SWEATING THE SMALL STUFF

For these Air Force innovators, boosting human performance is 99 percent perspiration

Abstract

Sweat doesn't just contain salt and water — it's actually a complex chemical cocktail containing many of the same biomarkers present in the human bloodstream. Researchers at the Air Force Research Laboratory's STRONG team, based out of Wright-Patterson Air Force Base, are using that fact, and cutting-edge flexible electronics, to develop wearable patches that can monitor the contents of a person's sweat in real time, providing a continuous stream of data about their hydration, stress levels, and other vital signs.

Air Force Research Lab
Materials and Manufacturing Directorate/711th Human Performance Wing
Wright-Paterson Air Force Base, Ohio
Public Affairs Contact: Laura McGowan, 937-522-3515; laura.mcgowan@us.af.mil

Prepared for the Department of Defense by
THE CENTER FOR HOMELAND SECURITY AND RESILIENCE

Submission Date
August 14, 2017

Sweating The Small Stuff

For these Air Force innovators, boosting human performance is 99 percent perspiration

Driving a racing car at speeds of 190 mph might sound glamorous, but for 28-year-old Ricky Taylor, it's a hot, sweaty business. Squeezed into the bucket-seat of his Cadillac DPi-V.R, with his heart racing at 180 beats per minute, the 28-year-old endurance driver – who in 2017 won 24 Hours of Daytona, the nation's premier round-the-clock racing event – faces temperatures that even in an air- conditioned cockpit can climb 18 degrees above the trackside temperature.[1]

"After a 24-hour race, I'll be about eight pounds lighter." Taylor said. "I sweat on the extreme side." That's challenging for the mechanics who tune Taylor's car: all that sweat winds up rusting its metal components. "They're constantly having to replace the floor," Taylor says with a laugh.

But it's also a physiological strain on Taylor himself: no matter how much Pedialyte he chugs before taking the wheel, it's hard to stay hydrated once the race is underway, and the fluid loss eats into his performance. "You feel yourself losing a little bit of focus, which isn't a good feeling," he says.

To stave off dehydration, Taylor and his teammates recently began testing a secret weapon: a high- tech patch, which looks like a Band-Aid but is packed with cutting-edge flexible electronics and biosensors. When Taylor slaps the patch on his arm, it wirelessly streams data to an in-car recording device that produces a real-time snapshot not just of how much fluid Taylor is losing, but also of the chemical composition of his sweat.

Poring over the data from the patch, Taylor's team soon realized that their star driver was not only a copious sweater, but also an exceptionally salty one, losing large amounts of sodium and potassium over the course of a race. That discovery allowed the team to supplement accordingly, putting Taylor on a regimen of custom-brewed, high-electrolyte Gatorade that reportedly tastes like sea- water, but that helps Taylor to avoid the physical and cognitive deficits that come with dehydration.

Drivers are considered tools, "like another piece of the machine," Taylor says."If we can operate at a higher lever, and not fade but stay in the race, it's a big advantage for us."

That's exactly the kind of performance boost that Air Force Research Laboratory scientists had in mind eight years ago, when they embarked on a pioneering research effort to develop the world's first sweat-based biosensors. The cutting-edge technologies inside Taylor's sweat patch are the direct fruit of an AFRL project that began as a tentative plan to develop noninvasive performance monitors for pilots, but which has evolved into a flourishing research and development (R&D) ecosystem linking academic research teams, startups, major sporting brands, and AFRL's own multidisciplinary researchers and engineers.

The first commercial sweat sensors are still a year or so from being market-ready. Still, thanks to an AFRL-led push to commercialize sweat-monitoring devices, the same prototype patches now being tested by Taylor and his teammates could one day be widely used by civilian doctors, athletes, andcasual fitness buffs — and also be worn by Air Force fighter pilots, special forces operators, and even recruits going through basic training.

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[1] Most details from interviews, but the temperature number is from https://goo.gl/IPdEMw

The ultimate goal is to boost warfighter performance, prevent injuries, and save lives, says Rajesh Naik, the chief scientist of AFRL's 711th Human Performance Wing, "This could be a game-changer on many levels."

Aviation's Birthplace

The leafy corner of southwest Ohio, where Wright-Patterson Air Force Base stands, is the birthplace of modern aviation. It was here, in the early 1900s, that the Wright brothers perfected the 1905 Flyer, the world's first practical airplane, and established their legendary pilot-training programs. It was here, too, that the Air Force Research Laboratory, now a major research organization spread across nine U.S. bases, got its start a century ago, with the opening of the first Air Service laboratory in 1917. Over the years, researchers at Wright-Pat helped launch the national space program, designed the rocket-powered jets flown by Chuck Yeager, and developed the technologies underpinning modern stealth aircraft.[2]

These days, Wright-Patterson remains at the center of Air Force innovation, the home of both the Air Force's weapons procurement programs and the Air Force Research Laboratory's leadership team, along with its materials, sensors, aerospace, medical, and human performance divisions.[3] That includes the 711th Human Performance Wing, established in 2008[4] to help the warfighter achieve their peak potential, and now home to Dr. Joshua Hagen, the brains behind the Air Force's sweat-patch program, and the man who kick-started the biosensor revolution that's helping Ricky Taylor to stay ahead of the pack.

Hagen was born and raised in central Ohio, and as a boy loved to visit the Air Force museum at Wright-Patterson. "Boys are into fast planes and things blowing up," Hagen says with a laugh. He found himself drawn back to Wright-Patterson while a graduate student studying materials engineering at the University of Cincinnati. An inspirational professor — Stephen Clarson, a polymer chemist[5] — usually had a couple of graduate students placed at AFRL, and Hagen pushed his way to the front of the line.

"When I decided to go back to grad school, his was the first door I knocked on," Hagen says. "I said hey, I want to work at Wright-Pat — and he said, okay, come on."

Hagen did most of his postgraduate research with AFRL's materials directorate, then dabbled in the private sector, exploring polymer encapsulation for Swiss flavor and fragrance-maker Givaudan. The lure of a private-sector paycheck seemed appealing, but Hagen was soon bored by the profit-driven nature of corporate R&D, and called his former AFRL supervisors to talk his way into a full-time job with the materials directorate.

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[2] Wright-Patterson 2015 Installation Guide, p5-9.

[3] Untitled publicity materials provided by Wright-Pat (map of research sites).

[4] https://health.mil/Reference-Center/Presentations/2014/11/06/711th-Human-Performance-Wing-Overview

[5] https://www.researchgate.net/profile/Stephen_Clarson

Military research is a "beautiful blend" of foundational scientific research and practical, real-world product engineering, Hagen says. "I don't necessarily have to worry about the bottom line, and making a profit -- it's all about helping our guys to get better," he says.

Hagen wound up splitting his time between the materials directorate and the 711th, trying to find ways to use new materials and advanced sensors to make elite warfighters even better at their jobs.

These days, Hagen — stubbly, bespectacled, round-faced, and fond of Under Armour athletic shirts — leads AFRL's Signature Tracking for Optimized Nutrition and Training (STRONG) laboratory, which focuses on identifying biomarkers that correlate with performance, measuring them in real-time, and developing ways to turn that data into real-world results.

A Eureka Moment

It was from Hagen's cluttered office in the STRONG lab — currently strewn with cardboard boxes, books, cables, radio-controlled cars, a large American flag, and an egg-shaped, soundproofed armchair — that Hagen and his longtime collaborator, Dr. Jason Heikenfeld of the University of Cincinnati, first set out to try to find a way to deliver actionable biometrics in real-time. The pair had previously collaborated on display technologies, so it was to Heikenfeld that Hagen first turned when he was tasked with finding ways to monitor pilots in real-time.

"There are two thousand sensors on a plane, and only one on the pilot," Heikenfeld says. "They said, what can you do with that?"

Hagen and Heikenfeld met at the University of Cincinnati, where Heikenfeld — a first-generation college student — was racing to finish his PhD in electrical engineering in record time. Since then, Heikenfeld has authored more than 100 peer-reviewed publications, won dozens of patents, spun off several companies — including Eccrine Systems, which helped develop the patch worn by Ricky Taylor — and founded UC's Novel Devices Laboratory, which is a world leader in fields such as reflective-display and microfluidic technologies.[6]

"Jason is rocket-propelled," Hagen says. "He's amazing. He's probably one of the best academics that I've seen." The pair initially set out to continuously glean data from their subjects' blood, much as a doctor would use blood samples to check a patient's health, perhaps using patch-mounted microneedle technologies to painlessly extract tiny droplets of blood.

Then, they had what Hagen calls a "eureka moment" — they realized that they could find many of the same biomarkers present in blood in a few drops of sweat.

Research has come a long way since Aristotle claimed that sweat and urine were essentially the same thing, and argued that our body simply ejected unwanted salt from food through our pores.[7] Scientists now know that sweat is actually a complex cocktail of chemicals: about 99% water, and certainly salty, but also packed with many hundreds of trace chemicals in quantities that closely track the same biomarkers' presence in the bloodstream.

"If you ask me if it's in sweat, I'm going to say yes," Heikenfeld says. "The real question is what's its concentration, and how does it correlate to blood, and can you build a sensor for it?"

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[6] From interviews and also http://www.uc.edu/news/NR.aspx?id=11798

[7] https://archive.org/stream/worksofaristotle07arisuoft/worksofaristotle07arisuoft_djvu.txt

While researchers were already looking for clinically useful biomarkers in sweat using conventional lab equipment, Hagen and Heikenfeld were among the first to seek to condense that technology down into a small, wearable patch capable of extracting data from sweat in real-time. “In the early stages we'd have a weekly meeting where we were talking over questions that nobody had answers for. We were just staring at a blank whiteboard,” Heikenfeld says.

Over time, the pair, supported by researchers from AFRL and Heikenfeld’s lab, have figured out many of the foundational challenges for sweat biosensing: how to use wafers of ultra-thin paper to wick sweat directly from sweat glands, so it doesn’t mix with contaminants on the skin; how to use chemicals to stimulate sweat, so the patch can still deliver data when the user isn’t exercising; and, most importantly, how to shrink down the biosensors themselves, and perform analysis that would ordinarily require lab equipment weighing several pounds using flexible, miniaturized electronics capable of fitting on a Band-Aid.

The simplest biosensors, like those on the patch worn by Ricky Taylor, use an ion-selective membrane to filter charged ions — such as sodium and potassium — from the wearer’s sweat. As the ions seep past the membrane, a charge builds up that can be detected by the patch’s onboard electronics, which then beam a signal via radio-frequency identification (RFID) or Bluetooth to a user’s smartphone or other data-recording device.

Better Than Blood

First-generation biosensors will likely focus on electrolytes such as sodium and potassium, in part because they’re one of the most prevalent chemical markers present in sweat. Down the line, though, Hagen and Heikenfeld expect to see sensors emerge that can detect dozens of other biomarkers, perhaps using tripwire-like DNA strands that would trigger a charge when they bind to specific molecules in a person’s sweat.

There are endless potential applications for sweat-based biosensors, Heikenfeld says, but every new biomarker that the team targets requires a custom-built sensor, often using completely different sensing technologies. That requires continuous detective-work to find sensing methods that are selective for a specific molecule, and that can be condensed down to work reliably in a flexible patch.

“Every time we go after a new application, you've got to make a sensor for it that works, and that is always a challenge,” he says. One application that could have a big impact on pilots and unmanned aerial vehicle operators is a patch that measures lactate and other biomarkers that can show when muscles are fatigued or damaged, as well as a set of four key hormones that, taken in aggregate, offer insights into a user’s levels of stress and exhaustion. That could allow troops to be given customized “neutraceutical” supplements to keep their performance at an optimal level, help people to avoid injury using tailored workout and recovery routines, or provide an early-warning signal when pilots or unmanned aerial vehicle (UAV) operators suffer lapses in concentration.

With 29 percent of the Air Force’s 1,100 UAV pilots reportedly suffering from stress-related burnout, and

operator error implicated in almost 80 percent of the Air Force's UAV mishaps, that's potentially a big deal.[8] Biofeedback from sweat sensors and other monitors could be used to reduce operator burnout and cognitive overload in real time, helping to prevent UAV accidents such as the 2010 incident that killed 23 Afghan civilians, according to a paper published in *The Armed Forces Journal* by AFRL researchers. "What's needed now is to 'close the loop,' where the physical and mental states of the operator are fed back into the weapon system, making the human a more seamless part of the overall system," they write.[9]

To get to that point, researchers need to develop sweat patches that can non-invasively and continuously deliver all the information you'd get from a blood test. Sweat patches will probably never be as accurate as lab-based blood analysis, Heikenfeld says, but the ability to continuously monitor key analytes could make them far more useful.

"If we're measuring for 24 hours, we can get information you aren't going to get from a blood draw," he says. "In the end, you can get information that's going to be better than blood, because you're taking a data point every couple of minutes. You're going to get context that tells you something you otherwise wouldn't know."

In practical terms, that continuous data-stream could be a lifesaver. Numerous would-be Air Force special operatives and Navy SEALs have died during shallow-water training exercises, points out Naik, the 711th Human Performance Wing chief scientist.[10] "These guys are so mentally strong that they try to hold their breath under water for long periods of time, and they black out," he says. But wearable patches capable of monitoring oxygen levels in real time could virtually eliminate that risk.

"They can have a simple device that can measure oxygen levels, so the trainer can know when they need to pull someone out," Naik says. Similar oxygen monitors could provide an additional line of defense against hypoxia episodes in pilots, Naik says. Other patches might provide real-time insights into the way medications or environmental toxins are metabolized, or help pararescuemen monitor injured airmen's vital signs. The C-130s used during extraction missions are "like an ICU (intensive care unit) on steroids," Naik says, but they're currently crammed full of the same bulky medical equipment you'd find in a hospital. Sweat patches and other wearable monitors would be far lighter, and potentially more useful and resilient in emergencies, he says.

The STRONG team has even discussed baking its sweat sensors into the base-layer for the planned Tactical Light Operator Suit, or TALOS, a kind of robotic exoskeleton being developed by U.S. Special Operations Command to provide new capabilities for special operations branches across the whole military. The TALOS suit, which has drawn comparison to Iron Man's armor, is designed to allow soldiers to wear heavier armor and carry heavier burdens almost effortlessly, and built-in biomonitoring would dovetail neatly with its dual goals of boosting performance and survivability.[11]

"To me, it's got applications everywhere," Hagen says.

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[8] http://www.npr.org/2011/12/19/143926857/report-high-levels-of-burnout-in-u-s-drone-pilots
http://www.colorado.edu/ASEN/asen5519_arg/papers/TVARYANA.pdf

[9] http://armedforcesjournal.com/the-quantified-warrior/

[10] http://militarymedicine.amsus.org/doi/pdf/10.7205/MILMED-D-16-00246

[11] http://scout.com/military/warrior/Article/US-Special-Operations-Command-is-Engineering-a-Next-Generation-E-101455258

The bigger question is figuring out how to use the bio-data generated by the patches to give the warfighter a real-world edge – and to figure out how to do that, the STRONG team is turning not to the laboratory or the military training ground, but to the football field.

Boosting the Buckeyes

When Ohio State's football players turn up for their daily practice sessions, they don't start with stretches or a warm-up jog — instead, they're handed a questionnaire, told to pee in a cup, and plugged into a heart-rate monitor. Sometimes, they're also asked to leap up and down a few times on a pressure-plate that monitors their muscle strength, or to strap on a commercial Polar or Zephyr heart-monitor while training. That all adds up to a firehose of biometric data, which gets filtered through an analytics suite custom-built by AFRL engineers, and condensed into a simple color- coded dashboard that coaches access on their iPads.

"It's as simple as someone's in the green, or in the yellow, or in the red," explains Ohio State athletic performance director Doug Calland. "If you're in the yellow three days straight, we'll need to adjust and do some things to help your recovery. If you're in the green then you're either feeling great, or not working hard enough."

The STRONG team started working with Ohio State's football players about five years ago, and the program has since expanded to include wrestlers, lacrosse players, swimmers, and tennis players. This summer, Calland says, the program will be rolled out to all 1,100 of Ohio State's athletes. "This is a huge advantage for us," he says. "It lets us put our best team on the field."

Hagen, who says he's equal parts sports junkie and military junkie, gets a big kick out of hanging out with the Buckeyes, and helping them to perform better on game day. "To think that I even have a small part in making Ohio State football better is pretty awesome," Hagen says. "I grew up on Ohio State football. I try to be professional when I'm there, but I'm giggling on the inside."

Still, he says, the partnership with Ohio State only exists because it delivers real benefits for AFRL. Much of Hagen's early work focused on special operations units, including the Navy SEALs and Air Force special operators, but embedding researchers with military units isn't cheap, especially compared to simply driving over to Columbus to work with the Buckeyes.

"Sometimes it takes a little explaining — what does football have to do with the Air Force?" Hagen says. "But if I get any pushback from the super-high-up bosses, I just show them how much money I'm saving them."

The bigger reason that Hagen wants to work with Ohio State, though, is that it's far easier to quantify success and failure on the football field than it is on a military training ground. Measuring how well a military trainee performs on an obstacle course or in a live-fire exercise is tricky, Hagen says, but sports coaches have huge amounts of hard data quantifying their athletes' collective and individual performance. "I have a score, I have statistics, I have batting averages, I have wins and losses, I have goals scored, field-goal percentage -- I have all sorts of interesting things I can correlate data to," Hagen says. "We could never do half of what we've done without having these data sets."

While the STRONG team does still test its devices and protocols with active military units, Hagen

has increasingly been using elite athletes as a proxy for combat troops, working with coaches not just at Ohio State and the University of Cincinnati, but also at a bevy of pro-sports teams — including the Detroit Pistons, the New Jersey Devils, the Cincinnati Bengals, and the Arizona Cardinals — to refine his team's ideas and learn how to turn data into a real-world performance boost.

AFRL has relatively few prototype patches to play with, and does most of its sweat-based testing in the lab. While they're waiting for commercial sweat biosensors to hit the market, Hagen and the rest of the STRONG team use off-the-shelf biometric equipment like Zephyr straps and Polar watches, along with everything from urine tests to pen-and-paper surveys, to monitor athletes' readiness. The goal, Hagen says, is to figure out precisely which biomarkers are predictive of human performance and determine how to turn that biometric data into specific recommendations to improve warfighter training and recovery.

Whole-Career Benefits

The results are clear, both on and off the field, says Calland. After the men's lacrosse team went through a streak of lackluster away-from-home performances, the data showed that the players had been sleep-starved and dehydrated. It's far easier to manage a squad's health and nutrition effectively when you have the evidence in front of you in red, yellow and green, Calland says. "We can make sure they're recovered and ready to put their best foot forwards on game day."

"Of course, we know when game day is. The military doesn't know when game day is, so they have to be ready all the time."

It's true that military operators face physical and mental challenges beyond anything experienced by a college athlete, Hagen says. Still, the tie in with Ohio State actually makes it easier to convince elite combat troops to take the STRONG team's data seriously.

"Everybody knows Ohio State football," Hagen says. "If we're helping those guys get better, then that gives us credibility."

Increasingly, the STRONG team is testing training and recovery technologies pioneered by special ops units, and encouraging Ohio State's athletes to use similar methods. Down the hall from Hagen's office stands a huge refrigerator-like appliance filled with white powder: a sensory-deprivation flotation tank, packed with Epsom salts and ready to be filled with blood-temperature water. Navy SEALs use tanks like these to help spur recovery, and the STRONG team has found it's possible to help athletes get their biometrics back on track — and perform better on game day — by having them bob about in the tanks.

Ohio State now uses flotation tanks for many of its athletes, and Hagen says he can easily spot who's been using the tanks based on the improvements in their data. The results are so impressive that Hagen often takes a dip in the tank himself when he's feeling run-down. "I've had mornings when I'm just super-stressed and can't get focused, and I'll get into our float tank and I'll do a 60-minute float session," he says. "I'll get completely focused — I'll come out and I'm shot out of a can and ready to go."

By having athletes test the float tanks, along with other recovery methods such as cryotherapy, yoga, and meditation, the STRONG team is able to figure out exactly what impact the different therapies have on both biomarkers and performance. Different therapies have different effects,

Hagen says, and athletes that pick the wrong recovery method can nudge biomarkers in the wrong direction, not only diminishing their performance, but also increasing their risk of injury.

"That's our big return on investment -- can we lower injuries? Can we reduce heat injuries? Can we reduce musculoskeletal injuries?" Hagen says. "If we can reduce those things, and use all this technology and all this data to keep you healthier and training more effectively, that's going to help your whole career."

Beating the Heat

When it comes to serious football injuries, the heat is even more of a threat than the other team's defensive linemen. Sitting in an air-conditioned office, the average person produces up to a pint and a quarter of sweat a day. A football player — sprinting around in the sun kitted out in pads and helmets — can sweat at a rate of six pints an hour, losing up to seven teaspoons of salt per day in the process.[12] If those fluids and salts aren't replaced, it can leave the athlete unable to sweat fast enough to cool themselves down, leading to dangerous heat exhaustion or heatstroke.

Between 1960 and 1970, at least 43 high-school and college footballers died from heat-related illnesses, in part because at the time many coaches believed dehydration made players meaner and tougher, and wouldn't let their squads anywhere near water during training or games. Even relatively lenient coaches allowed their players only a quick sip-and-spit, or passed around wet towels for players to suck on, in order to avoid filling their team's bellies with water.[13]

That began to change in 1965, when a University of Florida researcher named Robert Cade began studying the fluids lost by the Florida Gators' players. Based on the shocking amount of electrolytes the players were shedding during every game, Cade brewed up a briny, electrolyte-balanced beverage, squeezed a few dozen lemons into it to mask the taste — and Gatorade was born. Cade sold his first 500-gallon batch to the Gators for $1,800, then upped his price to $10 a gallon for the following season. The team's coaches paid up, somewhat grudgingly, then watched as their players turned in the best performance in the team's 61-year history, and went on to win the 1967 Orange Bowl.[14]

The Gators' stellar season catapulted Gatorade onto the national stage and helped turn electrolyte-balanced sports drinks into an $8.48 billion industry.[15] It also convinced football coaches across the country to let their players drink more freely, and led to a marked decline in heat-related football deaths: over the past five years, there have been an average 1.4 deaths per year from heat related illness.[16]

That decline isn't just due to Gatorade, of course; rather, it's thanks to a continued push by sports scientists and other researchers to understand the way the body responds to heat and dehydration, and to find ways to prevent elite athletes — and everyone else — from reaching the danger zone.

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12 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1725187/pdf/v039p00205.pdf

13 p28 — https://nccsir.unc.edu/files/2013/10/Annual-Football-2016-Fatalities-FINAL.pdf

14 https://books.google.com/books/about/First_in_Thirst.html?id=uNJIXCE7cSkC

15 https://www.statista.com/statistics/448605/dollar-sales-of-sports-drinks-in-the-united-states/

16 p28 — https://nccsir.unc.edu/files/2013/10/Annual-Football-2016-Fatalities-FINAL.pdf

The importance of that effort is something that Douglas Casa knows only too well. In August of 1985, when Casa was 16 years old, he was vying for a medal in the New York state athletic championships in Buffalo, and running the best 10K of his life, when disaster struck.

Coming into the final lap, Casa stumbled, picked himself up, ran a little further — then collapsed.

"It snuck up on me," he says. "The first indication that there was a problem was that my face was flat on the track."

Despite his youth and his training, heat exhaustion had suddenly struck him down. Casa spent the next five hours in a coma, as emergency crews worked to lower his core temperature and bring him back from the brink of death. Fortunately, he recovered — and went on to dedicate his career to the study of heat-related illnesses.

Now director of the University of Connecticut's Korey Stringer Institute, Casa is one of the country's top experts on heat stroke, and often attends marathons and track meets to help other runners to avoid heat exhaustion. In recent years, he has also worked closely with the Air Force's 59th Medical Wing and the 37th Training Wing to prevent heat-related illnesses at Lackland Air Force Base, where the Air Force conducts all its basic-training programs.

"They're one of the most proactive military bases in our country right now with trying to have best practices," Casa says.

The Air Force has been fighting heat-related illnesses at Lackland since the summer of 1956, when the 102-degree heat, combined with an influx of unacclimated trainees from recently closed training facilities in New York and California, led to 13 heat-stroke cases and two deaths.[17]

Early strategies, such as allowing troops to wear unstarched uniforms, gave way to more nuanced, science-based approaches, thanks in part to Casa's efforts. Lackland now has strict rules about the kinds of physical training that can be undertaken as temperatures soar, and maintains a network of emergency ice-baths dotted around the base to ensure that overheated recruits can rapidly be brought down to safe temperatures.

Even so, dehydration remains a major concern, both at Lackland and elsewhere. In 2016, the Armed Forces saw 2,536 diagnosed heat-related illnesses among active-service members, of which 202 occurred at Lackland.[18] Casa says many of the existing methods for monitoring recruits' hydration and body temperature are pretty crude; rule-of-thumb guidelines like drinking a full canteen every hour or so could leave some recruits dehydrated, while dangerously over-hydrating others.

If recruits could stick on a patch that broadcast their vital statistics to their Military Training Instructor in real-time, it would be far easier to keep them safe, Casa says. "In our world, the two biggest Holy Grails that have yet to be resolved are real-time assessment of hydration and body temperature. That's where we'll be 10 years from now."

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[17] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1522319/pdf/amjphnation00504-0076.pdf

[18] Medical Surveillance Monthly Report, March 2017 March Vol. 24 No. 3 p12

The Air Force Research Laboratory's sweat patches aren't ready for rolling out to trainees just yet, but the STRONG team is already working with Lackland's medical and training staff to provide real- time data about trainees' health. Since 2014, research psychologist Dr. Regina Shia has been using off-the-shelf Zephyr wearable bio-monitors to gather data from the base's Battlefield Airman Training Squadron, which trains special operations airmen including pararescuemen and combat controllers.

The Zephyr sensors don't measure dehydration directly, but they do provide a rough estimate of core body temperature by extrapolating from a users' heart rate, using algorithms developed by the U.S. Army Medical Research and Materiel Command.[19] Though less accurate than a conventional thermometer, the Zephyr gadgets are also far less invasive, and can be issued to trainees ahead of especially taxing sessions to provide their MTIs with continuous data about their welfare and performance. That lets instructors pull out individual soldiers who seem at risk of overheating, or send their entire unit for a dip in the pool if trainees' core temperatures are ticking upwards.

Even without sweat monitors, Shia's results are impressive: since testing at Lackland began, her sensors have provided early warning of about 40 impending heat-related health problems. That impressed Lackland's leadership so much that they asked Shia to let them keep using the monitors even after her own data gathering was complete.

An outside contractor now administers the STRONG team's biomonitoring protocols to about 1,000 special forces trainees a year, and Lackland leaders are hoping to expand the program soon to include recruits going through basic training.

The benefits will only increase as AFRL starts to add more sophisticated biosensors, including sweat monitoring, to the mix. "We're at a 60 percent solution right now, up from zero," Hagen says. "When electrolytes comes in, it'll get us another 10 or 15 or 20 percent." Besides further reducing heat injuries, hydration monitoring could help to reduce musculoskeletal injuries, which are known to correlate with dehydration. That could put a dent in the $43.7 million that the Air Force spends each year to deal with musculoskeletal injuries incurred during basic training, and significantly reduce dropout and recycling rates.[20]

Reducing Injuries

Preventing injuries at Lackland is only the beginning, Hagen says. Hagen routinely showcases his technology at Pentagon Lab Days, and has gotten used to seeing officers' eyes widen as they envision the ways his gadgets could help their troops. "I was just down at Quantico," Hagen says. "They had no idea this existed. Pretty much every single unit commander that came up to me said, 'We've got heat issues every day — can I use this?'"

Several Marine units are now working to bring the STRONG team's heat-monitoring tools to their trainees, and a number of special forces units are also trying out Hagen's protocols to help them train harder without injuring themselves. That could increase the number of people using Hagen's

[19] https://www.army.mil/article/186577/

[20] http://natajournals.org/doi/pdf/10.4085/1062-6050-51.10.10?code=nata-site

technology from a thousand or so special forces trainees at Lackland, to tens of thousands of trainees across the whole armed services. "Everybody goes through basic training, right? So if you can fix the heat issue there, that's pretty massive," Hagen says.

The Killing Heat

The next big leap will be to start finding ways to incorporate biosensors into warzone environments.

Military commanders have been grappling with heat-related problems for millennia: in 24 BC, a Roman prefect by the name of Aelius Gallus led 10,000 men into the deserts of southern Arabia — and while he lost only seven men in battle, he lost thousands more to the effects of heat and dehydration, and was forced to beat an ignominious retreat.[21]

In the Middle Ages, the crusaders routinely lost vast numbers to heat and dehydration. In one pivotal battle in 1187, a huge Frankish army of metal-armored knights was routed and massacred after Saladin's more appropriately dressed and better-supplied Muslim troops cut them off from their water source, then tormented the exhausted Franks by emptying spare canteens of water out onto the parched ground.[22]

And hydration wasn't just a concern for ancient warriors. In Vietnam, the "killing heat" led many soldiers to peel off their helmets and flak jackets while on patrol, and overwhelmed countless new arrivals. "It seemed like on every mission someone would fall out due to heat exhaustion, or they would pass out and we had to get them dusted off," Gary Franklin of the 198th Light Infantry Brigade later told a historian.[23]

The military is more mindful of heat illnesses these days, Hagen says, but dehydration remains a serious concern. Many of the special forces operators that Hagen works with have been deployed in hot, dry places like Iraq or Afghanistan, and most have stories about struggling with the heat, or seeing their units held up while medics treated a dehydrated soldier.

Between 2011 and 2015, there were 720 heat injuries among servicemen in Iraq and Afghanistan, counting only episodes serious enough to lead to medical treatment or lost duty time.[24] Hagen's sweat monitors could help to reduce that number, while also helping troops to avoid the cognitive and physical deficits that come with even relatively minor dehydration. "If we can prevent that, it's going to make everybody safer," Hagen says.

Scaling Up

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[21] http://www.jstor.org/stable/pdf/41538687.pdf?refreqid=search%3A4a13256ffaecd60807bfff80f68bf3b7

[22] https://books.google.com/books?id=6pkTDQAAQBAJ&printsec=frontcover&dq=hattin&hl=en&sa=X&ved=0ahUKEwiPkfq3nfvUAhVq0oMKHbiODgsQ6AEIKjAB#v=onepage&q=water&f=false

[23] https://books.google.com/books?id=W8zvCwAAQBAJ&pg=PT63&lpg=PT63&dq=It+seemed+like+on+every+mission+someone+would+fall+out+due+to+heat+exhaustion,+or+they+would+pass+out+and+we+had+to+get+them+dusted+off,&source=bl&ots=BVO_ZXeGcm&sig=vYYolz5rlDg8Xrh-Ag8TfdpyIYA&hl=en&sa=X&ved=0ahUKEwid30TenfvUAhVJ20MKHXwtDCEQ6AEIKDAA#v=onepage&q=It%20seemed%20like%20on%20every%20mission%20someone%20would%20fall%20out%20due%20to%20heat%20exhaustion%2C%20or%20they%20would%20pass%20out%20and%20we%20had%20to%20get%20them%20dusted%20off%2C&f=false

[24] Medical Surveillance Monthly Report, March 2016 Vol. 23 No. 3 p16

Laura Rea did as much as anyone to turn Hagen's high-tech dreams into a commercial reality. A self-described military nerd, Rea grew up watching the Apollo moon landings and longing to be an astronaut. That didn't pan out, but a career as a military scientist proved almost as satisfying. After studying materials science at Wright State and the University of Dayton, she joined AFRL, and managed well over $500 million in technology investments during her 36 years there.

Rea, who retired in the summer of 2017, was AFRL's program officer for the Nano-Bio Manufacturing Consortium (NBMC), an AFRL sponsored network of private sector players. Established in 2013 to mainstream Hagen and Heikenfeld's sweat-patch research, the consortium's aim is to bring companies together to solve some of the big technological challenges facing sweat-patch manufacturers, and to accelerate the development of a flexible-electronics manufacturing base.

"Companies have to have skin in the game, " Rea says. Anyone who partners with NBMC has to "be willing to put up, and has to care enough about it to be willing to fund it. "

The NBMC funds some academic projects, and recently chipped in $200,000 to support a sweat-patch project run by Esther Sternberg, the researcher whose publications first gave Hagen and Heikenfeld the idea of exploring sweat biomarkers.[27]

The group's focus is commercialization. One of the NBMC's biggest current projects, spearheaded by GE Medical, is a sweat-patch prototype that aims to combine hydration monitoring with sensors capable of providing continuous blood pressure, heart rate, blood oxygen, and electrocardiogram measurements.

That technology, intended for use in hospital settings, has seen some successes in testing, but it's not ready for prime time-yet, Rea says. "Some of the challenges, technically, are things like how can we know we're getting fresh sweat? That's a phrase I never thought I'd utter professionally, but these are important things."

A Competitive Edge

Besides the work being done by the NBMC, a number of startups have grown out of the STRONG team's work. One of the most promising, Eccrine Systems, was founded by Heikenfeld himself after he was introduced to the company's future CEO through a connection at AFRL. Heikenfeld wound up taking a sabbatical to get the company off the ground, and last summer Eccrine was awarded a $3.96 million contract to produce a hydration-monitoring sweat patch for AFRL.[28] Work is already well under way, and president and COO Keith Grimes says he expects to deliver a viable prototype next year.

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[25] https://www.youtube.com/watch?v=6WUPAQL5g-k

[27] http://www.nbmc.org/nano-bio-manufacturing-consortium-selects-project-proposed-by-arizona-center-for-integrative-medicine-to-optimize-human-performance-monitoring-techniques/

[28] http://www.businesswire.com/news/home/20160825005243/en/Eccrine-Systems-Awarded-3.96M-Air-Force-Contract

That's a goal Grimes takes personally: during the 1990s, he served as a Navy SEAL in the Persian Gulf and in Central and South America, and as his unit's medic saw many missions disrupted by dehydrated or heatstruck troops. Looking back, Grimes says he can clearly see the boost that real- time hydration monitoring would bring to units like his. "There's a need for technology like this," he says.

Detecting electrolytes in sweat might make it easier to prevent dehydration, but it wouldn't necessarily be a silver bullet when it comes to tackling heat-related illnesses. A 2005 study found that efforts to ensure troops stayed hydrated had reduced military heat exhaustion rates from 60 per 100,000 soldiers in 1991 to 10 per 100,000 soldiers in 2002 — but also revealed an eightfold increase in heatstroke hospitalizations over the same period.[29] The problem, researchers theorized, was that better-hydrated soldiers were able to stay on their feet longer, but would still ultimately overheat if they pushed beyond their limits.

"The increased emphasis on maintaining hydration to sustain exercise performance might allow compromised subjects to avoid heat exhaustion and continue to exercise until more severe heat injury or stroke occurs," the researchers warned.[30]

Still, hydration-monitoring patches would give medics and drill instructors important new insights into their soldiers' physiology, Grimes says. People have been monitoring dehydration for centuries using crude tests like the color of a person's urine, and trying to prevent it by telling soldiers when and how much to drink, but dehydration and heat illness have continued to incapacitate soldiers. "There's still a need for tech like this," he says.

It's critically important for the military to keep investing in sweat technologies, and driving both ARFL and private-sector R&D forward, Grimes says. "The Department of Defense's focus on the next generation of technology such as ours is absolutely instrumental for us to maintain our competitive edge, both militarily and industrially."

Bringing Down Costs

In addition to its work with AFRL, Eccrine Systems licenses some of its technologies to CoreSyte, a Virginia startup part-funded by investments from Gatorade and Under Armour, which manufactured and tested the sweat patch used by Ricky Taylor and his endurance-racing teammates. CoreSyte was conceived through a tech accelerator program designed to help turn AFRL research into commercial products, and is squarely focused on athletic applications for sweat-patch technologies, says CEO Scott Ackerman.

The technology behind CoreSyte's hydration patch is more or less proven, Ackerman says, and is awaiting a formal thumbs-up from AFRL's validation teams and from Gatorade's sports scientists. The long-term goal is to incorporate the patch into Gatorade's GX platform, which will channel data from the patch to a high-tech sports bottle that will automatically dispense customized Gatorade tailored to athletes' specific needs.[31] "Gatorade wants to go to market with a digital sweat patch, and CoreSyte wants it to be ours," Ackerman says.

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[29] http://www.dtic.mil/dtic/tr/fulltext/u2/a443873.pdf

[30] http://www.medscape.com/viewarticle/512284_4

CoreSyte is also in talks to begin testing its patches with other motor-sports drivers, as well as several NBA and MLB teams, but like Eccrine, CoreSyte doesn't expect to have a patch on the market until 2018 at the earliest. The biggest challenge, Ackerman says, is bringing the cost per patch down to levels that will appeal both to consumers and to military buyers.

It currently costs about $58 to manufacture a patch, but it should be possible to bring the cost below $20 as manufacturing scales up, and below $10 soon thereafter. "We know we need to get it down into single digits," Ackerman says. "Right now we could never sell them in the commercial market, but we're working with manufacturers to scale it and bring the cost down."

Foreign Militaries

The development of reliable, affordable biosensors can't happen soon enough, says Dr. Scott Galster, a dapper, grey-haired research psychologist who until recently headed up AFRL's applied neuroscience division, and now runs AFRL's international outreach and industrial collaboration programs.

There's little doubt, Galster says, that other militaries are also working on quantified-warrior programs, including advanced wearables and biosensors like those coming out of Wright-Patterson.

"I've had military leaders from other countries literally tell me: we're going to do this, because we can," he says. Foreign militaries are actively investigating genetic markers of performance, with a view to recruiting soldiers who are biologically predisposed to perform at a high level. Galster assumes they're also pushing forwards on less invasive biochemical performance indicators like those being explored by the STRONG team.

It's even possible that some countries have a head start on the U.S.: many of the biometric technologies now being tested by AFRL, and adopted by U.S. athletes, were first used by professional soccer and rugby teams in Europe and Australia. It was only with the rise of Major League Soccer, and the arrival of European physiologists and strength trainers, that American teams started to get serious about data-driven training, says Jason Eckerle, a former assistant director of sports medicine at Miami University who now runs the STRONG team's equipment-packed testing gym. "All this is so new, even in the athletic community, the stuff Josh is doing," he says.

The 'Quantified Warrior'

If Galster has his way, Hagen's novel technologies will be pushed into the commercial mainstream as quickly as possible, and mature, affordable technologies will soon be available to military procurement teams. Galster, who worked with Hagen and the STRONG team on a daily basis before switching into his current industry-facing role, is one of the chief evangelists for the concept of the "quantified warrior" — a warfighter whose performance is optimized not through instinct and guesswork, but by leveraging a continuous stream of hard data.

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[31] https://www.forbes.com/sites/michellegreenwald/2017/06/15/the-key-ingredients-behind-the-great-gatorade-gx-platform/&refURL=&referrer=

A late arrival at AFRL, Galster graduated from Ohio State with a degree in psychology, drifted out to Portland, worked with the disabled, then moved back east and founded a company selling overhead bridge cranes. Successful but bored, he joined a PhD program, and wound up cold-calling an AFRL human-factors researcher, selected at random from an academic directory, to request permission to conduct a study at Wright-Patterson.

"I said, 'you don't have to pay me, I just want to do some data collection,'" he says. "So I did my dissertation work up here, and ended up getting hired."

Galster's early work focused on using sophisticated sensors, from eye-tracking devices to electroencephalography (EEG) caps, to monitor cognitive overload in UAV pilots, and create systems that could optimize their performance in real-time. Human performance is increasingly the weakest link in military aviation, but while sensors in fighter jets deliver thousands of data points every second, the human pilot is effectively a black box, Galster says. Gather physiological data about pilots in real-time, he says, and you can then start to figure out ways to improve their performance — something that could mean anything from preventing dehydration by giving pilots a glass of Gatorade before a mission, to recalibrating software to provide better auditory or visual cues to an overburdened pilot.

To explain his ideas to higher-ups in the Air Force, Galster scribbled some notes that evolved into a 2013 paper — now something of a classic in the field, and effectively the STRONG team's manifesto — that described human performance work using a framework Galster termed "Sense-Assess-Augment." The idea, he says, is rather like Western medicine: just as a doctor checks symptoms, makes a diagnosis, and prescribes treatment, so human-performance practitioners should aim to identify suboptimal behavior, understand it, and resolve or mitigate it.

That's a simple concept, which is why it's effective, Galster says. The "Sense-Assess-Augment" framework has been championed by senior AFRL leaders, and widely adopted by military, academic and commercial researchers.[32] People were already trying to improve human performance, but the Galster's framework helps scientists from different disciplines — from electrical engineering to cognitive psychology — to speak the same language, and to draw together their specialties into a coherent research program.

That kind of alignment will be increasingly important as commercial sweat sensors begin to hit the marketplace, Galster says. According to him, it's inevitable that the first sensors will be designed not for pilots or special forces operators, but rather for athletes like those Hagen works with at Ohio State. "The military is a small market, especially for patches and things like that. But there are millions of athletes, and of those there's a certain percentage that'd be very interested in these patches," he says. "The market is on the side of the commercial athletics."

The key will be to make sure that the commercial technologies that are developed — like CoreSyte and Eccrine Systems' patches, or Gatorade's custom-beverage platform — can be easily adapted for military use. "That's why we like to be involved in the development, to make sure the interests of the government are represented in that development," Galster says.

[32] http://armedforcesjournal.com/the-quantified-warrior/

Closing that loop, and bringing commercial products back into military settings, is something the STRONG team and everyone else at AFRL are continuously thinking about. "Our job is not to make athletes better. It's just not," Galster says. "It's to make our warfighters better, and make our airmen better."

Hagen thinks it will take another year to begin rolling out sweat-based hydration patches for large-scale testing, and probably another two or three years beyond that before the technology is perfected. Sweat patches capable of reliably testing for smaller, less prevalent molecules, like stress hormones, could be six or seven years away.

Cautionary Tale

Wearable technology is complicated, even with commercial R&D teams trying to propel the industry forwards, Hagen warns. He points to wrist-based heart-rate monitors as a cautionary tale: despite the best efforts of companies such as FitBit — which last year was hit by a class-action suit over the alleged inaccuracy of its devices — wrist-based monitors simply don't work very well, he says.[33] "There's a giant industry pushing just millions and millions of dollars into that, and it's still not good," he says. "Knowing that, and knowing how much harder our challenge is, we're trying to be realistic."

That's partly why Hagen, having spun off his technology to various commercial developers, is now focused on validating commercially available biometric monitors, and offering third party testing to companies like CoreSyte and Eccrine Systems. Every prototype Hagen sees, he says, is something that could one day be depended on by American troops to ensure their safety.

"I won't let anything get on those guys that isn't high quality," Hagen says. "Once it gets through that rigorous testing, and it's legit and helps them get better, that's what'll be really exciting. We just need to make sure it gets to that point."

Hagen says he tries to be conservative about the potential for sweat-monitoring technologies. Still, he adds, the concepts he and Heikenfeld first scribbled onto their blank whiteboard have now evolved enough, and built up enough momentum, that it's only a matter of time until wearable sweat-sensors are being used by everyone, from elite combat troops to the Couch-to-5K crowd.

"Every single one of these things can be applied to an everyday Joe, and I think actually we'll get a bigger benefit from it than with the elite operators, because we have so much farther to optimize," Hagen says. "If this can make somebody who's already amazing five percent better, then it can make me 50 percent better."

The rapid maturation of the technology has been remarkable, and it's something that could only have been spearheaded by AFRL, thanks to its unique combination of research scientists and engineers, and its ability to draw together real-world scientists, athletes, combat airmen, trainees, entrepreneurs and corporate players, Hagen says. Those connections, and the ability to turn basic

[33] https://topclassactions.com/lawsuit-settlements/consumer-products/388621-fitbit-pushes-arbitration-fitness-tracker-class-action-lawsuit/

science into products that will give a real edge to the warfighter, are what make working at Wright-Patterson so rewarding for him.

“If we were just stuck in a lab coming up with things and reading papers, it’d be pretty boring,” he says. “But once you see real guys training down at Lackland and Ohio State, and see the ways you can help keep them safe, and help them not get injured, and help them perform at a higher level — that, to me, is the fun part. It's translating real research to real actions.”

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