Subconcussive Blows in High School Football: Putting Young Brains at Risk

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ABSTRACT:

In 2009, Larry Leverenz, Eric Nauman, and Thomas Talavage at Purdue University formed the Purdue Neurotrauma Group (PNG), and set out to study concussions in high school football. They set up a study that combined helmet sensors with fMRI brain scans and cognitive testing, hoping to figure out what happens when a player gets a concussion on the field. Instead, they uncovered something shocking and wholly unexpected. Players' brains were significantly changing even in the absence of concussions, due to an accumulation of smaller impacts called subconcussive blows. Years of subsequent research have only confirmed their initial results—season after season, they found that about half of the players in their study that didn't sustain concussions exhibited significant brain changes over the course of a season. They don't yet know exactly how these brain changes relate to short or long-term cognitive damage, but when their findings are scaled across the landscape of high school football, the implications are enormous—brain changes may be occurring in some half a million teenaged athletes. However, even as public awareness of concussions and chronic traumatic encephalopathy (CTE) reaches new heights, subconcussive blows continue to fly under the radar. For the past seven years, the PNG has run their research on a shoestring budget, and now, at the end of their funding, they are running out of time and options. Meanwhile, in a few short months, 1.1 million high school football players will suit up for the start of football season.

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Football and violence have always been linked. In the early 1900s, not long after its inception, the sport was expanding to prep schools and universities across the country. The game was so dangerous, however, that players regularly died on the field from head and spine injuries.

In 1905, with the death toll climbing, President Theodore Roosevelt threatened to ban the game. In response, 13 colleges and universities met and changed the rules to reduce the violence of the sport—for example, they legalized the forward pass, which spread out the field, and made the game less focused on brutal scrums at the line of scrimmage, and more focused on skill, speed and strategy.

At a follow-up meeting, 62 higher-education institutions created the Intercollegiate Athletic Association of the United States, which later became the National Collegiate Athletic Association (NCAA), to monitor the situation. The changes did decrease the number of deaths, but head injuries were still a problem, which is why in 1933, the NCAA added a section to its Medical Handbook on concussions and the need to take them seriously.

This type of concern about head injuries has not always been shown in the decades since. Most notably, officials and executives in the National Football League have downplayed the gravity of concussions, insisting that the skull-rattling hits that are a feature of the sport didn't cause lasting cognitive issues. The NFL continued to insist this was the case even in the early 2000s when scientists began finding evidence of Chronic Traumatic Encephalopathy (CTE), a degenerative brain disease that causes early-onset dementia, in the brains of deceased football players. (It wasn't until the spring of 2016 that a top NFL official finally acknowledged the link between the repeated blows to the head players experienced on the field and long-term, irreversible brain damage.) Today, over a hundred former football players, some as young as 17, have been have been definitively diagnosed with CTE, which can only be confirmed during a brain autopsy, and many others suffer from suspected cases.

The NFL's stubborn denial did not, however, stem the public's concerns. Participation in high school and youth football has decreased, and many teams are now using more stringent concussion protocols to keep players safe. Young players have begun turning down college scholarships rather than risk injury, and there are even NFL stars retiring just a few years into their careers, citing concerns about concussions and long-term health.

It has been a long time coming, but football is finally taking concussions more seriously, in part because of a growing body of scientific research. Yet some of the most basic questions about concussions in football still have not been answered, which is what three researchers at Purdue were hoping to accomplish with their study seven years ago.

In 2009, Larry Leverenz, Eric Nauman and Thomas Talavage at Purdue University in West Lafayette, Indiana, decided to use brain scans, cognitive tests and helmet sensors to study concussions. Before the season started, they tested players on a local high school football team in order to get baseline readings on their subjects. Then they sat back and waited for what they assumed would be inevitable—a concussion.

One week passed, then two, and still nothing. After three weeks without a concussion they began getting restless. Rather than sit idly by, the researchers decided to bring in some players and re-test them to double-check their protocols. They were shocked by what they found.

"We were scared, actually," says Nauman, "because we didn't know what the hell was going on."

Eight years ago, Leverenz, Nauman and Talavage, who barely knew each other at the time, started the Purdue Neurotrauma Group (PNG). They have been meeting together weekly ever since. Their windowless conference room in the Materials and Electrical Engineering building at Purdue is fairly standard—a long, gray Formica table runs down the middle, a projector screen hangs over a worn couch patterned with faded geometric shapes, and a small white microwave is perched on a file cabinet. Over the years the room has also accumulated some of the researchers' own, unique clutter: posters of their research are on the walls, and large images from scans are propped up against computer monitors on one side of the room, white brains with patches of bright red, blue and orange. Two white football helmets sit on the conference table, alongside a stray mouth guard and a worn football sporting a shiny gold "P".

The researchers themselves are a balanced team. Talavage, a professor of computer and electrical engineering and biomedical engineering, is excitable and quick to laugh. As the brain scan specialist in the group, he is prone to lapsing into bursts of jargon when he is enthusiastically explaining the technical parts of the group's work, and he isn't afraid to criticize the NFL or the NCAA. Nauman, a professor of mechanical engineering, is a calmer presence with a clear and direct communication style. He excels at explaining complicated concepts in easily comprehensible language. Leverenz, the elder statesman of the group, is a professor of health and kinesiology and also the director of Athletic Training Education at Purdue. He is soft-spoken and quiet, yet quick to challenge Nauman and Talavage when he thinks their ideas need to be fleshed out. (When I spent several days with the trio, Leverenz referred to himself as a wet blanket more than once.) Their comfortable rhythm is the result of years of collaboration: while Nauman and Talavage are busy finishing each other's thoughts, Leverenz holds back, interjecting every now and then with an insight or question. During thousands of hours of meetings, the three have grappled with everything from what their results mean, to what they should to do next, to how they can keep their research moving forward on a tight budget.

The human brain is a staggeringly complex organ: its three pounds of tissue makes up a tiny percentage of our body mass, but uses 20% of our energy. It is responsible for virtually everything we do, from automatic processes like breathing and blinking to complex tasks like solving problems or storing memories.

Unsurprisingly, it takes a long time for this complex cognitive system to fully mature—well beyond the age we consider the beginning of adulthood. We might be able to vote and join the military at 18 and drink at 21, but our brain doesn't fully mature until around age 25. Until then, it is undergoing major chemical and physiological changes. (Of course, even though 25 is considered a benchmark for brain maturation, the brain continues to change throughout our lives—it is by far our most dynamic organ.)

The very complexity and dynamicity that make our brain capable of so many different activities also leave it vulnerable to injury. Fortunately, nature has provided us with some serious, built-in protection for our most precious possession. The first line of defense is our skull, a thick layer of bone that is extremely crush-resistant: it can tolerate a half ton of weight before it will begin to compress, which means an African elephant could stand on your skull without it collapsing—although you'd probably have a pretty nasty headache. Ounce for ounce, the human skull is stronger than steel or concrete—and, given our propensity for slamming it against these surfaces, that's a good thing.

Our brain, on the other hand, is so soft and gelatinous that it would collapse under their own weight if it weren't suspended in cerebrospinal fluid, a clear liquid that both supports the brain's weight and protects it from hitting the inside of our skull.

For added protection, the brain and spinal cord are swathed in three thin membranes called meninges. The innermost membrane, called the pia mater, is the thinnest and most delicate, and clings to every contour of the brain and spinal cord to create an impermeable coating akin to Saran Wrap. The middle membrane, the arachnoid mater, is slightly thicker, and named for its spider web-like appearance; it fits over the brain and spinal cord like a loose sac, holding the cerebrospinal fluid around the brain. The thick outer membrane, the dura mater, is attached to the inside of the skull—it's tough, durable and fibrous, and often gets compared to duct tape.

This multi-layered system to protect the brain evolved over millennia. It lets us go about our daily lives with our brain out of harm's way, leaving it free to do all of the intense work that our bodies constantly demand. It was not, however, designed with ski jumping, mountain biking, or brutal collision sports in mind. Take football: a single hit can cause a force of more than 100 gravities (Gs), which is on par with a car crashing into a wall at over 70 miles per hour. In football, the force of this punishing violence is brief—that's why we can survive it at all—but that doesn't mean our brain escapes unharmed.

Each concussion that results from such a hit is unique, a violet snowflake caused by countless variables converging in a specific combination: the force of the impact, the location of the blow, the strength of the players involved, previous injuries, and so on. In most instances, however, the general sequence of events is similar. A player sustains a blow to the head, and his brain, suspended inside his skull like the last pickle floating inside a jar, rocks against the skull or spins inside of it, much like if you picked up that pickle jar and shook it.

The brain does not sustain structural damage from the impact—nothing is broken or torn or bruised, and there is no bleeding, which is why the damage doesn't show up on an X-ray or a brain scan. Instead, the force of the impact sets off a cascade of chemical changes that disrupts how calcium flows in and out of the brain cells. To recover from this disruption, the brain cells require fuel, in the form of glucose, but the impact also reduces blood flow in the brain, which prevents glucose from traveling to where it is needed. Suddenly the brain is facing an energy crisis—the brain cells don't have the energy they need either to heal from the physical impact or to carry out all of the brain's processes—and external concussion symptoms emerge.

Football is held in high esteem in West Lafayette: the road signs for parking at Purdue football games are the same dark brown with white lettering typically reserved for national parks and historical monuments, and during the fall, some 40,000 people turn out to watch the Boilermakers tangle with their opponents in Ross-Ade stadium.

Like seemingly everyone else on campus, Leverenz, Nauman, and Talavage can't help but show off their Purdue pride. On a winter Thursday afternoon devoid of sporting events, Nauman and Talavage were both wearing black Nike shirts emblazoned with the school's logo, while Leverenz had on a wool Purdue letterman's jacket that elicited the vocal envy of his colleagues.

The researchers never considered studying football until 2008, when the state of Indiana earmarked a large pot of money to study head injuries, prompting the trio to form the PNG, design a study, and apply for a grant. "We went in with the exact same question everybody else had," says Talavage—namely, what factors determine whether or not a given impact will result in a concussion?

Initially they planned on using the Purdue football team as subjects. However, Danny Hope, Purdue's newly hired coach, said he did not want his team to be involved, concerned that it would be a distraction for his players that were already facing demanding schedules.

The researchers switched their focus to high school, enrolling 21 local players. Each was fitted with the Head Impact Telemetry (or HIT) System, six helmet sensors embedded in a horseshoe shaped piece of dense white foam that fits between the pads in the top of the helmet. The sensors recorded the number and magnitude of all the impacts that players experienced during practices and games, which the researchers combined with baseline cognitive tests and detailed brain scans. Their plan was simple: retest players that ended up with concussions, and use all of their data to figure out how the players' brains were changing.

Concussions affect young, immature brains differently than they affect mature adult brains. In general, children are more resilient when it comes to recovering from injuries—everything from their cuts and scrapes to broken bones heals faster than they do in fully grown adults. The reason kids can seem almost indestructible, bouncing back to their feet uninjured after even the nastiest falls, is because they are actively growing, so their bodies are already in construction mode when it comes to creating new tissues. Consequently, for a long time, many people assumed that children's brains healed more quickly and successfully than adult brains after a concussion.

However, we now know that because young brains cannot regulate blood flow as efficiently as adult brains, they are more vulnerable to injury, and oftentimes take longer to recover. Moreover, because children acquire many new skills as they mature, brain injuries can cause significant harm by disrupting this process. If that disruption interferes with learning a particular skill or hitting a certain developmental milestone, the damage can be permanent.

Concussions in children are also more difficult to diagnose than they are in adults—concussion diagnosis depends on how well a patient can describe his symptoms, and children are not as good as adults at identifying or communicating the details of their symptoms, nor are they always motivated to do so. High school football players, awash in adrenaline and caught up in the competitiveness of the game, may be especially disinclined to pull themselves off the field after a head injury and accurately disclose their symptoms.

The director of the Sports Concussion Clinic at Boston Children's Hospital, Michael O'Brien, has seen this time and time again with his patients. "They feel like they have an obligation to get back and help their teammates and do as best they can, especially if they're searching for scholarships and things like that."

Many football players also hesitate to seek medical attention after the game because they don't want to miss games, or they don't recognize the severity of their injury.

"Historically boys and men have been less forthcoming with their symptom reporting, which is a huge part of concussion management, says O'Brien. "And the fact is I only see the patients who come in and see me."

To call the beginning of the PNG's study rushed is a bit of an understatement—the researchers were notified about their grant just months before the start of football season, and realized that if they didn't do their baseline testing immediately, the season would be lost.

"One of my grad students and I actually threw the imaging protocol together on a Thursday night, and then we ran the first subjects Friday afternoon," says Talavage. "So we didn't have any idea if this was actually going to be reproducible"

The majority of the researchers' work is done on a General Electric MRI machine, an off-white plastic tube seven feet in diameter with such thick walls that the narrow hole through the center hardly looks wide enough to accommodate a child, never mind a bulky football player.

The machine houses a magnet six times stronger than the magnetic field of the earth which creates images by interacting with protons, positive atoms inside the hydrogen molecules in our cells. Its magnet is so powerful, in fact, that a huge warning sign posted on the door warns against entering the room with metal of any kind including pacemakers, scissors or keys. When I visited, a graduate student reminded me to leave my cell phone, credit cards and watch at the door if I want them to stay intact.

Just outside the MRI room is a control room where three monitors display a quick succession of line graphs and black and white brain images. The electric current that shuts on and off to create the magnetic field is shockingly loud. Outside the room it sounds like a mash-up of a dial-up internet connection, an old phone ringing, and the beeping of a car alarm. I can't even imagine what it's like for the player inside.

All of this is used to measure changes in blood flow through the brain, which can serve as a proxy for brain activity. That first season, the researchers had players perform a working memory task that required them to remember and match letters and patterns they saw through goggles during the scan. Prior to the scan, players also completed the imPACT, a standard computerized test of cognition and memory that many high schools use for concussion diagnosis.

The researchers assumed that combining data from helmet sensors and fMRIs with neurological and cognitive testing would allow them to better understand how the brain changes after a concussion.

Once they completed their initial round of tests, the PNG group waited for players to get concussions. After a few weeks of concussion-free football, they decided to double-check their protocols. To their shock, some of the players had imPACT results that were significantly different from their baselines. "We weren't expecting it," says Leverenz. "There was nothing wrong with these kids. They were showing absolutely no symptoms."

At first, they assumed it was a problem with the test. But when they retested the players, they got the same result. They then began analyzing the players' brain imaging data.

"[Some of the players] were showing very different imaging data than they had at the beginning of the season," Talavage says. Or, as Nauman puts it, "Pretty soon [we] realized that, holy crap, their brains are really different."

Maybe, the researchers thought, their scanner was broken. Or maybe they weren't administering the tests properly. One by one they ruled out every other plausible explanation before settling on the most frightening one of all: even in the absence of concussions, on the field hits were causing significant brain changes. Was it possible that an accumulation of small impacts—referred to as subconcussive blows—were just as bad as actual concussions?

When they were finally able to compare non-concussed athletes to concussed ones, they realized that not only were the brains of many of the non-concussed athletes changing, but some of them were actually changing more than the brains of the concussed players.

It seemed as if Leverenz, Nauman, and Talavage had stumbled onto something big and wholly unexpected. The researchers quickly changed course and reformulated their work in an attempt to answer a new question: can repetitive subconcussive blows cause permanent changes in teenagers' brains?

By January 2010, the researchers were done collecting data from the previous football season, and they were eager to dig deeper into subconcussive blows. Realizing that their results could be controversial, they focused on improving their protocols and gathering additional evidence to support their findings.

Over the next six seasons they incorporated more football teams, along with non-contact athlete controls who participated in sports like swimming or track, and refined their scanning schedule to better track brain changes over time. They also added a suite of new fMRI imaging tests that looked at additional aspects of brain function.

As the results poured in, season after season, they all pointed to the same conclusion—the brains of non-concussed football players were changing over the course of the season. The players were also consistently failing the imPACT. None of these changes were observed in the non-contact athletes.

Then, one of Nauman's graduate students figured out how to flatten the data from each player's helmet sensors like a two dimensional map of the earth, and plot all the hits, color-coded by magnitude, from the entire season. "All of a sudden it all ties together," Nauman says. "All the [players] that have the massive hit distributions are the ones that are testing positive for changes but not showing any symptoms."

In other words, despite their lack of symptoms, the non-concussed players that sustained a lot of hits appeared to have similar brain changes to those of the concussed players. A helmet image of an offensive lineman, whose brain changed dramatically during the season, drives the point home—it has an almost solid, mushroom shaped constellation of blue, green and yellow dots representing over a thousand subconcussive blows he sustained during the season, some 90-100 hits every week. He never had a concussion, but where his brain is concerned, the end result was the same as if he had.

The more data they collected, Talavage says, the more it "emphasized that what we saw that first season was extremely real." Initially, they'd had no reason to think non-concussed players would show signs of brain injury. "It's only if you are looking at how the brain is actually performing the task that you can actually observe that, wow—this is a really radical departure from what it should be."

Year in and year out, Leverenz, Nauman, and Talavage found that around half of the non-concussed players were showing significant brain changes by the end of the season. When that is scaled across the entire landscape of high school football in the United States, the implications are enormous. Of the 1.1 million high school football players, roughly 10%, or 110,000, are diagnosed with a concussion every season. (The actual number is likely even higher.) If the PNG's work proves to be correct, that would mean an additional half million students experience significant brain changes.

"You start asking what is the multiplier here [for high school players]," says Leverenz. "You know, I see this change in one season. I've now played ten seasons. What is that cumulative change?"

In the years since the Purdue team started its work, the field of subconcussive blows has grown. Other research groups are also pairing impact sensors with intensive brain scans. At the University of Rochester, a researcher named Jeffrey Bazarian at has been studying collegiate football players, and came to a similar conclusion about subconcussive blows around the same time as the PNG. At Wake Forest University, a team led by Joel Stitzel is studying middle school football players to see if there are brain changes in even younger players. (Stitzel's team also found brain changes in high school football players.)

Recent research also seems to suggest that repetitive head impacts may cause brain issues down the line. A study in the *Journal of Neurotrauma* found that former high school and college football players with greater exposure to repetitive head impacts had higher incidence of mental health issues such as depression, apathy and memory loss in later years. And research presented at the 2016 American Academy of Neurology determined that 40% of the retired NFL players they studied had brain changes extreme enough to be classified as brain trauma. These players also struggled with cognitive tasks like reasoning, problem solving and memory, and the amount of brain damage and cognitive dysfunction did not correlate with the number of concussions, which suggests subconcussive blows were to blame.

Still, not everyone is convinced by the Purdue group's evidence. Andrew Mayer, who uses brain imaging for his research on mild traumatic brain injury at the Mind Research Center in New Mexico, believes more work needs to be done before broad conclusions can be reached.

"Natural biology is extremely variable," he says, "So you have this tremendous amount of variability in terms of pre-disposing factors, and individual differences in brain physiology that each person brings to the table."

What's more, he points out, while imaging has made a lot of advances over the past 20 years, it is still an imprecise technique, which makes repeatability a problem. "I haven't seen any clear and convincing evidence, including my own, from an imaging modality, that we can document these things called subconcussive blows," he says.

For Mayer, this is not surprising: there isn't even an imaging test for concussions, and subconcussive blows have yet to be clearly defined. There are also numerous potential confounding variables. Perhaps subconcussive blows only become dangerous if a player has a history of concussions, or maybe brain changes that results from subconcussive blows have a different effect than brain changes that occur after concussions.

"Right now what's established is that we need to worry about repetitive head injury," Mayer says. "But that doesn't necessarily establish the subconcussive part."

Steven Broglio, who is the head of the NeuroSport Research Laboratory at the University of Michigan and is involved in a study on repetitive head impacts in collegiate athletes, has a slightly different take. Based on the current research, he is convinced that something is definitely changing in how the brains of these non-concussed players operate. However, he thinks additional work is needed to fully assess whether or not these brain changes are problematic, and it doesn't make sense to change the game until we know there is a problem.

"Just because something changes doesn't necessarily mean that it's bad," he says. "We need to understand what it actually means before we're going to limit the number of head contacts somebody has."
In Broglio's view, truly understanding the meaning of these results will require a multi-decade longitudinal study that follows players throughout their football careers and beyond.

"Up until that point, people are going to have to be patient," he says. "They're just gonna have to use their best judgement in making decisions about participation for themselves or for their child."

As he sees it, research on head injuries in football still has a long way to go. "We're in the infancy of concussion research as a whole," he says, "And now we've added another layer on top of it [with subconcussive blows].

So where does that leave the Purdue researchers?

"I now have a yellow flag up," says Leverenz. "What I want to know is should I put the red flag up. And that answer we don't have yet. But we're getting close."

But should we wait for a definitive red flag that may only come after decades of research before taking action? The PNG doesn't think so. Which raises the question: what might this mean for the future of football?

Sarah Fields, who studies the intersection between sports and American culture at the University of Colorado, Denver, points out that football has evolved continuously over the course of its history, yet has always managed to survive and maintain its popularity, despite initial resistance to changes.

"If you think about it, there's nothing natural about football. You don't go out in life and do that," she says. "People have learned to play the game in that particular way. They can learn to play another way."

This has been true even over the past few years, as the NFL has instituted changes to reduce the number of big hits, such as adjusting the kickoff spot, and penalizing helmet-to-helmet contact.

The PNG researchers believe that the most direct way of keeping players safe from subconcussive blows is by reducing exposure to repetitive head impacts, something they have observed firsthand. The team in their study with the fewest brain changes had so few players that their coach virtually eliminated tackling from practices to avoid injuries. "They had a big clock with an alarm going and every five minutes they moves from one drill to the next drill, and they'd be just running routes," says Talavage. Teams in their study with better tackling technique that focused on avoiding head contact also sustained fewer hard hits.

"I think there's a lot of good evidence in our data that says you can play these games safely, says Talavage. "You don't have to get rid of the sport, you can change it," Leverenz adds.

The popularity of football in the US means the sport likely isn't going anywhere anytime soon, but if even a small but significant percentage of the 1.1 million kids currently playing high school football switch to another sport, it could have a dramatic effect on every level of the game. As an NFL league official famously said to Bennet Omalu, the pathologist who initially discovered CTE, "If 10% of mothers in this country would begin to perceive football as a dangerous sport, that is the end of football."

In 2015, 24 year old NFL linebacker Chris Borland retired after a successful rookie season that set him up to earn millions with the San Francisco 49ers, ultimately deciding that the potential for long-term brain damage was too great. Other NFL players, including 24-year-old Adrian Coxson and 25-year-old Anthony Davis, have come to the same conclusion—in fact, 19 players age 30 or younger retired in 2015.

And it's not just happening at the professional level. In February 2016, John Castello, a high school football star from Pittsburgh, turned down football scholarships from a dozen colleges because he was worried about head injuries. And over the past five years, the number of high school football players has dropped 2.4%.

Because football requires many more players than others sports—high school teams generally carry 50-70 players—football programs are vulnerable if interest or participation in the sport drops off, which has already happened at some smaller high schools. Maplewood Richmond Heights High School in Missouri made it to the state championship game in 2010, but was forced to end their program in 2015 after waning interest left them with only 14 healthy players at the end of the previous season. In fall 2015, Camden Hills

Regional High School in Maine disbanded their team three games into the season after player injuries left them with low numbers.

The decline in interest at the youth level is even greater: there was a 9.5% drop in participation in Pop Warner—a youth football organization for 5-16 year olds— between 2010 and 2012. "It's not a huge number," says Fields, "But it's not an insignificant number." It doesn't help that Pop Warner recently settled a law suit with the family of a player who hanged himself at age 25. The player, whose brain showed severe signs of CTE, started playing Pop Warner football at 11, and his parents sued the organization for employing improperly trained coaches and trainers that did not remove their son from the game after he sustained multiple head injuries. This law suit was the first of its kind, but more are sure to follow.

This situation is not without precedent. Boxing in the United States was wildly popular from the 1920s to the 1980s—at one time, even high schools and colleges had teams, and matches were aired on basic cable most nights. However, during the 1980s, the medical community began to increasingly recognize the dangers of repeated blows to the head. Once doctor even published a series in the *Journal of the American Medical Association* titled "Boxing Should be Banned in Civilized Countries." As concerns about head trauma pervaded the sport, boxing became less popular. Professional boxing still exists today, though as a niche sport, and high school boxing is almost nonexistent.

"Part of the reason that boxing disappeared from high schools, quite frankly, is the high schools' insurance companies wouldn't pay for it anymore," says Fields. "They wouldn't cover it. The day may come when we see less high school football because the insurance companies are reluctant to cover it, or it's too expensive to pay for the coverage."

Six years ago, *Sports Illustrated* highlighted the PNG's work in a cover story on concussions, referring to subconcussive blows as "the hits that no one is noticing." That level of public recognition was nice, but still, Leverenz, Nauman, and Talavage have struggled to secure funding for their work.

Their roadblocks began even before their first paper on subconcussive blows: after being accepted by the *Journal of Neurotrauma,* publication was delayed for years. The group was never given a concrete reason for the holdup even after repeatedly following up with the editor.

The PNG has had a number of grant proposals rejected by the NIH. Oftentimes, the stated reasons, including concerns about substance abuse problems in high school football players, or that the PNG only has access to one MRI machine, seemed spurious. (They recently looked into filing a formal grievance against the NIH, though they eventually dropped the idea after Purdue balked).

As the group's frustrations mounted, they began to suspect that their work was being blocked by the NFL. "We've talked to enough people that we're pretty sure at least on two occasions the NFL has said, Yes, we're putting this money out, but don't give it to Purdue," says Nauman. "And we're pretty sure that a lot of our grant applications have been knocked down by the NFL."

Despite promising to respond to a list of questions, the NFL refused to comment on the Purdue group's suspicions, but its track record with funding and research on head injuries is less than stellar.

Recently, the Democratic members of the House Committee on Energy and Commerce released a 91-page report detailing the NFL's "longstanding pattern of attempting to influence the scientific understanding of the consequences of repeated head trauma." The report claims that its investigation "has shown that while the NFL had been publicly proclaiming its role as funder and accelerator of important research, it was privately attempting to influence that research."

The smoking gun? In 2012, the NFL gave the NIH a $30 million "unrestricted gift" to fund research on brain injuries, then later pressured the NIH to take back $16 million it had committed to Boston University researchers developing a CTE test for living patients. (The test would allow them to determine the percentage of living football players that suffer from CTE.) When the NIH wouldn't yield to the NFL's demands, the league backed out of the research, leaving taxpayers to pick up the tab.

That did not come to light until 2015, but even before that, in the 2013 book *League of Denial*, ESPN reporters and brothers Mark Fainaru-Wada and Steve Fainaru revealed the extent to which the NFL had sought to hide the effects of head injuries on its players.

At the time, even as the NFL was agreeing to pay a $765 million settlement to former players and their families over long-term cognitive issues, the league still denied any connection between the sport and CTE. It wasn't until 2016, 14 years after CTE was first diagnosed in NFL players, that an NFL official publicly acknowledged the link between repetitive blows sustained in football and CTE. (Others in the league still deny the connection.)

Finally, in spring 2016, *The New York Times* uncovered that the NFL failed to enforce accurate concussion reporting from 1996 to 2001, which resulted in over 100 concussions that went unreported, many of which were sustained by high profile players. The NFL also padded the numbers to make concussion rates appear lower.

Of course, there may also be other reasons for the Purdue group's lack of funding—Nauman points out that they don't have a medical doctor on their research team, which the NIH values. Bazarian, the University of Rochester researcher doing similar work, has a slightly different take.

"My sense is that a lot of the money that's gone to study concussions went to the Department of Defense, and they got together with the NCAA and funded several big, huge, multi-center studies," he says. "If you become part of a big network, you can't have a new idea and go forward, you gotta do what the network wants to do. But [the PNG] and I are doing stuff that's a little outside the box, and I think there's just less funding available for that kind of thing."

Regardless of the reason, at the moment the PNG is out of money and out of options. Still, the researchers are determined to continue their work. In December 2015, they released a video in what turned out to be an unsuccessful attempt at crowdfunding. They are now frantically searching for grants of any size that they can cobble together for another season of tests. Nauman and Talavage are even considering putting up funds out of their own pocket, something they have done in the past to keep their research going.

"Every year so far we've scrambled and we've taught extra classes and we've done whatever, we've squeezed money," says Nauman "I don't know if we'll be able to do it next year."

For now, all the researchers can do is keep scanning players for as long as they can, publish as much of their research as they can, and hope for a funding Hail Mary.

A short drive up the road from Purdue is Gordon Straley Field, home of the West Lafayette Junior/Senior High School Red Devils. The school's large stadium boasts a scoreboard, lockers rooms and a sizeable press box, where a banner hanging outside celebrates the Red Devils fall 2015 playoff run—all the way to the state championship game.

For the past 16 years, Brock Touloukian has been the athletic director at West Lafayette. Touloukian was wearing a gray Red Devils pullover and black dress pants when I visited, and his office is cluttered with every kind of sports paraphernalia imaginable. Footballs, baseballs and basketballs crowd rows of sports books on shelves with medals hanging from their corners. A row of trophies lines a top shelf, the golden figures frozen in time, and framed newspaper clippings trumpeting the success of various teams are intermingled with family photos. Behind his desk, a small gold Purdue football helmet sits in a clear plastic box, bookending a row of thick binders. A black director's chair, stamped with "Athletic Director" in white block letters, sits unoccupied next to a bulletin board of athletic schedules.

The high school has been involved in the PNG's research since 2011, and for the past two seasons, Touloukian's son Luke, a gangly 6'2" sophomore receiver on the varsity football team, has participated. Touloukian is excited that his school takes part in the research, but at the moment, he and Luke are not particularly concerned about the results. I could hear the pride in Touloukian's voice as he talked about Luke's athletic gifts, and his son's decision to join the study. After days of poring over the nameless, faceless brain scans that are the results of the imaging tests, it was disconcerting to see Luke draped on a chair next to me, a living, breathing reminder that each image is attached to a young man on the cusp of adulthood with his own reasons for playing the game, and his own plans for the future.

In a few short months Luke, along with 1.1 million high school players, will suit up for the start of football season. He, like so many others, doesn't know if he will play football after high school, but chances are he won't end up playing in the NFL, and he will certainly need a healthy, fully functioning brain for whatever his future holds.

Notes:

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