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Additive Manufacturing for the Production of a Low Cost Knee Prototype

Dr. R. Radharamanan, Mercer University

Dr. R. Radharamanan is currently working as Professor of Industrial Engineering and Director of Mercer Center for Innovation and Entrepreneurship (MCIE) at Mercer University in Macon, Georgia. He has forty three years of teaching, research, and consulting experiences. His previous administrative experiences include: President of International Society for Productivity Enhancement (ISPE), Acting Director of Industrial Engineering as well as Director of Advanced Manufacturing Center at Marquette University, and Research Director of CAM and Robotics Center at San Diego State University. His primary research and teaching interests are in the areas of manufacturing systems, additive manufacturing, rapid prototyping, robotics and automation, innovation and entrepreneurship, quality engineering, and product and process development. He has organized and chaired five international conferences, co-chaired two, and organized and chaired three regional conferences. He has received two teaching awards, several research and service awards in the United States and in Brazil. His present and past professional affiliations include ASEE, IIE, ASQ, SME, ASME, and ISPE.

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Abstract

This paper presents the design of a right knee joint prototype, from a 3D scanner, and then obtaining an output STLfile for the 3D printer. Two different types of plastic (ABS and PLA) and two models of 3D printer (MakerBot Replicator 2X and Flashforge Creator Pro) were used in achieving the goal of reproducing as accurate as possible and cheaper than the original knee prototype made of polyvinyl chloride (PVC) plastic by a German factory specialized in making scientific prototypes. Visual quality, production time, and weight of the printed parts were compared with reference to the machinery, material types, quantity, and printing parameters. Through this hands-on project, the students were trained in emerging manufacturing technologies such as 3D scanning, 3D printing and rapid prototyping, and additive manufacturing. Some of the difficulties encountered and the learning experience from the student team are also presented and discussed.

Introduction

One of the most distinguishing factors that the human has different from other species is the way of displacement. Because of human's gait, structure and position, the knee is one of the biggest and more essential joints in the human body, with a particular way of working, difficult to be analyzed by medical students. The loss of mobility in the human knee joint can happen because of injuries, deformities or illnesses due to swelling or advanced age. When this occurs, a replacement by prosthesis can be performed in order to improve the quality of life of the subject. Developing solid models of the knee is one of many steps involved in using engineering principles to solve medical problems within the human knee joint. Injuries to the knee joint are amongst the most common in sports activities and understanding the anatomy of the joint is fundamental to develop prosthesis better, more adapted to the natural human gait.

The overall objective of this project is to design and make low cost knee prototypesusing reverse engineering and additive manufacturing technologies within the ten weeks duration of Mercer Summer Engineering Experience (MeSEE) academic training program. A multidisciplinary team of three students (industrial, mechanical, and production) participated in this project. They used the NextEngine 3D scanner and obtainedoutput STL files for printing. They useddifferent types of plastics (ABS, PLA, and NinjaFlex) and two 3D printers, MakerBot Replicator2X and Flashforge Creator Pro) for achieving the goal of reproducing the knee jointswith accuracy and low cost compared to the original knee prototype made of polyvinyl chloride (PVC) plastic by a German factory that makes this kind of scientific prototypes. In addition, visual quality, production time, and weight of the printed parts are objects of comparison regarding the machinery, material types and quantity as well, and printing parameters used in the printing processes. The results obtained are presented and discussed with conclusions and recommendations for future work related to 3D scanning and rapid prototyping.

In addition, this project is designed to fully/partially satisfy some of the ABET's student learning outcomes that include:

b. An ability to design and conduct experiments, as well as to analyze and interpret data;
c. An ability to design a system, component, or process to meet desired needs within realistic constraints such as safety, manufacturability, and sustainability;
d. An ability to function on multidisciplinary teams;
g. An ability to communicate effectively (orally and written);
k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Background

Additive Manufacturing

The rapid prototype process allows the fast creation of products' prototypes eliminating considerable amounts of resources and time spent on the project when compared to traditional development design methods[1]. In Additive Manufacturing (AM),a model initially generated using a three-dimensional Computer Aided Design (3D CAD) system, can be fabricated directly without the need for process planning. Although this is not in reality as simple as it first sounds, AM technology certainly significantly simplifies the process of producing complex 3D objects directly from CAD data. This technology came about as a result of developments in a variety of different technology sectors. The seven main manufacturing steps of generation of an additive manufacturing process[2] are described below:

1. Every AM process starts using any professional CAD solid model, with the obligation that the output must be a 3D solid or surface drawing. This project used reverse engineering equipment (laser scanning).
2. AM machines accept the STL file format, which every CAD system can output such a file format. This file describes the external closed surfaces of the original CAD model and forms the basis for calculation of the slices.
3. Sometimes, when the STL file is applied in the AM machine it may need some general manipulation of the file so that it is the correct size, position, and orientation for building.
4. AM machines can work with different materials, which have different settings that would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc. To deal with it, appropriate settings of AM machine parameters such as extruder temperature, platform temperature, print speed, infill percentage, and layer thickness are necessary depending on material used to build the chosen part.
5. Building the part is mainly an automated process and the machine can largely carry on without supervision. So, it requires only a superficial monitoring during the build process.
6. Once the AM machine has completed the build, the parts must be removed.One must do this action carefully to avoid the destruction of the piece that was made.
7. After finishing all the steps above, the parts may require additional treatment before they are acceptable for use. For example, they may require priming and painting to give an acceptable surface texture and finish.

Knee Joint

The knee joint is the largest joint in the human body[3], which consists of four bones and many ligaments and muscles. It is the connection between the thigh and leg. Three bones come together at the knee joint, and the knee is surrounded by four major ligaments. The knee joint surface is covered by a layer of smooth cartilage, and shock-absorbing meniscus[4]. The knee anatomy is shown in Figure 1.

Figure 1: Knee anatomy

3D Scanner (Reverse Engineering)

Using a 3D scanner to obtain solid models from an existing product in order to create a new one is a process classified as a reverse engineering method. Abella et al[5] described reverse engineering as "the basic concept of producing a part based on an original or physical model without the use of an engineering drawing". Based on this concept, the reverse engineering was applied in this project through a 3D scanner. A 3D scanner is a device for creating high resolution, accurate digital 3D models from real-world objects. The scanner is built around stereo-vision and structured light projection in order to generate 3D. The scanner is controlled by 3D scanning software that runs on a computer. A 3D scanner is also capable of capturing the color map of an object. By merging the color map onto the 3D model, a color 3D digital model is created.

Types of 3D Scanner

According to Vinesh[6], 3D scanners are based on two principles: contact scanners and non-contact scanners. As their own names tell, the first type is characterized by scanning the pieces through direct contact with them. These scanners have a better precision than the non-contact type, normally with a tolerance range of +0.01 to 0.02mm. However, they have some drawbacks. For example, some specific types of materials cannot be scanned with good accuracy or it is at least very hard to obtain a good scan.

The second type, non-contact scanner, was utilized in this research. This scanning method does not occur by touching the parts to be scanned, but by lasers that identify the shapes and surfaces of the part in the programmed range of scan. Its precision does not have a great tolerance range as contact scanners. It is within ±0.025 to 0.2 mm[6]. However, the researches towards laser development and optical technology continue to grow, the accuracy of the commercially available non-contact scanning devices is beginning to improve[7]. Furthermore, another positive point is that it is the best way to scan some objects (i.e. artifacts) that needs to be scanned avoiding the maximum of contact possible due to high fragility[8].

NextEngine 3D Laser Scanner

The NextEngine HD 3D laser scanner[9] (Fig. 2) is the scanning machine used in this project to generate some printable files of components of the prototype to be produced. This scanner is classified as a non-contact scanner and it is also one of the best micro scanners commercially available. Its accuracy can reach up to 0.13 mm, and its multi-lasers can capture objects in full color. An auto drive and a part gripper are features of this scanner that allow a good fixation of the component to be scanned.

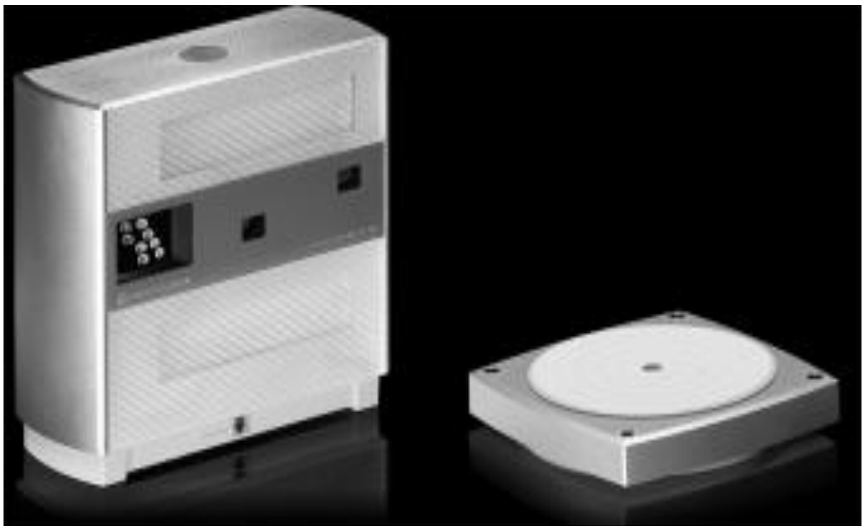

Figure 2: NextEngine 3D scanner[9]

This machine works with triangulation principle (Fig. 3), which is the principle that enables 3D scanning technologies to determine the dimensions and geometry of real-world objects (LMI Technologies[10]). It can be obtained through of the distance and angles between images and the projected laser creates a base of the triangle. The angle of the projected light returning to the image from the surface completes a triangle where a 3D coordinate can be calculated. By applying this principle of solving triangles repetitively, a 3D representation of an object is created (Vision Doctor - Solutions for Industrial Machine Visions, n.d.)[11].

The software ScanStudio assists in the entire procedure, generating a point mesh for each created image. This software is essential for the machine operation, since it allows the user to select and make adjustments before and after the scanning process. For example, determining the number of divisions per round can be adjusted before starting the scanning cycle, and filling holes is a tool to be used right after when the scanning process is over.

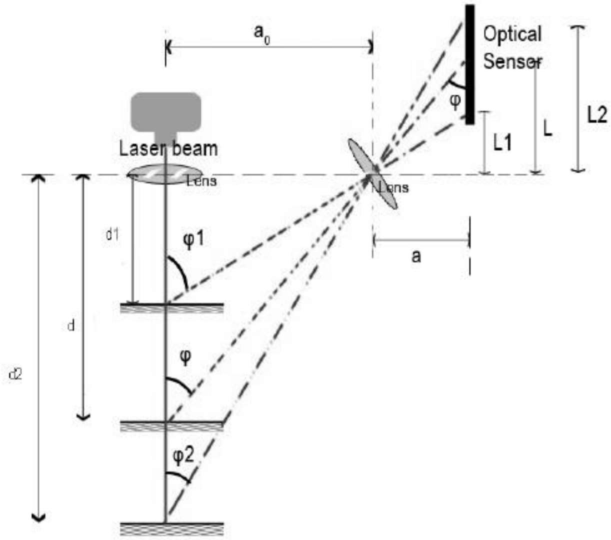

Figure 3: Triangulation principle

3D Printing

The invention of 3D printing can be traced back to 1976, when the inkjet printer was created. Since then, a variety of applications of 3D printing technology have been created across different segments and industries. 3D printers replicate not just themselves but everyday objects as well. The first 3-D printers were developed in the nineteen-eighties, by an American engineer named Charles Hull. The "ink" was an acrylic liquid that turned solid when exposed to ultraviolet light, typically from a laser beam. Makers of cars and airplanes could design complicated parts on a computer and then print out prototypes for manufacture; now they often print the part, too. Professional 3D printers can be used in 3D print shops, the copy shops of the future, and in social manufacturing services, anyone can offer the capacity of his or her 3D printer, or distribute templates to print utility or design objects. This project was executed with 2 models of 3D printers (MakerBot Replicator 2X and Flashforge Creator Pro). Shortly, 3D printing provokes human minds to think creatively. It inspires to seek new ways to old solutions and improve how existing things work. Creativity should not have any boundaries, so that every individual can experiment and become an innovator.

MakerBot Replicator 2X[12]

This is a 3D Printer that works only with ABS filaments, making snaps, living hinges, and threaded objects. In addition, this machine can control heating and cooling better with a superflat heated aluminum build plate, also helps prevent uneven cooling, shrinking and cracking. MakerBot Replicator 2X[12] (Fig. 4) uses the software "MakerBot MakerWare" and it accepts input files as STL, OBJ or THING. A great advantage of this machine is about its small size and weight. The one that was used in this project has a size of 19.1" x 16.5" x 14.7" and weight of 25.4 lbs.

Figure 4: MakerBot Replicator 2X

Fleshforge Creator Pro[13]

This is a 3D Printer that works both with ABS or PLA filaments. Flashforge Creator Pro (Fig. 5) has a dual extruder that has no limits. In stock form, Flashforge Creator Pro prints ABS, PLA, nylon, dissolvable filament, and even composite materials such as wood and metal. The extruders can be modified to print flexible and other composite materials that may come out in the future. The Flashforge Creator Pro[13] uses the software "MakerBot MakerWare" as well and it accepts input files as STL, OBJ or THING. A great advantage of this machine is also about its small size and weight. The one that was used in this project is of 18.7" x 15" x 13.1" size and weighs 23 lbs.

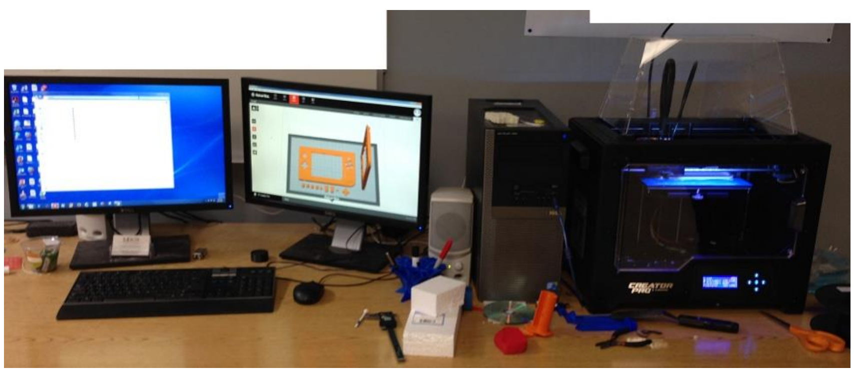

Figure 5: Flashforge Creator Pro

Methods and Materials

Creating the Project

A knee joint prototype, 3B Scientific A82/1 Deluxe Functional Knee Joint Model, was purchased from a website in order to be a basis to start the project. It is the reference measurements for the CAD drawings as well as the model used in the reverse engineering (3D scanning) and assembly process. A picture of the full object is shown in Figure 6 with each component indicated separately[14]:

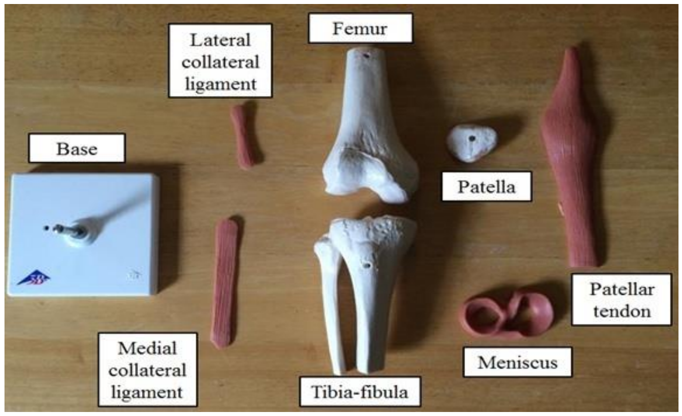

Figure 6: 3B Scientific A82/1 knee joint

Computer Aided Design (CAD)

The patellar tendon, lateral collateral ligament, and medial collateral ligament were designed using the software Pro-Engineer (student version), best known as Creo^{TR}. From a knee prototype bought on the market, a digital caliper (Vernier Caliper 150mm/6inch Micrometer) was utilized for getting its measurements.The patellar tendon required a central attention. Due to its complex design, tools such as sweep blend, sweep, and extruder were used for its bumpy form. Also, for the purpose to obtain a union with the patella, the tool revolve was used for removing material from patellar tendon. Furthermore, basic tools such as, line, circle, and mirror were utilized for getting the lateral and medial collateral ligament. Finally, the round tool was selected for a better finishing, removing their sharp edges.

Additionally, the base for the knee prototype (Fig. 7) was projected with some modifications. The team members' names and the University logo were customized in order to have a better identification. Then, the drawings were transformed in a binary Stereolithography (STL) file and exported to MakerBot software[14].

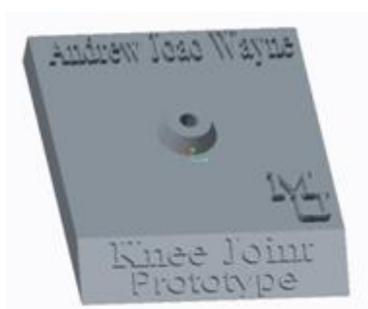

Figure 7: Final base designed by Creo^{TR}

3D Scanner (Reverse Engineering)

The Tibia-Fibula, Patella, Femur, and Meniscus were scanned using the NextEngine 3D scanner (Fig. 8). The already mentioned part gripper of the scannerwas the base to put and hold these parts during the scanning process.

Figure 8: Scanning procedure

After scanning the part as many times as necessary the trim command was used to remove undesirable features shown at the scanned model. Then, the align tool was used in the following way: three reference points between each pair of scanned models - aligning and combining them into one until getting the final model (Fig. 9). After using the trim and align commands, the buff and remesh tools were utilized respectively. The buff command was utilized for getting a better finishing, thus removing imperfect shapes and/or spots on the model surface. In sequence, the remesh tool was used for the purpose to fill all holes and/or open surfaces that were generated during the scanning process. Finally, once a completely solid model was created the next step was to save the drawing in a supported 3D printing format. In that case, the format used was the Stereolithography (STL) file. By then, the part was ready to be printed[14].

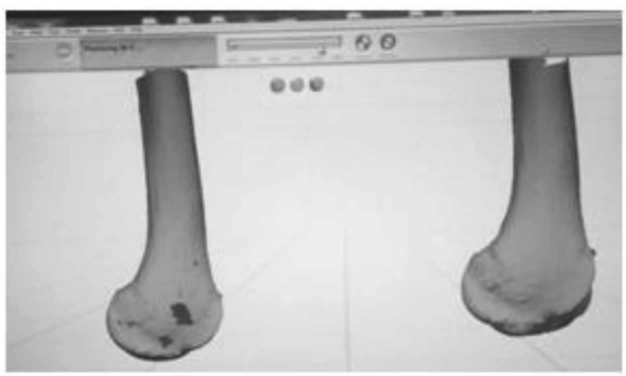

Figure 9: Align command processing

Project Execution

After the femur, tibia-fibula, patella, patellar tendon, meniscus, medial and lateral collateral ligament were designed, they were manufactured using two 3D printers, the MakerBot Replicator 2X and the Flashforge Creator Pro. Basically, their operations are pretty similar and have the same purpose.First of all, using the MakerBot software, completed STL files were adjusted. Positions, angles, and rotations were the main tools for their adjustment; also, a lay flat was required for a better printing, avoiding troubles during the process. Settings were adjusted according to the kind of material; raft and support were selected for a better fixation in the platform. Finally, an extruder was selected. The adjustments made to the femur model are shown in Figure 10[14].

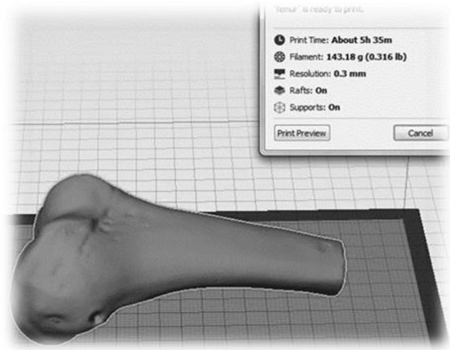

Figure 10: Adjusting the femur model

Once adjusted, the filament plastics were fitted at the nozzles' extrusion. A load extrude command was selected after this process, and the sound alert sounded when it was completed. Returning to the software, those STL files were reviewed and printed using the print button. This procedure was repeated for each piece printed.

Plastics

Three types of plastics were used for printing the objects: the Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), and NinjaFlex filament. As previously mentioned, each one of them has its own print settings, and this factor created the necessity to do some research to find proper adjustments for print settings.The PLA and ABS plastics were used for manufacturing the bone parts (femur, tibia-fibula, and patella) and the prototype base. The PLA parts were printed using the Flashforge Creator Pro, and ABS parts were printed using the MakerBot Replicator 2X, due to technical recommendations.For the purpose of getting flexible parts, the NinjaFlex was used to achieve the ligament models' flexibility. The manufactured parts by this type of plastic were the patellar tendon, the meniscus, the lateral collateral ligament, and the medial collateral ligament. About the others parts, the ABS and PLA models were printed using two brands: for printing the test pieces and the patella, MakerBot white filament was used; for the prototype base, MakerBot yellow filament was chosen; and for the skin color parts, the filament brand BuMat Elite was used (the parts destined for the final assemblies).

Final Assembly

The two final assemblies (PLA and ABS) were composed each by the femur, tibia-fibula, patella, patellar tendon, lateral collateral ligament, medial collateral ligament, meniscus, and knee prototype base. Both assemblies were made in the same way as described in the following steps. The first step was to obtain a better surface finish on non-flexible parts which had some supports' fragments from the printing process. An electric sander was utilized in the polishing procedure.The parts were assembled using super glue (Loctite) and it was based on the original assembly of the 3B Scientific A82/1 Deluxe Functional Knee Joint Model (Fig. 6). The first step for getting the final assembly was to gather the tibia-fibula and meniscus together. Thus, allowing a better mobility for the femur, reaching the objective of getting a real knee movement.Secondly, the base part of the tibia-fibula was glutted in the middle of the customized base, which has a support designate to fix the fibula standing. Meanwhile, the patella was glutted in a tendon cavity, just like the knee joint model was manufactured. Finally, the patellar tendon, lateral collateral ligament, and medial collateral ligament were assembled.

Student Learning Outcomes and Assessment

Four student teams (three students in each team), a total of twelve students, participated in four different MeSEE lab oriented hands-on projects. At the end of the academic training, each student team submitted a written report and a poster to the academic advisor. They made oral and poster presentations to the peers and faculty members. Each team was evaluated by other 3 teams (9 students), and two faculty members. The student teams were evaluated by their peers and the faculty members using the questionnaire in Table 1 and the Likert scale.

Table 1: MeSEE project evaluation questionnaire

1. To what extent did the team demonstrate the ability to design and conduct experiments, as well as to analyze and interpret data? - (b)
2. To what extent did the team demonstrate ability to design a system, component, or process to meet desired needs within realistic constraints such as safety, manufacturability, and sustainability? - (c)
3. To what extent the team was able to function on multidisciplinary teams? - (d)
4. To what extent did the team use the techniques, skills, and modern engineering tools necessary for engineering practice in their MeSEE project? - (k)
5. To what extent did the team demonstrate breadth and depth in developing their MeSEE Project (product design, manufacturing, and prototyping)? - (k)
6. Please rate the overall oral presentation of the MeSEE project on the students' ability to communicate the design and manufacturing aspects of the solution to the complex design/manufacturing problems to a specialized audience (technical personnel in their field). - (g)
7. Please rate the overall written presentation of MeSEE project on the students' ability to communicate the design and manufacturing aspects of the solution to the complex design/manufacturing problems to a specialized audience (technical personnel in their field). - (g)
8. Please rate the overall presentation of the MeSEE project on the students’ ability to communicate with design/manufacturing oriented mindset in solving complex engineering/technical problem. - (g)

   For items 1 through 8 Likert scale used (1 – 5: 1 being the lowest and 5 being the highest):

Low	= 1
Fair	= 2
Good	= 3
Very Good	= 4
Excellent	= 5

9. From your perspective, how productive was the team overall (in completing their MeSEE Project with design/manufacturing oriented mindset in solving complex engineering/technical problem)?
    1. Accomplished minimum of the MeSEE project’s requirements
    2. Accomplished some but not all of the MeSEE project’s requirements
    3. Met the MeSEE project’s requirements but could have done much better
    4. Efficiently accomplished goals that they set for themselves
    5. Went way beyond what they had to do exceeding even their own goals

Results and Discussions

CAD Drawings

The drawings obtained from CAD software were adjusted to better apply to the project, thereby being different than the original parts as a consequence of applied customization and some existent constraints.The customization can be verified in the base of the knee prototype where the team members' names and the University logowere inserted. As a consequence, the length of the base needed to be increased in order to accommodate the modifications. Regarding the constraints, the first limitation to generate the drawings from CAD software was the level of complexity of some parts. These parts (the patellar tendon, the lateral collateral ligament, and the medial collateral ligament), flexible and difficult to hold and scan using the NextEngine scanner, require a high level of expertise in CAD software to design and obtain more accurate results regarding shapes and surfaces. Additional training is needed in CAD for the students to successfully design these parts. Only 2/3 of the students trained (8 out of 12) were able to successfully design and print these parts. The other constraint is the maximum printable area of the printing platform that can limit the sizes of the parts to be printed. Due to this constraint, the patellar tendon needed to be reduced 40mm on its total length. Even though all those modifications were made, one point that needs to be addressed is that all the models created from CAD software maintained the most important shapes and sizes needed for creating the final assembly.

3D Scanned Drawings

Among all the available resources for creating solid models to be printed, the NextEngine 3D Scanner was the most accurate and easiest to use. Also, it was the fastest tool too. In comparison, drawings made from a CAD software, simple to complex parts, took 1 hour to 4 hours (the time spent to get manually the necessary measurements of the parts is counted), while a complete scanning process of simple to complex parts took 30 minutes to 2 hours until the final solid model was generated. Another point to be considered is that the complexity of the scanned parts is much higher than the solid models generated by the CAD software. However, it had a drawback. The most flexible parts could not be scanned because it was not possible to fit and hold those parts into the scanner plate. But besides that problem no other issues were identified.

3D Printers

In the process of printing all the necessary components for the assemblies, different results were achieved regarding printing time, part weight, and finishquality. Those variations occurred because combinations of different print settings with different materials were tested. Table 2 shows the different materials used and their proper print settings that impact the printing time and weight values. As an example, the infill configuration used for the base in PLA had a considerable variation in the part weight compared with the same part printed in ABS. In addition, the type of the material's brand used affected the outcomes as well. As an example, the parts printed with BuMat filament (both ABS and PLA) showed to be heavier than the parts printed with MakerBot filament. Furthermore, using that same material, the surface smoothness was not good at the bottom of the parts (where the support is created) and some layers did not adhere properly with their previous layers during the printing process, occasioning some fissures in the finished part. In a different way, the NinjaFlex filament worked as expected, resulting in good quality parts and presenting just some settings issues.Analyzing the parts separately, the prototype base was the only component that showed similar problems while printing in both PLA and ABS materials. As mentioned previously, for the prototype base MakerBot yellow filament was used, but the printing outcomes were not as expected. For unknown reasons, the upper surface finish was never satisfactory, always showing very noticeable imperfections, such as missing layers. The best, but still not good, two outcomes of this part was destined to the final assemblies. Regarding the printers, no considerable differences were encountered comparing the printing results of both machines. Support material removal and cleaning time on average for the larger parts such as base, femur, and tibia-fibula was between 20 to 30 min where as for the smaller parts it was between 10 to 15 minutes.

Table 2: Results of 3D printed parts[14]

Part Name	Printer Settings					Printing Time	Weight (g)	Weight Decrease (PLA Compared to ABS)
	Extruder Temp. (ºC)	Platform Temp. (ºC)	Print Speed (mm/s)	Infill (%)	Layer Height (mm)			
Tibia-fibula, ABS	230	110	90	50	0.3	5h 26m	94.29	-
Tibia-fibula, PLA	220	60	90	50	0.3	5h 25m	76.17	19.22%
Femur, ABS	230	110	90	50	0.3	5h 33m	102.87	-
Femur, PLA	220	60	90	50	0.3	5h 35m	84.75	17.61%
Patella, ABS	230	110	90	50	0.3	0h 32m	7.12	-
Patella, PLA	220	60	90	50	0.3	0h 30m	6.96	2.25%
Meniscus, NinjaFlex	240	40	15	50	0.3	2h 9m	10.40	N/A
Patellar tendon, NinjaFlex	240	40	15	50	0.3	5h 12m	19.21	N/A
LCL, NinjaFlex	240	40	15	50	0.3	0h 35m	1.62	N/A
MCL, NinjaFlex	240	40	15	50	0.3	1h 44m	4.61	N/A
Base, ABS	230	110	90	50	0.15	8h 17m	89.49	-
Base, PLA	220	60	90	25	0.15	7h 4m	44.64	50.12%

Assembly

The creation of the final assembly did not present any major issue. As commented before, the original prototype was the basis for assembling the new knee joint prototype, being an excellent support to avoid errors while joining the components. It was an easy process that required approximately just 30 minutes to finish each assembly. The final assemblies (ABS and PLA) are shown in Figure 11[14].

Cost

The student team made two prototypes one in ABS and one in PLA. The cost of producing one unit of knee joint prototype considering material cost, machine cost, and the labor cost is summarized Table 3.

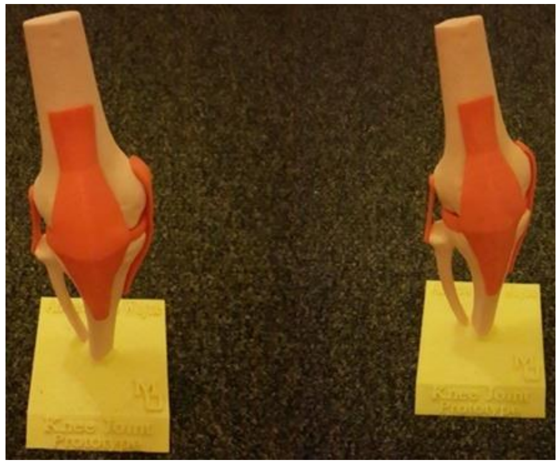

Figure 11: Final assemblies: ABS (left) / PLA (right)

Table 3: Cost of producing one knee joint prototype

Material cost: 500 g including raft and support material @ $ 40.00/kg	$ 20.00
Machine cost: Printing time approximately 30 hours @ $ 0.50/hour	$ 15.00
Labor Cost: 7.5 hours @ $10/hour [Machine setup (2 hours) + Print supervision time (2 hours) + Removing raft/support material & cleaning (3 hours) + Assembly time (0.5 hour)]	$ 75.00
Approximate total cost for the Lab/prototype	**$ 110.00**

Student Learning Outcomes and Assessment

The following ABET's student learning outcomes were fully/partially achieved by the student team through this project:

b. An ability to design and conduct experiments, as well as to analyze and interpret data: Knee joint parts were scanned, redesigned and 3D printed using different materials and two 3D printers; measurements were made on 3D printed parts and the results were analyzed, compared, and interpreted;
c. An ability to design a system, component, or process to meet desired needs within realistic constraints such as safety, manufacturability, and sustainability: Knee joint parts were designed, 3D printed, assembled, and tested;
d. An ability to function on multidisciplinary teams: The student team was multidisciplinary (industrial, mechanical, and production) and they were able to work together in the lab environment and also achieve the overall objective of this project within the 10 weeks period;
g. An ability to communicate effectively (orally and written): The student team submitted the written report and the poster; they made the oral and poster presentation at the end of the academic training period;
k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice: The student team used the techniques, skills, and engineering tools they learnt and practiced to successfully complete this hands-on project within the academic training period of 10 weeks.

The four teams' assessment results are presented in Table 4. Figure 12 compare the results of the four teams using the 5-level Likert scale in all five ABET's student learning outcomes. Assessment made on this project by student peers and the faculty members indicated that the student team of this project (team 1) fulfilled their initial goals and objectives of producing low cost knee prototypes using reverse engineering and additive manufacturing technologies and this project was rated as one of the best projects done by the student teams under the Academic Training program with an average score greater than 4 (4.2) in the 5-level Likert scale in all five ABET's student learning outcomes (b, c, d, g, and k) considered for this project. One of the projects was rated with an average score less than 4.0 (3.6). The overall mean and standard deviation of the evaluations respectively are 4.1 and 0.36.

Table 4: Student teams' assessment results

Question	ABET's Student Learning Outcome	Evaluation by 9 Students and 2 Faculty Members							
		Team 1*		Team 2		Team 3		Team 4	
		Total (55)	Average (5)	Total (55)	Average (5)	Total (55)	Average (5)	Total (55)	Average (5)
1	b	47	4.3	48	4.4	47	4.3	40	3.6
2	c	50	4.5	51	4.6	50	4.5	44	4.0
3	d	49	4.5	44	4.0	45	4.1	37	3.4
4	k	44	4.0	46	4.2	44	4.0	38	3.5
5	k	46	4.2	49	4.5	46	4.2	35	3.2
6	g	45	4.1	48	4.4	42	3.8	41	3.7
7	g	43	3.9	45	4.1	43	3.9	36	3.3
8	g	45	4.1	49	4.5	45	4.1	43	3.9
9		46	4.2	46	4.2	46	4.2	38	3.5
	Sum	415	37.8	426	38.9	408	37.1	352	32.1
	Average	4.2	4.2	4.3	4.3	4.1	4.1	3.6	3.6

* Student team of this project

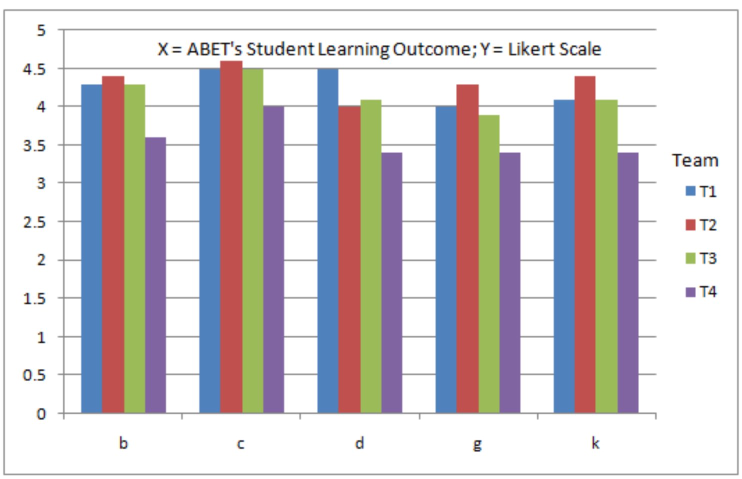

Fig 12: MeSEE teams - ABET's student learning outcome on Likert scale

Conclusions and Recommendations

After all the steps taken to perform this project, some conclusions and recommendations can be drawn regarding the set of variables involved in an Additive Manufacturing process.First, the Reverse Engineering method was essential in achieving solid models of the most complex parts.

However, as some parts could not be scanned, the CAD software used (Creo™) was a very important additional tool. Then, different tools were combined while creating solid models to be printed; this was the best approach to complete the project. Second, even though two 3D printers were used, all the printed parts could be obtained just using the Flashforge Creator Pro which accepts many different types of plastic filaments. However, printing components simultaneously using two printers revealed to be a great increase in time performance. As the last point, regarding the materials used, MakerBot filaments would be chosen for future projects instead of BuMat filaments for reasons already discussed in this paper. Also, for better aesthetic results, PLA filaments would be selected as the main material for solid non-flexible parts. But, due to mechanical properties ABS plastic would have preference for more applicable parts (i.e., prosthesis). Overall, this project was successful and had achieved the goal of creating as accurate as possible a low cost knee joint prototype using additive manufacturing concepts and tools.

Challenges and Lessons Learned

Initially, the student team needs to be trained in CAD, 3D Scanning, and 3D printing using the available lab facilities. They need to learn about human anatomy, knee joint, and its functions. Some problems arose during the process, like delay in the arrival of some materials, problems with the 3D printer, assembly errors, sizing issues, software incompatibility, among others. These problems were solved referring to resources such as internet, reference manuals, and books as well as watching online tutorials and reading related articles. Focus and dedication of the student team was the key to successfully complete the project and assemble the knee prototypes.

Recommendations

From the outcome of this project evaluation, it is noted that the students need additional training in CAD and 3D scanning. They are encouraged to read related materials (reference manuals, books, articles, internet resources, etc.) and watch online tutorials and YouTube videos on CAD, 3D scanning, AM processes, and related topics.

As recommendation for students who like to work on hands-on manufacturing and rapid prototyping projects the following suggestions are made: Take proper training in CAD and use of 3D printers; conduct background research on CAD, 3D scanning, and rapid prototyping technologies; read carefully the related materials (reference manuals, books, articles, internet resources, etc.) and watch online tutorials; and take proper safety measures while using lab machines and equipment.

Creation of a low cost Rapid Prototyping Lab requires a minimum of $10,000 to start with [a high quality 3D scanner ($ 4,000) + 2 desktop computers ($ 2,000) + 2 3D printers ($ 2,000) + other equipments and supplies ($ 2,000)]. Several open source materials from the websites can be used free of charge for enhancing the lab activities. With this facility, several hands-on student projects similar to the one discussed in this paper can be planned and executed during every academic year.

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