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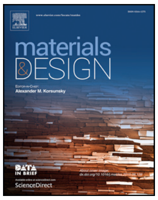

# Constrained topological optimization of a football helmet facemask based on brain response

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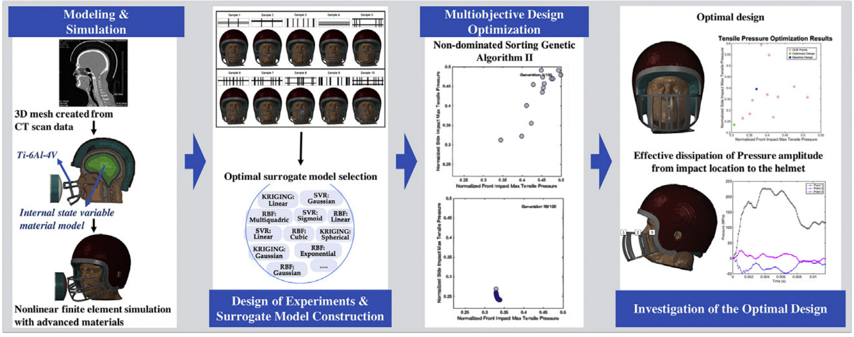
## HIGHLIGHTS

- Surrogate model-based design optimization was performed on a football helmet facemask to reduce brain injury metrics.
- Differences in brain response as high as 194% were observed by simply changing facemask topology.
- Peak head acceleration was not a good indicator of pressure or shear strain in the brain.
- Maximum tensile pressure and maximum shear strain in the brain were reduced 7.5% and 39.5%, respectively.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Surrogate model-based multi-objective design optimization was performed to reduce concussion risk during frontal football helmet impacts. In particular, a topological decomposition of the football helmet facemask was performed to formulate the design problem, and brain injury metrics were exploited as objective functions. A validated finite element model of a helmeted human head was used to recreate facemask impacts. Due to the prohibitive computational expense of the full scale simulations, a surrogate modeling approach was employed. An optimal surrogate model selection framework, called Concurrent Surrogate Model Selection, or COSMOS, was utilized to identify the surrogate models best suited to approximate each objective function. The resulting surrogate models were implemented in the Non-dominated Sorting Genetic Algorithm II (NSGA-II) optimization algorithm. Constraints were implemented to control the solid material fraction in the facemask design space, and binary variables were used to control the placement of the facemask bars. The optimized facemask designs reduced the maximum tensile pressure in the brain by 7.5% and the maximum shear strain by a remarkable 39.5%. This research represents a first-of-its-kind approach to multi-objective design optimization on a football helmet, and demonstrates the possibilities that are achievable in improving human safety by using such a simulation-based design optimization.

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## 1. Introduction

Even with recent advances in helmets, approximately 1.6–3.8 million sports related traumatic brain injuries (TBI's) occur each year [1]. Although no universally accepted definition of "concussion" exists, a consensus has arisen that a concussion is "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces" [2]. Recently, brain injuries suffered by National Football League (NFL) players have gained a great deal of attention. In 2005, a study found that NFL players exposed to multiple concussions suffered clinical depression at three times the rate of the rest of the population, and other studies showed that NFL players with concussion history are five times more likely to suffer cognitive impairment [3,4]. A recent National Collegiate Athletic Association (NCAA) study demonstrated that players with a history of previous concussions were more likely to have future concussive injuries than those with no history [5]. A different study showed that >5% of high school and collegiate players sustained a concussion in a season [6]. Similar stories surfaced frequently during the past several years, in which NFL players were diagnosed with Chronic Traumatic Encephalopathy (CTE), which is a buildup of tau protein in the brain, leading to memory loss, behavior and personality change, confusion, dementia, and depression that has sometimes led to suicide [7]. One of the most recent examples of the gravity of the TBI problem in professional football comes from a court filing involving the NFL. In 2014, lawyers for the NFL stated that approximately 28% of former players are expected to suffer from some type of neurological problem [8].

Despite all of the studies showing the dangers of concussions, we have only seen very incremental improvements of the football helmet design and fabrication during the past few decades and scarcely any changes to facemasks. When attempting to improve helmet protection, facemasks are typically overlooked, and the focus is usually directed to the foam liner. However, a recent study of 182 severe NFL impacts found that 29% involved the facemask. The study also found that the concussions occurred at the lowest peak head acceleration in facemask impacts at 78 ± 18 g's, compared to 107-117 g's for shell impacts [9,10]. Craig [11] demonstrated that removal of two facemask bars caused a reduction in head acceleration of approximately 30%, which clearly shows that helmets can be made safer by optimizing the facemask.

Very little research exists concerning computational design optimization of any type of helmet. Tinard et al. [12] applied manual modifications to a motorcycle helmet based on modal analysis in order to reduce von Mises stress in the brain. Shuaeib et al. [13] performed single objective optimization on a motorcycle helmet to determine foam density, foam thickness, and shell thickness in order to minimize the peak acceleration, but this did not include the human head. Our research is the first of its kind to perform multi-objective design optimization on a football helmet, and is also unique to most design optimization methods in that brain injury metrics (tensile pressure and shear strain) are used as objective functions.

## 2. Methods and materials

### 2.1. Simulation setup

A three-dimensional finite element mesh was created from Computed Tomography (CT) scan data using the ScanIP software environment (Simpleware Ltd., Exeter, UK). The scan data consisted of a human head and football helmet provided by Rush Sports Medical. The resulting human head model comprised eight different materials representing the helmet facemask, helmet shell, helmet liner, flesh, cortical and cancellous bone, cerebro-spinal fluid (CSF), and brain. Because facemask topology optimization was the goal of this study, the original facemask was not needed. However, a baseline simulation was performed using the original facemask to compare the brain response in the optimized facemask design.

In order to perform topology optimization, a new facemask was built in SolidWorks (Dassault Systèmes, Waltham, MA), with the entire design space modeled as solid material as shown in Fig. 1. The design space consisted of the front portion of the facemask that protects the player's face. This model was then meshed using Hypermesh (Altair Hyperworks, Troy, MI). The design space of the facemask was made up of 61,100 hexahedral elements. The meshed facemask with the complete helmeted head model contained 2,578,464 elements. The design space of the facemask was then separated into cubic sets of elements, forming a grid on the solid facemask region. Each set was approximately a 6 mm cube, which was chosen to match the thickness of state-of-the-art facemask bars. The cube sets were produced so that different candidate designs could be created by activating or deactivating the sets, rather than creating a new FE model for each design. The grid setup also limited the designs to combinations of vertical and horizontal bars for this initial study. The purpose of this assumption was twofold. First, the limitation simplifies the coding of the candidate design generation. This simplification was necessary because an automated design generation and meshing routine was not available with the software employed, which required the same mesh to be used. Second, limiting designs to vertical and horizontal bars decreased the size of the design space and reduced the number of training points required for surrogate modeling. Reducing the number of training points was especially important in this study, considering the very high computing cost of approximately 96 h for simulating each candidate design/training sample even when running on a distributed computing facility. Further explanation on the solid facemask design is provided in Section 2.5 below.

To model the effects of jaw loading during the impacts, a chinstrap was modeled using axial connector elements in Abaqus (Dassault Systèmes, Waltham, MA), along with a kinematic coupling on the chin to represent the chin cup. A surface was created on the chin and included in a kinematic coupling with a reference node to control the behavior. An elastic axial connector element connects the reference node of the chin surface to four points on the helmet shell to represent the chinstrap behavior. The axial load in the connector element corresponded to tensile behavior of current chinstraps, which produced primarily a linear elastic behavior during in-house testing.

The helmeted head model was impacted by a linear impactor matching a proposed test standard by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). The majority of all football organizations, including the NCAA and NFL, require football helmets and facemasks to be certified by NOCSAE before being used in a game. The proposed standard consists of an impactor head mounted on a pneumatic ram that impacts a stationary helmeted headform on a Hybrid III neck at different velocities. The linear impactor head weighs 13.3 kg and contains a convex nylon face backed by 35 mm of foam. The impactor foam and convex face were modeled in Abaqus, and the remaining mass (13.3 kg − (foam mass + convex face mass)) was applied to a rigid plate and added to the back of the impactor foam. Two impact

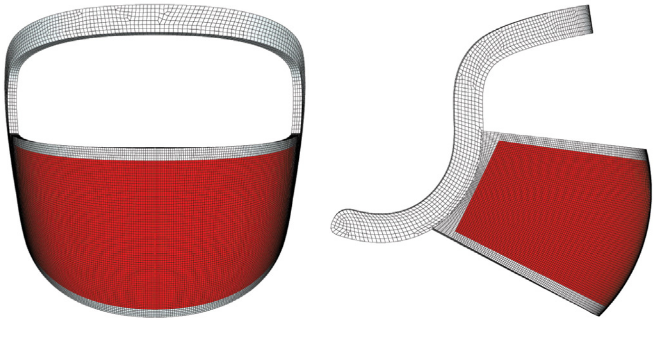

**Fig. 1.** Facemask mesh using three dimensional hexahedral elements with design space highlighted in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)