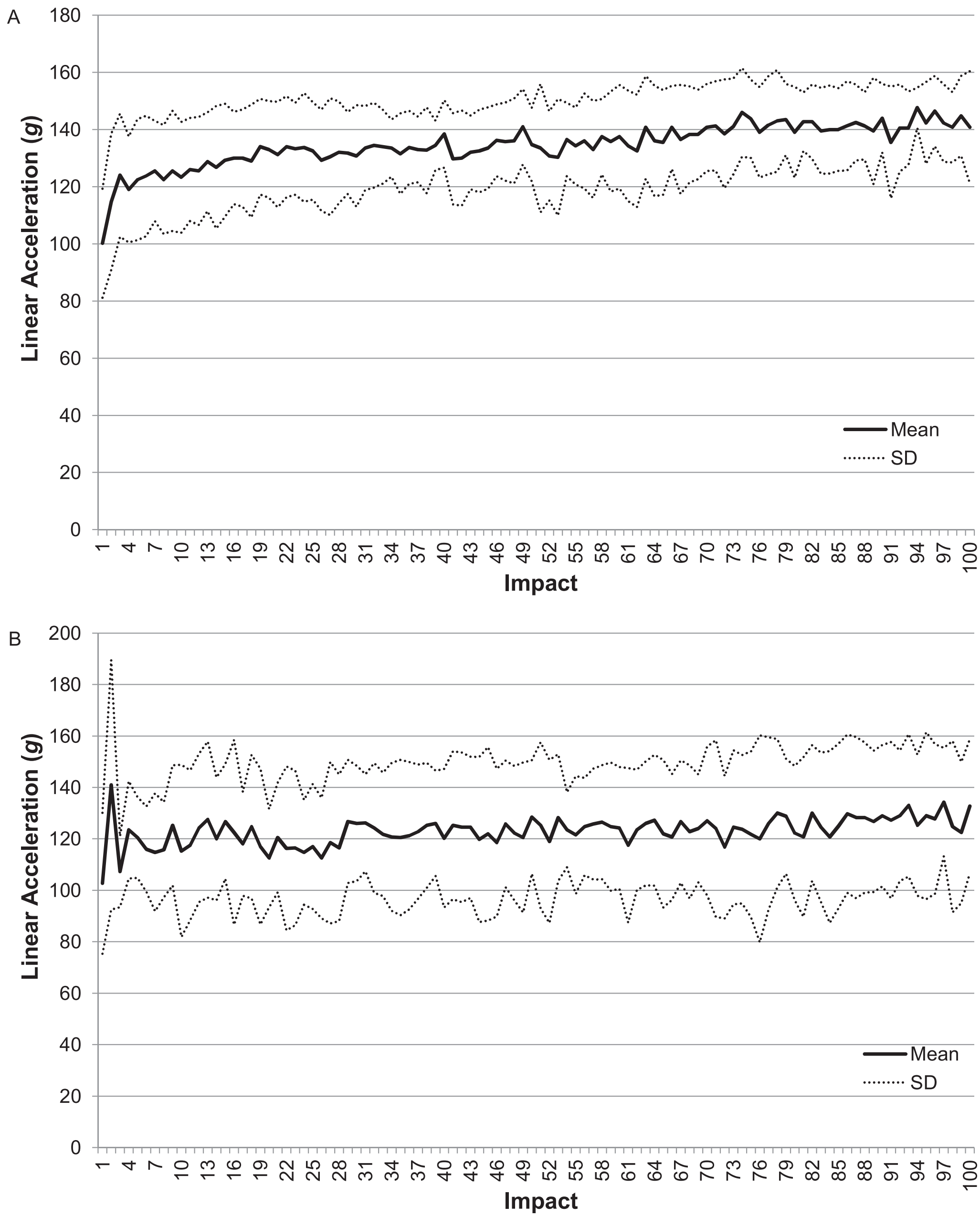


**Figure 3. Linear-acceleration responses for the helmets for impacts to the A, Front, and B, Front boss.**

signals, which were filtered using a J211a JUN 80-channel class 1000 NOCSAE filter according to SAE recommended practice with the cutoff at 1000 Hz.[8]

Four different new and unimpacted NOCSAE-certified helmet models were used in this research. They contained either vinyl nitrile multi-impact foam liners or thermoplastic polyurethane; the characteristics of the helmets are shown in the Table.

**Table. Helmet Characteristics**

| Helmet | Liner Materials | Mass (kg) | Liner Thickness (cm) |
|---|---|---|---|
| A | Thermoplastic polyurethane | 1.844 | 3 |
| B | Vinyl nitrile | 1.832 | 3 |
| C | Vinyl nitrile | 1.844 | 2.3 |
| D | Thermoplastic polyurethane | 1.991 | 2.3 |

## Procedures

According to the NOCSAE standard drop-test method, we conducted a pretest before the helmet impacts and a posttest system check. We positioned the helmet on the NOCSAE headform according to the manufacturer's recommendations and impacted each site 100 times per the NOCSAE standard.[8] The impact drop height was 60 in (152.4 cm), which is the most severe impact used in current NOCSAE helmet drop testing. Each helmet was fit to the headform in accordance with the standard NOCSAE method: the ear holes of the helmet were concentric with the headform ear-index holes, and the lower rim of the helmet was appropriately positioned according to the manufacturer's instructions.[8] We then firmly attached each helmet to the headform by means of a chin cup and tightened the chin strap so the helmet would not come loose

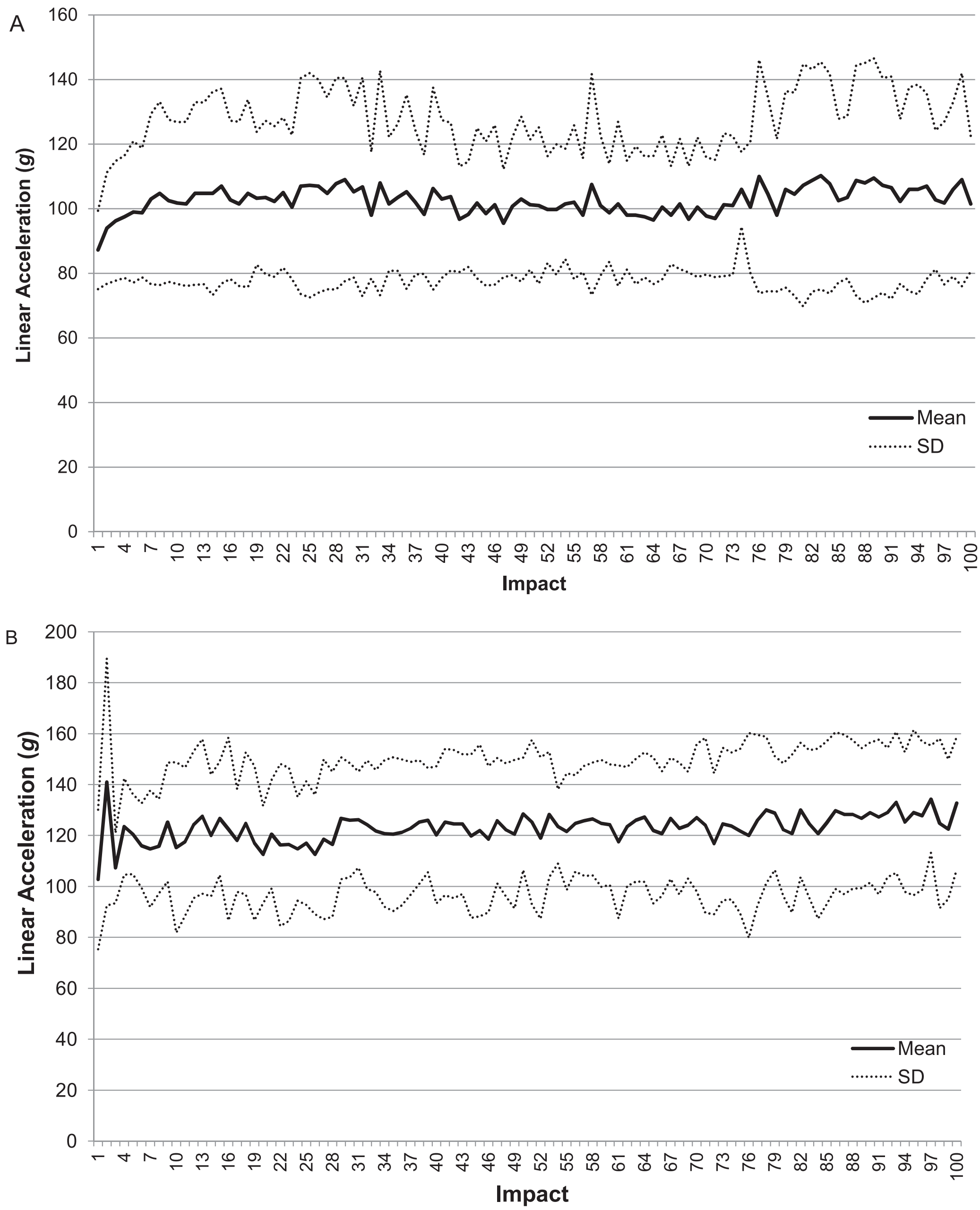


**Figure 4. Linear-acceleration responses for the helmets for impacts to the A, Side, and B, Rear boss.**

during testing. We monitored the chin-strap tightness and the helmet positioning and fit throughout the 100 impacts to maintain NOCSAE standards and the manufacturer's specification and readjusted if needed. Time between impacts was 75 ± 15 seconds, and we conducted the impacts at ambient temperature (22°C ± 2°C).

### Statistical Analysis

We used SPSS statistical software (version 19.0; IBM Corporation, Armonk, NY) to perform a paired-samples $t$ test with $\alpha = .05$ to determine if the mean of the last 10 impacts (impacts 91–100) was greater than the mean of impacts 11–20. This analysis was conducted for each impact site based on the results of the impact protocol in peak resultant linear acceleration for all helmet models combined. We excluded data from the first 10 impacts to the helmets to prevent bias from the conditioning of the helmet materials.[9]

## RESULTS

The results of the pretest and the posttest system check were within the allowable 7% as described by the NOCSAE drop-test standard. The mean linear accelerations for impacts 11–20 and 91–100 at the front, front-boss, side, rear-boss, rear, and top locations are illustrated in Figure 2. Linear accelerations at the front ($P = .001$), front-boss ($P = .001$), rear ($P = .027$), and top locations ($P = .001$) were greater for impacts 91–100 than for impacts 11–20. There was no difference at the side ($P = .66$) and rear-boss locations ($P = .578$). The linear-acceleration results for the impacts to the helmets at each site are found in Figures 3 through 5.

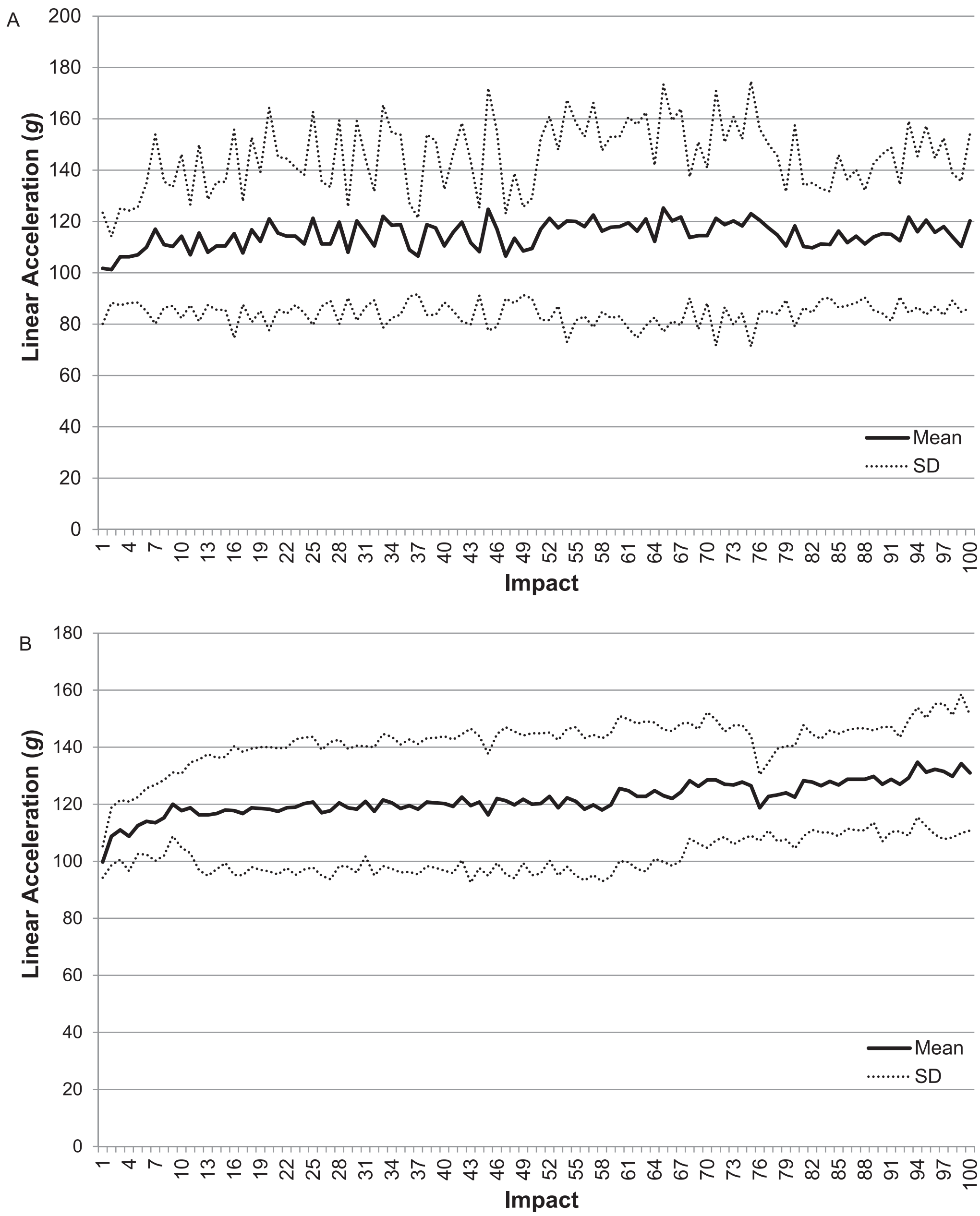


**Figure 5. Linear-acceleration responses for the helmets for impacts to the A, Rear, and B, Top.**

## DISCUSSION

Head impacts are common in football players and can lead to serious injuries. Current American football helmet standards are evaluated by way of linear acceleration, which has been shown to be related to the risk of head injuries.[6,7] Football activity can result in up to 1400 head impacts over the course of a season; therefore, the possibility that football helmets may lose protective capabilities and increase the risk of head injury is an area of concern. Our findings showed differences in the linear-acceleration response in the first impacts to a helmet and after multiple impacts to specific locations (front, front boss, rear, and top). However, although these results reached statistical significance, the differences in linear acceleration were at most 14*g*, which is well below the value of 300*g* that has been suggested as representing a 50% to 60% likelihood of head injury in a distributed impact.[10,11] Considering that the method we used to evaluate the helmet performance reflects a severe loading scenario and that lower levels of impact are more common on the field, the results suggest that American football helmets maintain protection against head injury over the course of a season. In comparison with the literature,[12] the linear-acceleration values obtained in this study were also below the proposed threshold for subdural hematomas of 192*g* to 234*g*. This indicates that, despite the decreased management of peak linear acceleration, the helmets maintained their protective capacity against head injuries.[13,14] However, when the protective capacities of the helmets against concussion were considered based on linear acceleration, the values were all above the proposed 80% risk.[15] This suggests that, under the conditions tested in this study, football helmets are not designed to provide protection against concussive impacts. However, we intentionally used high-energy impacts, and the football helmets did provide protection against head injuries for multiple impacts.

In addition to the impact-absorbing results, a material-conditioning phase of the helmets was demonstrated (Figures 3 through 5), with an increase in linear-acceleration responses over the first 5–10 impacts, followed by a plateau. The increase in linear acceleration was site specific but was in the range of 10*g* to 20*g*, as represented by the mean of the impacted helmets. This increase is the likely result of the impact-absorbing material's being "broken in," ie, the material loses some stiffness to absorb the energy of the impact over the first 10 impacts but maintains a slightly reduced impact-absorbing capacity for the next 90 hits. However, the difference between this conditioning phase and the plateaued response (when the helmets produce similar results regardless of the number of impacts) was not enough to increase the risk of head injury as described in the literature.[13,14]

In this study, we impacted the helmets a total of 600 times at an energy that would reflect a very severe impact, such as falling to the ground from a standing height. In addition, the impacts in this research were produced every 75 seconds, as that is the time permitted for restitution of the impact-absorbing material in the American football helmet as defined by NOCSAE standard protocols. It is possible that allowing more time for the energy-absorbing material in the helmet to recover from the impact may result in linear accelerations that are closer to those for the first impacts all the way up to the 100th impact. However, to our knowledge, no researchers have examined the effect of time between impacts on helmets' protective capacity. In addition, it is unlikely that athletes are impacted at such a high energy so frequently during a game or a practice. As a result, our work may represent a more rigorous analysis of helmet performance at the NOCSAE standard test heights. Given these results, we can speculate that less frequent and lower-energy impacts are equally well managed by the helmet, but that analysis is beyond the scope of our study. Other aspects of helmet performance that we did not examine are short-term and long-term helmet conditioning. These factors may affect helmet-material performance and would be an interesting area for further study.

## CONCLUSIONS

American football helmets demonstrated a measureable decrease in the capacity to attenuate linear acceleration with 100 impacts. However, this decrement in American football helmet performance after multiple impacts is unlikely to be a factor in head-injury causation during a game or over a season.

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