



3D Printing to Help Tortured Bones

A Yale surgeon's modern approach
to improving medical care

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For one recent case, Dr. David Frumberg had to figure out how he was going to fix the left leg of his patient, a 14-year-old girl.

“She has an abnormal connection between these two bones, and she’s missing half of her tibia,” said Frumberg, assistant professor of orthopaedics and rehabilitation. “Have you ever had pain on the outside of your foot? It’s awful, and she experiences that with every step.”

It’s a tricky case, and X-rays and CT scans weren’t giving him enough information to go on. To better understand what was going on, Frumberg went to the Center for Engineering Innovation & Design (CEID) to get a 3D-printed model of the joints. Having the model allowed him to hold the problem in his hand, turn it around, and help him see things he couldn’t before.

“For me, the model helps in so many ways,” he said. “It helps me come up with a plan, it helps me figure out the relationships between all the different complex deformities, and what needs to be repaired and what doesn’t.”

It’s one of several bone models that Frumberg has had printed at the CEID in the last year. They’re especially useful for the more complicated cases, and go a long way to reduce a lot of guesswork. And now, when he opens up a patient, there aren’t so many surprises to work out on the fly. “Every time I get a model, it changes my plan 100%,” he said.

That’s because his procedures involve not just a lot of parts, but parts that often don’t look like anything he’s seen in previous cases. Many cases in the field of orthopedics fall under the “routine” category — that is, they require textbook-style knowledge of standard treatments. Frumberg specializes in the other kind.

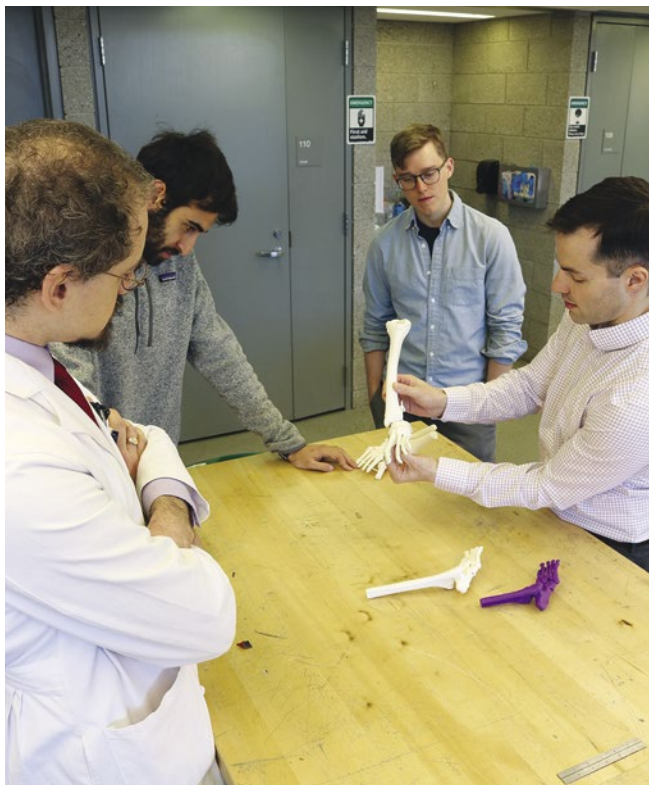
“I never see the same patient and I rarely do the same operation,” he said.

“My work is this: How do I take this uniquely abnormal limb and what can I do that’s best for the patient? It’s that kind of critical thinking that makes it interesting to me.”

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Preparing for an upcoming surgery, Dr. Frumberg and the team observe and discuss a recently printed 3D model.



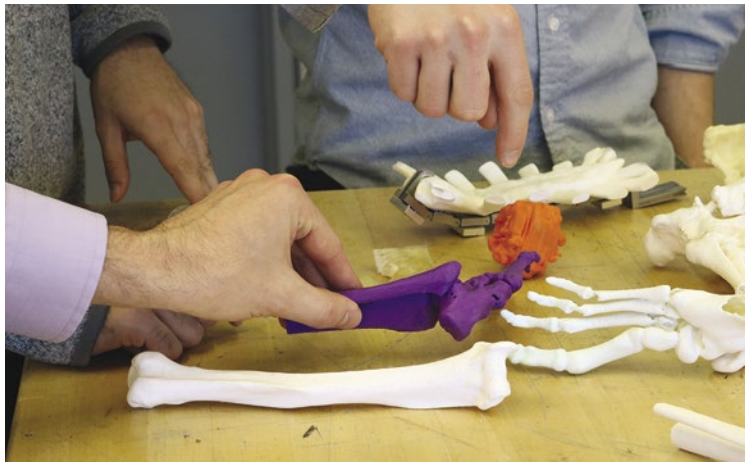
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His focus on the unusual cases is how he came to take on the case of an 11-year-old girl from the Middle East. Her family moved to the U.S. last year and was steered toward Frumberg because of the complexity of her condition.

“The outside half of her leg doesn’t grow well, and as a result, she has a significant deformity. You can see her tibia, ankle, and foot are all misaligned and the leg is much shorter.”

The first part of the treatment entailed a complicated reconstruction of the foot and ankle. A few months later, he brought her back to lengthen her leg. The first part was like “nine procedures in one,” he said and could take many hours. The 3D model helped a lot with his planning. “Without the model I had a list of treatment options, but once I held the model in my hand I knew exactly what I was going to do,” Frumberg said.

The way Frumberg discovered the value of the 3D models is typical of how a lot of things happen at the CEID. He first came to the makerspace looking to use its laser cut-



ter to devise a grid that would better ensure the proper alignment of bones. He took a look around the room and got some new ideas. “There were students there doing the most amazing things.”

He asked about the 3D printers, and former CEID Fellow Dante Archangeli '17 brought out some samples made for other doctors and told Frumberg to come by again if he ever had a case that could use one.

“A few weeks later, he came back and said, ‘I have one for you,’” Archangeli said.

Archangeli then spoke to Sean Lisse, a resident in Radiology, who had been spending a lot of time at the CEID working on his own project [see sidebar on right]. Lisse converted the scans into formats that can be used with the 3D printers. He then handed them to Archangeli, who did the printing.

Archangeli said the CEID’s printers have helped out a lot of doctors — some

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Augmenting the Ultrasound

Dr. Sean Lisse became involved in using the 3D printer to make bone models with Dr. David Frumberg through a separate project of his, also being worked on at the CEID.

Along with Fabian Laage Gaupp and Jitendra Bhawnani, both also in Radiology, Lisse has been working on a medical device that uses augmented reality (AR) to help physicians perform certain procedures that require ultrasound.

Currently, a doctor using ultrasound has to look at the image on the monitor, which could be a good distance from where he’s supposed to stick a needle, insert a tube, or whatever other procedure is being performed.

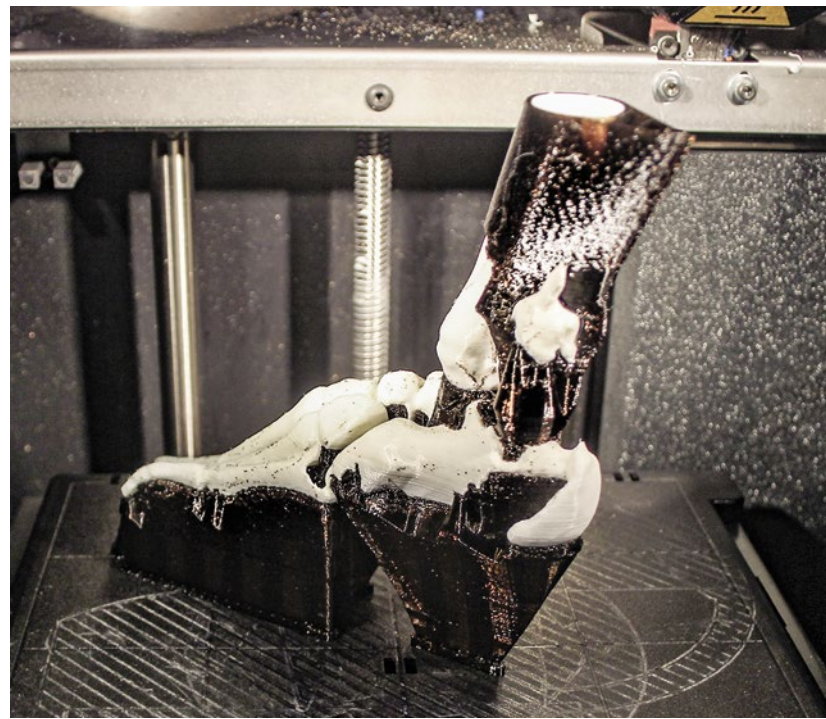
“It can get very, very awkward,” Lisse said. “It’s like trying to manipulate a Rubik’s Cube but you’re not allowed to look at the Rubik’s Cube — you’re only allowed to look at your hands on a video monitor to your left, while your hands are actually off to your right.”

Using AR, which displays graphics relative to the user’s field of view, the device would project the patient’s anatomy in the right place.

Lisse had been at the CEID, printing out pieces for the device, which is when CEID Fellow Dante Archangeli connected him with Brian Beitler (see page 49) and Frumberg.

A few years into the project, Lisse and his team have made an impression. The project won at the Radiology Healthcare Hackathon hosted by the Yale University Center for Biomedical Innovation and Technology, and they are currently talking with the Philips company about collaborating.





Left: A scan of the foot and leg of one of Frumberg's patients prior to surgical intervention.

Right: The 3D model in the process of printing. The models can take a few hours to print but costs only a few dollars to make.

for bones, but others have asked for models of neurons and various organs. It can take a few hours to print out the models but only about 15 minutes of prep time. And each model only costs a few dollars.

"I think there's no other technology that would be able to make the things that he wants made," Archangeli said.

Another CEID regular, Brian Beitler '19, a Yale medical student who recently graduated with a degree in mechanical engineering and molecular biophysical & biochemistry, has since taken over for Lisse in formatting the scans for the 3D printer. He has accompanied Frumberg in the operating room, and even there, the 3D models come in handy. "He'll often refer to the model in the operating room itself," he said. "Someone on the outskirts of the room will essentially hold up the model so he can look at it."

Indeed, Frumberg has become something of an advocate for the 3D models, talking them up with other orthopedists.

"Now that I've had all these cases, I've been telling my colleagues that it's available," he said. "I've gone to the OR in every single room to show everyone. 'Look at this! This is what we can do at Yale!' And everyone's like 'Really? Where? How?'"

Unorthodox cases require unorthodox methods — and a lot of thinking and studying. One of the ways Frumberg prepares for surgeries is by staring at images of the limbs he's working on. Not just in his office — crammed with bone models and frames — but everywhere. He'll hang X-rays in random places in his house as a way to keep his mind on the problem. But 2-dimensional images have limitations.

"For complicated deformity corrections it is challenging to plan the surgery," he said. "When I use external fixators, I must plan where to mount them and where to make bone cuts, which tendons and ligaments to reconstruct, which growth centers to modulate — it can get really complicated. And there are a lot of ifs."

For instance, he brings out a model of the bones of a man in his 30s born with a clubfoot, a condition in which the

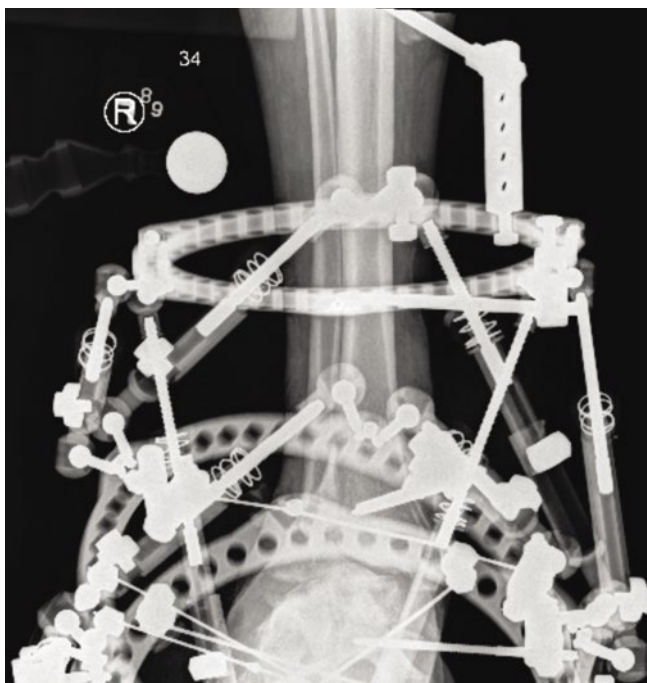
feet turn inward. He had lived with it until the pain and difficulty of walking became too much. A groundskeeper, he found it increasingly difficult to work. A look at the 2D images gave Frumberg an idea of what to do. The 3D model, though, significantly changed his approach.

“Among a few other things, I didn’t fully appreciate how much of his foot was skewed this way up in the air,” he said, pointing to the bone of the big toe, which heads skyward. “I can’t really picture from x-rays exactly what I’m looking at, or even

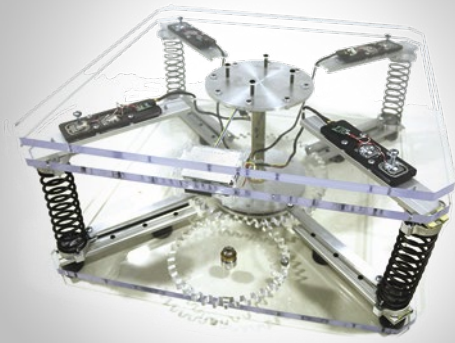
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While X-Rays and CT scans help Frumberg comprehend a patient’s problem, he says 3D printing is key for a more complete understanding.



X-rays courtesy of Dr. David Frumberg



The (Virtual) Reality of Concussions

Brian Beitler '18 got involved in printing bone models also through the CEID. Both as an undergraduate Mechanical Engineering major and currently as a medical student at Yale, Beitler’s been working at the CEID developing OnTrack Rehab, designed to help doctors better diagnose and rehabilitate patients with concussions.

The device, which grew out of Medical Device Design and Innovation (MENG/BENG 404), features a virtual reality headset with eye tracking and motion detection, a physical balance board with adjustable stability that tracks the center of gravity, and a cloud platform that collects and synthesizes the data. He developed it with fellow students Holly Zhou '18, Mrinal Kumar '18, and Pong Trairatvorakul '18.

To use it, a traumatic brain injury patient outfitted with a VR headset tries to balance on the platform, which measures the patient’s center of gravity. While balancing, the patient interacts with a virtual environment through the VR system. Physicians evaluate the patient’s recovery progress by analyzing the data collected by the balance board and assessing the patient’s own descriptions of symptoms.

This year, it won the \$15,000 Rothberg Catalyzer Prize at StartUp Yale, a three-day event sponsored in part by the Tsai Center for Innovative Thinking at Yale (CITY).

For all its success, though Beitler said there’s still work to be done on it.

“We’re improving the functionality of it and getting to a form where we’d be happy giving it to researchers or selling it to physicians,” he said.





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Dr. David Frumberg

looking at the CT scan. Some people are really good at studying 3D imaging and figuring out in their head where everything is. For me, though, 3D printing is the key.”

The models also go a long way in getting his patients on board with whatever approach Frumberg is planning. “It helps parents and the patients themselves understand what I’m proposing and why I am proposing it.”

He showed the printed bones to the groundskeeper with the clubfoot.

“He had no idea what I was talking about. He asked, ‘What do you mean I have abnormal contact between my fibula and my calcaneus?’ And then I showed him the model and he understood: ‘OK, I get it now.’”

It’s especially helpful with his younger patients. Some of them think the models are really cool and want to keep them. More importantly, it helps them see how a certain procedure may change their body appearance.

“There’s a lot of really cool outside-the-box thinking in my line of work. The CEID is full of engineers and smart minds with great ideas.”

› Dr. David Frumberg

“It’s hard enough to tell a kid that he or she has to wear a brace for scoliosis, but imagine how hard it is for a child to hear me say ‘I’m going to cut your foot open,’” he said. “With the model, though, I can show them, ‘This is your foot, this is what makes it different — I can correct this, and this is how I’ll do it, and this is what I think it would look like when I’m done’ — then it goes a lot easier.”

Archangeli said he’s heard similar experiences from other doctors who have come to the CEID for assistance.

“For them, they see this stuff all the time in and textbooks and in patients so for them, it’s just another case, but for

the patients, this is the first they’ve ever seen this, so definitely having something in front of them that’s physical is probably really helpful,” he said.

Frumberg grew up wanting to be an architect, and said he gravitated toward orthopedics partly because it’s closely related to engineering and construction. He plans to continue working with the CEID on future projects.

“There’s a lot of really cool outside-the-box thinking in my line of work. The CEID is full of engineers and smart minds with great ideas. I appreciate most how much room there is for growth and collaboration.” 🏆

Below: (l to r) Dante Archangeli '17, Dr. David Frumberg, Dr. Sean Lisse, and Brian Beitler '19.

