Advances in Additive Manufacturing of Materials: Current status and emerging opportunities

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In this last series of lectures of this NPTEL course, I will be discussing the challenges and opportunities in the field of additive manufacturing. As you have gone through several hours of previous lectures in this course, I have covered from design to different variants of additive manufacturing techniques to the. several scientific case studies as well as clinical case study to explain you that how additive manufacturing can play an important role for myriad of engineering applications including biomedical applications for healthcare. in this backdrop what I am going to do in this lecture as well as subsequent lectures, I will explain you how this field can further contribute to the manufacturing of patient specific implants to the kind of that artificial intelligence and machine learning models can be more useful in predicting. the 3D printing processes and so on. having said that this would be the topics to be covered in this lecture as well as few subsequent lectures, creative designs and manufacturing validation.

3D extrusion printing related challenges, exploiting artificial machine learning to accelerate AM process optimization, additive manufacturing of structurally complex implants for clinical applications, translation regulatory approval and certification. In this lecture, I will be largely focusing on the creative designs and manufacturing validation. Now, I will start with this particular one example of the healthcare related applications and where I will be showing you what is the clinical relevance of patient specific implants particularly in the context of hip disorder. Now, if you look at this is the normal knee joint.

is the normal knee joint. you can see this is the region here it is the synovial fluids and this is the white part in the top of the knee you can see this part tibia this is cartilage. this is like fresh cartilage on both the sides. you might have heard this osteoarthritis and this is a kind of a common disease. If not in your family, in the neighbor's family or in your extended family, there may be one patient who is suffering from osteoarthritis in countries like India and so on.

what happens in osteoarthritis, this cartilage is thinned down. leading to the closeness of these two opposing bone and then if there is a friction the patient will feel the pain and therefore this normal walking these two things will be rubbing like against each other and as a result patient will feel the pain. this is one such cases where the patient has to undergo knee surgery. if you know all the standard medical treatment by injecting the cartilage regenerating drugs or some other painkiller that will not remove and then the gap is very very less then the patient has to undergo knee surgery. and that is very much prevalent in many elderly patients.

Now, in other cases like you know that you have a normal bone structure. what you learn from before it is the cortical bone structure and this is a cancellous bone structure. Cortical bone is much stronger, solid, cancellous bone is much weaker and then they have a porous structure. Now, bone with osteoporosis, whenever patient has osteoporotic bone, that means the bone density decreases. Now if the bone density decreases bone becomes much more porous that means it is much weaker and any increasing in the porosity or the bone becomes deficient in bone mineral like calcium apatite.

while osteoarthritis is characterized by reduced cartilage thickness, osteoporosis essentially is characterized by low bone density and modulus. in case of the bone, there is a direct relationship between the bone modulus and then density. now the second important thing that I wanted to mention is that there is also gender specificity. gender specific anatomical morphological variations. You have a male patients and you have female patients.

Now, if you just look at this hip, now in that hip you have this in the natural in the natural hip I am talking about. So, you have the femur, this part is femur and then it goes to the acetabulum and you have a femoral head and there is an acetabulum. So, this color coding essentially shows the left hand part of the things is it all for male, this part is all for male and this part is all for female. So, what you see here in the case of male patients, male they have a large shaft, high CCD, CCD angle is Caput column diaphyseal angle, this is the angle that essentially defines that what is that angular orientation between that femur as well as the tacitabulum, so that angle. And then there is also high offset and another thing in case of the male patient is a long neck.

Female patients typically they have a short neck, there is a thin shaft and then low CCD angle that is again this particular angle you can see this is the particular angle, this angle I am talking about and there is a low offset and higher antiversion. So, females because of these anatomical morphological variations, females typically experience higher hip forces than males. So, these are the aspects which one needs to clearly consider while selecting the total hip replacement device like THR device, total hip joint replacement device. Now, this is the gender specific, then right hand side what I am going to explain that ethnicity specific variation. Ethnicity specific variation means so if you consider this large femur I wherever I have mentioned I for Indians from India and C is Caucasians population and in a particular what they have mentioned.

For example, if you consider that this particular angle E, E is the neck shaft angle, for Indians it is 131 degree and for Caucasian it is 124 degree. Then D is the canal width at the level of lesser trochanter. So, in Indians it is 34.87 canal width and this is in millimeter and in Caucasian it is 29.

4 millimeter. So, there is a difference and this difference is almost of the order of 10 to 15 percent difference. This neck diameter that C this is the C part neck diameter this part this part neck diameter in Indians is around 28.66 or Caucasian it is 33 millimeter. Femoral head diameter for Indians is 41.77 like 42 millimeter, Caucasian it is 46 millimeter, it is larger size.

And femoral head offset is also mentioned. So, it is either 10 percent or there is a difference between 10 to 15 percent variations. And these kind of variations in the dimensions essentially tells you that the implants which are good for the Caucasian population patients, those implants will not anatomically fit into the Indian patients. So, therefore, we need to consider gender. we need to consider ethnicity while selecting this kind of implants for biomedical applications.

So, this is more for example in the context of hip disorders. Similar variation exists whether it goes to knee or elbow joints or many other joints. So, essentially the physiological complexity or anatomical morphological variations exist in different bone structure, different joint structure of the Caucasian patients with Indian patients and among all other different ethnicity like if you go to African patients there again the variation will be very different. Therefore, we are interested in human shape modeling. There is a large variability among human beings, the reasons being due to age, height, sex, ethnicity that I have been mentioning over last 10 minutes or so and also weight.

So, every patient comes with a different weight. So, depending on what is the body weight, all these articulating joints and load-bearing joints, they will also experience different kind of stresses, right. So, that is very clear to everybody. Then comes on finding implant design that fits each patient well is indeed very challenging as bone morphology greatly varies among patients and besides ethnicity such as pathology also influence the bone morphology. So, I would like to draw your attention to these factors and I would also like to draw your attention such as pathology also influences the bone morphology.

And applications of statistical shape modeling like to study bone growth and bone remodeling, that is important. Improved prosthetic design, for example, that external devices prosthesis design. Then to understand how bone shapes influence biomechanics and movement, for example, particularly sports medicines. Then, disease detection by identifying changes in bone shape. So, for example, in the knee joint area that what is the disease detection.

Then, to study variations in bone shape across different populations. For example, that has been shown here. And then, designing implants. For example, this is the case for the knee implants. So, this is like you know different kind of So, different kind of applications of statistical shape modeling and in this statistical shape modeling what are the most important thing is that essentially it depends on the patient data.

So, larger the patient cohort you use in the process of statistical shape modeling. Better would be the predictability in terms of the design and in terms of the clinical outcomes that the implants when implants will be placed in human patients that it will have. So, how to generate the statistical shape modeling? So, we have the 3D scans like CT or MRI scans that you have seen that we use it is the first step in the 3D printing that I have mentioned to you before. Now, you do the segmentation of the 3D scans like CT and MRI scan. Then after segmentation, you import STL into SSM generating softwares like this is the SSM generating software, you get the inputs.

And then surface mesh generation for segmented bone model, then you can essentially generate the surface meshes, you can see that this bone actually you essentially generate that different mesh structures in the bone. Then comes mesh alignment and parametrization, then comes aligned meshes and then you do this SSM construction by combining all 3D bone models. You combine all different patients 3D models and then you do applications either for knee implants here, you know. tibia, fibula and all these parts of the implants that you can essentially experience. So, this is that overall kind of workflow for generating the statistical shape modeling approach.

This is some examples that you know where statistical shape modeling has been used in the past along with the references. Now, if you see that in one of this paper Dupraz essentially take considered 120 Caucassian patient CT scan and 112 Asian patient CT scan which are used for the total knee arthroplasty and they have technique that they have used is the convergent test and principal component analysis. One of the Indian study which is published in Journal of Orthopaedic Surgery, they have considered the 50 CT scan data of human patients. One is the proximal femoral medullary canal, this radiography, CT and calipers. These are like three different techniques that they have used for anatomic measurements.

In another population which is studied is Europeans, 72 patients, they have used the distal femur and medullary canal, again the convergence analysis using MATLAB and SSM in

Python. European patients 142 femur and 154 tibia, then they have done AMIRA software for semi-automatic segmentation. Now there is another study, they have used different populations, European, American, African, and Eastern Mediterranean. And they have essentially considered the hip joint, 80 unique populations, and they have used the radiography and CT scan. European populations, 137 patients, they have used the humerus , and they have used the materialist mimics, 3-matic, and principal component analysis.

Out of that what we have found out the 3-matic is the less explored platform which is used in this kind of statistical shape modeling approach. here more the size of patient cohort better is the predictability of SSM approach. for example, if you start with 50 patients and if you go to 250 patients, certainly that their statistical predictability would be much higher. That is the point I was trying to make here. Now, what you are going to do in the overview of statistical shape modeling for the designed implants.

So, this is a very busy slide. What you have seen, what you see here that I have told you earlier that there are three different parameters. One is the physiological load that the materials, second one is the subject parameters like human patient parameters, bone condition, body weight. Third one is the implant design. And what is the cases? This is kind of abnormal hip anatomy. I told you earlier that there is a difference in terms of ethnicity, age, sex.

These are the parameters which are to be included also here and there is a difference and then I have discussed before then these parameters also will influence physiological anatomical variation, anatomical morphological variation in the articulating joint system. Now all these particular parameters if you do then that will give rise to a range of biomechanical responses and so on and so forth. Then you start doing the statistical shape model right as I have explained using different computational platform. and which involves deep learning model here and there it will be essentially encoding the shape code. It will generate shape code, then non-linear mapping, stress code and stress discoding.

At this point, I would like to remind you that when we started discussing artificial intelligence and machine learning, one of the things that I have mentioned to you that all these deep learning, machine learning approaches are most useful when there is no direct empirical relationship between independent and dependent variables in a particular study outcomes, okay. Here you can directly see that all these you know the physiological loads will be different. You know the bone condition, body weight, ethnicity, age, sex will be different for different patients. But how to correlate all these factors with a specific implant design like how to choose that what would be the correct implant design that a clinician will use to treat abnormal hip anatomy for example. And in this kind of situation machine learning or deep learning essentially will play an important role and earlier also I have mentioned that deep learning is more useful only when number of data points or data sets are much larger.

And machine learning is typically the performance of machine learning improves with time and as this model is exposed to more amount of data. So, these are like some of the fundamentals you can recall from my earlier introductory lectures on the concepts of data science approaches. So, I bring in I would like to remind you here again that why we are bringing in deep learning models because all these different variations in that not only subject specific but also ethnicity, age, sex specific and physiological loads that will generate and if you consider those factors into account while designing the implants that will generate significant amount of biomechanical data. And those biomechanical data subsequently will be used in the deep learning model for shape encoding or stress decoding. And this stress strain predictions essentially as I have mentioned would be then used as an input to the minimization of stress shielding and maximization of the bone density, okay.

This will lead to optimized design of the implants. And this is the example, this is the total hip joint replacement device and in this device this is the femoral stem, this is the acetabulum. And here you can see this is that knee joint that this osteoarthritic knee, there is a 3D printed joint and these are conventional implant. So, these are sacrificing joint and 3D printed joint, 3D printed implants is more for the preserving joint. So, I have mentioned about the clinical relevances.

In this slide, I have particularly mentioned is DDH is the developmental dysplasia. So, what happens in the developmental dysplasia in the normal hip, you can see this is the head of femur. In the developmental dysplasia, you can see there is a hip socket here. and there is a head of the femur here. So, this is the case for that abnormal hip anatomy and these are the patients where standard implants cannot be used.

So, here again the statistical shape modeling plays an important role where standard implant sizes, standard implants do not work. for a patient. So, therefore, we need to essentially develop patient specific implants for the treatment of that specific clinical cases, right. So, remember all the total hip replacement devices or total knee joint replacement devices, they are available in a range of sizes depending on the patient's anatomy and clinicians are provided with the range of sizes. They select and choose based on that their MRI, CT scan data and they can see that what kind of implant will go for what kind of cases.

So, patient cases and then accordingly they can use it. But in case of the abnormal hip anatomy, in case of the larger hip disorders and so on where the standard sizes cannot be used then this is the patient specific implants is the best way and this actually has lead to the lead to the development of a new field in the medicine what we call personalized medicine. Personalized medicine, the word The word personalized medicine essentially means that the clinical treatments are essentially more personalized or this patient specific implants are used in this for example in this particular case. So, these are the two case studies that I can tell you. This is the case study is that open foam and mesh like structures in total knee arthroplasty.

TK stands for total knee arthroplasty to tackle stress shielding. You see that there is 2 type of materials that have been mentioned. One is a titanium 6% aluminum, 4% vanadium and one is a cobalt chrome. In both the cases, these particular researchers they have used that different kind of a lattice structures form, okay. These are the examples of lattice structures like open foam or mesh like structures here.

So, they use these as an input, these kind of structures as an input to electron beam melting. So, you remember that electron beam melting is one of the 3D printing processes and their high energy electron beam is used and one of the major advantage of electron beam melting is that it does not require post fabrication heat treatment procedure. So, that total manufacturing time can be reduced significantly. Then, in these particular cases what you see that is a stress shielding design graph. So, stress shielding design graph is that elastic modulus, normalized elastic modulus, normalized density.

And you can see that what is the Ti6Al4B tibial knee stem and what is the cobalt 26% chromium 6% molybdenum femoral knee components. So, in these two knee components you can compare and then thereafter you can essentially compare produce this cobalt chrome femoral component or Ti6Al4B TBL component. And this femoral component you can see very nice well-designed lattice structures can be printed. In the TBL component you can see this particular part you can introduce in the titanium 6 aluminum 4 vanadium part. In the TBL component you can essentially introduce this is the characteristic mesh structure.

So, tailoring relative density is essentially was pursued to reach lower modulus in these two particular cases. Another one is the triply periodic minimum surface approach, right. That TPMS essentially stands for triply periodic minimal surface. Then triplipyridic minimal surface approach it has a gradient porosity and you can see that this gradient porosity has this kind of a structures and this particular gradient structure porosity has these 3 different levels. And these particular cases proper replication of the natural acetabulum connection to that femoral stem is required and essentially these are used for stress-helding approaches.

Now this what is TPMA structure, what are the different lattice structures? This has been taught to you before and you can recall from those lectures that this is lattice structure was very much useful and if it is introduced in the femoral stem or acetabular socket that kind of region, then you do not need additional hydroxyapatite coating to improve the osseointegration. Because this lattice design structure itself can promote the osseointegration, can promote the bone growth in a very very clinically acceptable manner. So, you reduce one more step of hydroxyapatite coating in the entire process of the implant manufacturing. Now, these particular things, I will end this lecture by showing this. In this particular case, you can see that artificial machine learning from a group has allowed one of the Indian company to produce this kind of lattice structures not only for acetabular socket in THR, but also for spinal cages.

And they essentially mentioned natural bone anatomy implants, ANBA implants and natural bone anatomy implants are essentially are manufactured very routinely by using this designed lattice structure. So, thank you and I will come back to you in the next lecture with this particular challenges and opportunities on the additive manufacturing.