Rapid Prototyping for Rehabilitation Purposes

Issam S. Jalham,[*1] Ziad M. Hawamdeh,[2] and Bassam A. Ammari[3]*

Abstract

Integration of technologies such as medical imaging, types of software such as pro engineer, and modern fabrication processes such as RP is important in the medical field. It enabled to solve some medical problems specially those considering bio-parts replacement and prosthesis. This study presents a methodology that helped replace the wearied hip joint by a bio-product with the same dimensions, size, and shape as the patient's hip joint using CAD system and a Rapid Prototyping technique.

Keywords: Rehabilitation, Fabrication, Prosthesis, Rapid prototyping, Femur, Hip.

(J Med J 2008; Vol. 42 (2): 73-81)

Received	Accepted
October 1, 2007	January 2, 2008

Introduction

Recently, the design and development of bio-parts materials is one of the most challenging problems to prostheses technology. As shown in Figure (1), the hip consists of a ball and a socket. Humans suffer from the various hip joint problems namely osteolysis, osteoarthritis, avascular necrosis, rheumatoid arthritis, fracture neck of femur, other inflammatory arthritis, developmental dysplasia, Paget's disease, arthrodesis (fusion) takedown, tumour, road accident, injuries etc. [1] These diseases lead to severe disability. As a result, people are focused to seek surgical options involving bone replacement in order to get rid of their suffering and keep their joints mobile. Sometimes the problem of pain is severe and the condition of the hip joint is very bad, leading to a need for artificial hip joint replacement. Several variations on design, materials, and techniques of this joint replacement are still being experimented with since 1840. [1]

Total Hip Arthroplasty (THA) Technique is the technique where acetabulum cup and femoral head both can be replaced. This led to the need to search for some materials, which could be utilized to resurface or even replace the hip. [2] Surgeries were undertaken for hip joint replacement in orthopedics by Charnley's using low-friction UHMWPE-on-metal design. This design suffered from the problems of high wear rates and low useful life of joints. Techniques used before 1960s gave no more predictable results. After 1960s, the THA technique gave excellent results. This modern technique was the actual invention of the Total Hip Replacement. Metal-on- Metal (MOM) and Ceramic-on-Ceramic (COC) joints were developed to improve wear rates and joint strength. Today, however, MOM and COC joints have received increased attention due to their potential in reducing the wear rate of arthroplasties, especially for young active patients. Nevertheless, the proliferation of current MOM and COC alternative bearing technologies for hip replacement has been limited

1- Professor, Deputy Dean of the faculty of Graduate Studies for Scientific Faculties Affairs, University of Jordan, Amman, Jordan.
2- Assistant Professor, vice Dean, Faculty of Rehabilitation Sciences, University of Jordan, Amman, Jordan.
3- Professor of Urology, Dean, Faculty of Rehabilitation Sciences, University of Jordan, Amman, Jordan.
*** Correspondence should be addressed to:**
Issam S. Jalham
E- mail: jalham@ju.edu.jo

due, in part, to stringent manufacturing requirements, contributing substantially to lead to higher cost relative to designs incorporating UHMWPE. The survivorship of MOM and COC designs is especially sensitive to the implantation technique, and thus these alternatives are perceived as “less forgiving” than UHMWPE bearings for an orthopedic surgeon who may perform only a few THA procedures per year. Widespread clinical adoption of MOM and COC has also been limited due to additional unique risks related to long-term toxicity (in MOM bearings) and implant fracture (in COC bearings). It is worth mentioning that all these designs are called custom designs (Figure 2) and used as standard designs for all patients. Sometimes you need a special design which may be expensive to design and manufacture. In this work, a methodology and fabrication technique used to produce typical hip joint with the same dimensions, shape, and size to replace the diseased one, using new technologies, is presented. The new techniques can be used to copy any body part and are called prototyping techniques. Prototyping is the process of building a model of a system. In terms of an information system, prototypes are employed to help system designers build an information system that is intuitive and easy to manipulate for end users. One of the most important types of prototyping is Rapid Prototyping (RP) which can be defined as a group of techniques used to quickly fabricate a scale model of a part or assembly using three-dimensional Computer-Aided Design (CAD) data. Rapid Prototyping has also been referred to as solid free-form manufacturing; computer automated manufacturing, and layered manufacturing. It is widely used in the automotive, aerospace, medical, and consumer products industries. The RP techniques that are currently commercially available are Stereolithography (SLA), Selective Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Solid Ground Curing (SGC), and 3D ink-jet printing techniques. [3] The last technique was the one used in this investigation.

These "three-dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two-dimensional pictures. Such models have numerous uses. They make excellent visual aids for communicating ideas with co-workers or customers. In addition, prototypes can be used for design testing.

This work aims at combining the techniques used in medicine (such as Computed Tomography (CT) scanning) and those used in engineering (such as prototyping techniques) through the use of information technology tools to solve the problems of the body part replacement by creating an identical part similar to that of the human. Identical means the same shape and size.

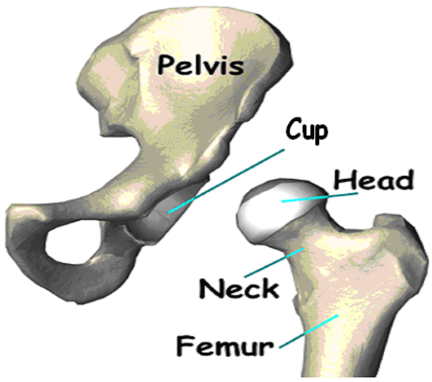


Figure (1): The anatomy of the Hip.

Figure (2): The custom Hip design.

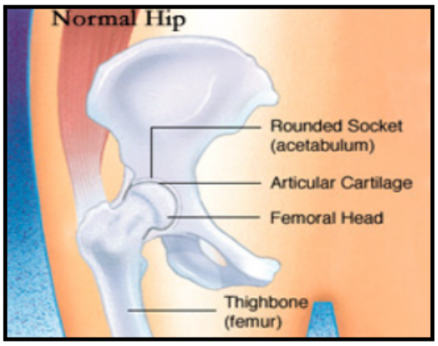


Figure (3a): Normal Hip.

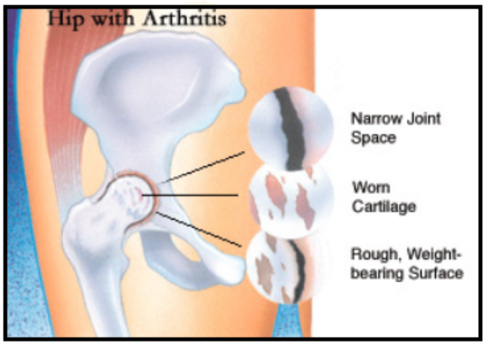


Figure (3b): Hip with Arthritis.

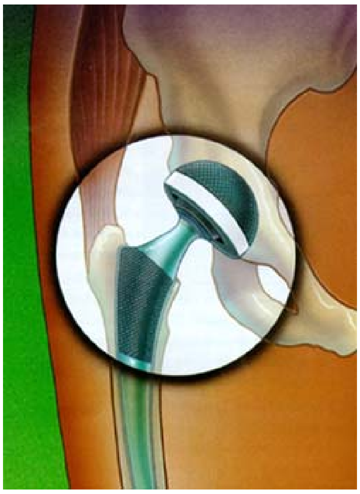


Figure (4): Artificial Implant.

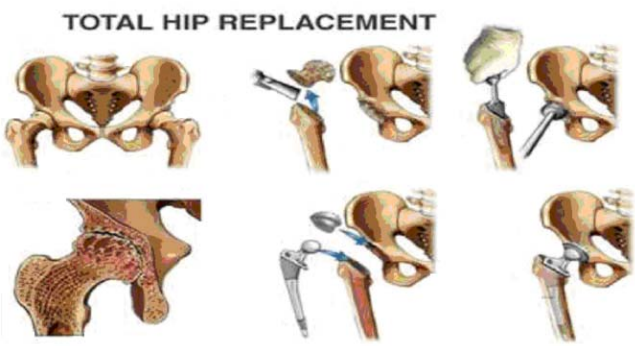


Figure (5): Total Hip Replacement Procedures.

Methodology

A logical, systematic approach to problem solving follows the basic sequence of problem recognition, problem definition, problem analysis, choice of appropriate action and solution was used in this investigation. The problem was recognized by the highly qualified specialists in Al-Khaldi private hospital while the other steps of sequence will be discussed in the following sections.

Problem Definition: This investigation considers an artificial hip replacement for X-patient in Al-Khaldi private hospital in Jordan. This patient is a 55-year-old man suffering from loss of articular cartilage (osteoarthrosis) in the hip region which causes a lot of pain for him. It was recommended by the specialists that hip arthroplasty is the only way to eliminate the pain that he suffers from.

Analysis of the problem: Total hip replacement can benefit individuals suffering from a variety of hip problems resulting from either wear and tear from a lifetime of activity or from disease and injury. In our case, the patient is a 55-year-old man who suffers from loss of articular cartilage in the hip region which causes a lot of pain and limitation of motion for him. Hip arthroplasty is the only way to eliminate the pain he suffers from. A comparison between normal and pathological hips are shown in figures 3a & b. Hip arthroplasty is recommended in this case where the ball-and-socket mechanism of the hip is replaced by artificial implants as it is shown in figure (4). [4]

In general, the artificial joint implants used in the non-cemented procedure are larger than those used with cement but are still proportional to the size of the individual bone. The total hip replacement procedures is shown in figure (5). [4]

Individual differences among people and the arising of special cases among patients led to thinking about treating each patient as an individual case and not to think about the traditional hip joint replacement by using custom designs, taking into consideration time and cost savings. Knowing the ability of the new rapid prototyping techniques in copying any shape and size of the organs helped to combine these techniques with those used in medicine such as the Computational Tomography (CT) scanning. The idea of building a 3D model from the CT scanning pictures by putting each at the top of another is similar to that of the layers additive nature of manufacturing by rapid prototyping. So, the approach concentrated on overcoming the obstacles that may face the conversion of the 3D model file format which is taken from the CT scanner into ∗.STL format which is understood by the 3D Printer of the 3D Ink jet prototyping technique. A lot of difficulties were faced and overcome such as the building of a solid model from the thin layer 3D model developed by the CT scanner, replacing the diseased femur head by the normal one, and calculating the length that should be added to the design for fixation purposes. For simulation purposes and because of the high cost of medical materials, it was decided first to start with the manufacturing of the part using ABS polymeric material in our product development laboratory, in the industrial engineering department at the University of Jordan.

Choice of appropriate actions and solutions

The main actions that were taken to realize this work are:

1. Determination of the suitable position for the patient when performing the CT scanning activity. The best position was that shown in Figure (6).
2. CT Scanning of the body part and collecting all the 2-D photos which are of DICOM type files.
3. Converting all of the 2-D photos from the CT machine DICOM type files into a picture format that can be converted into 3-D model (JPEG type files) with no change in the characteristics.
4. Converting the JPEG pictures into 3D – image using MIMICS software. This results in a thin-layer (shell) 3-D image.
5. Converting the 3-D shell image into CAD solid model using Pro-Engineer software because the later one helps in converting the solid CAD model into a format that can be understood by the prototyping machine (*.STL type)
6. Replacing the head of the diseased femur by generating the head in the normal side.
7. Generating a stress and strain analysis to predict the desired length and diameter of the part that is needed for fixing.
8. Designing the desired hip joint with the actual size and shape from the CT scan model.
9. Designing the socket (Cup).
10. Assembly of socket, femur head and femur shaft.
11. Manufacturing the designed part using the 3D-Printing Rapid Prototyping Technique.

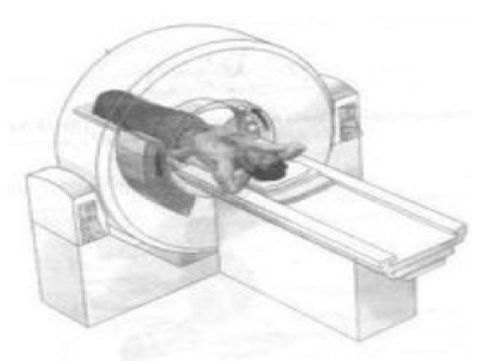


Figure (6): The best position to perform the CT scanning activity.

The design stage: The above-mentioned actions were taken to replace the diseased hip joint with a typical artificial one. Both diseased and healthy joints were CT scanned. A number of 355 CT slices were taken. The first 23 are presented in figure (7). Each of them was converted into JPEG format by exporting each slice stored in the DICOM software of the CT scanning machine (stored as *.obj format file). Using MIMICS software, a 3-D shell image was generated as shown in Figure (8). The dark area is of interest. Replacing the diseased head by the healthy one needs a solid model (not shell). So, a huge problem was faced after transferring the 3-D model from MIMICS into Pro-Engineer software. This problem was overcome by filling the inner space of the shell model with generated patches from thousands of auto defined surfaces which took a lot of effort and time. Steps of inner space filling are shown in Figure (9). It starts from the cutting of the diseased head, through the definition of the starting curve, definition of the patch structure, ending with the complete patch surfaces definition.

After the completion of 3-D model filling, the head of the diseased femur was replaced by a generated one from the normal side. Then the generated healthy head was attached to the femur as shown in Figure (10b). This assembly needs to be fixed in the bone from the bottom which made it necessary to determine the fixing length and to add it to the assembly. The stress analysis approach was used to determine the needed fixing length taking into consideration the material type of the manufactured hip. The material type was selected to be Ti-6Al-4V alloy based on callister.[5] The mechanical properties of this alloy are shown in Table (1). To proceed the calculations, the forces that may act on the designed hip were analyzed as shown in Figure (11). It is known that the load on the abductor muscles (Fm) equals one-half the weight of the body, and R is the resultant force. Given that the loading is complex and compensating for running, the weight load (Wt) was taken as 4 times the user's body weight.[4]

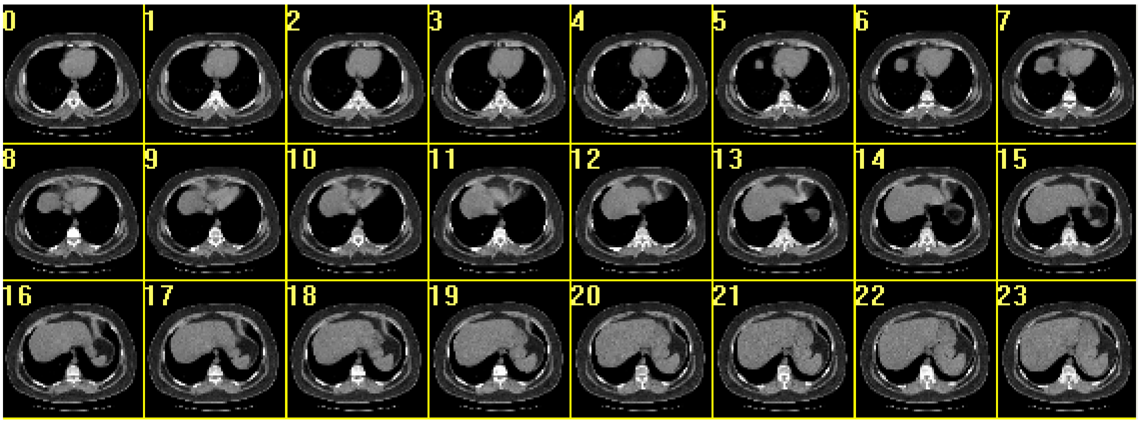


Figure (7): The first 23 CT slices of a total number of 355.

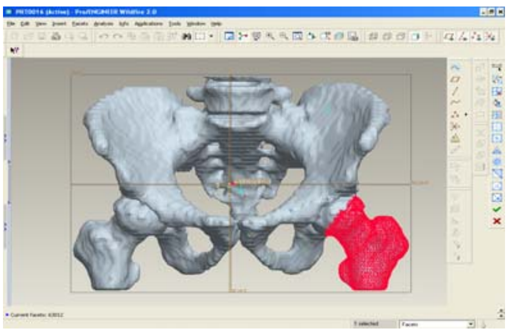
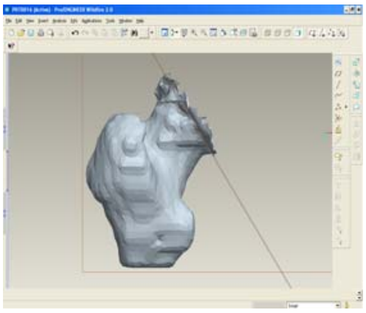
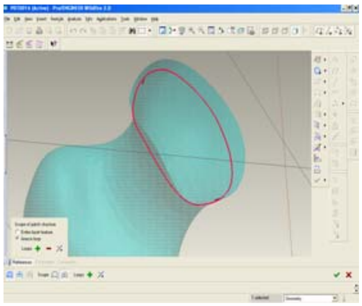


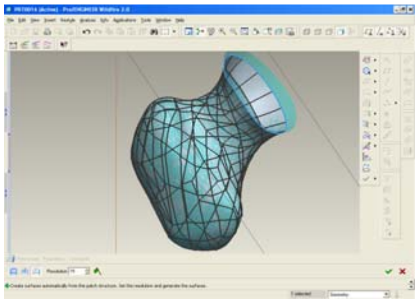
Figure (8): 3D shell image after putting the slices over one another. The red (dark) area is the diseased one.



Step 1. Cutting of diseased head.

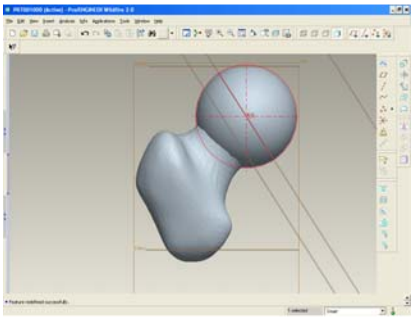


Step2. Definition of the starting curve.

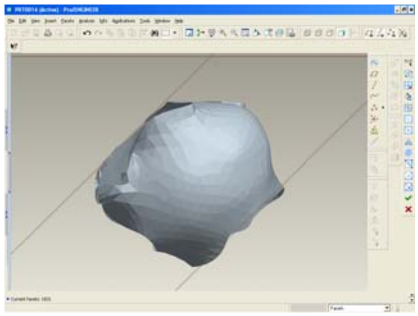


Step 3: Complete patch surfaces definition.

Figure (9): Steps of inner space filling.



(a) Generating new head.



(b) Attachment of the head to the femur.

Figure (10): Generation of a new head from the normal side.

Table (1): Mechanical Properties of Ti-6Al-4V.

Hardness, brinell	*334 HB*
Hardness, knoop	*363 HV*
Hardness, rockwell C	*36 HRC*
Tensile strength, ultimate	*950 Mpa*
Tensile strength, yield	*880 Mpa*
Elongation of break	*14%*
Reduction of area	*36%*
Modulus of elasticity	*1138 Gpa*
Compressive yield strength	*970 Mpa*
Notched tensile strength	*1450 Mpa*
Ultimate bearing stength	*1860 Mpa*
Bearing yield strength	*1480 Mpa*
Poisson's ratio	*0.342*
Charpy impact	*17 J*
Fatigue strength	*240 Mpa*
Fracture toughness	*75 Mpa-m½*
Shear modulus	*44 Gpa*
Shear strength	*550 Mpa*

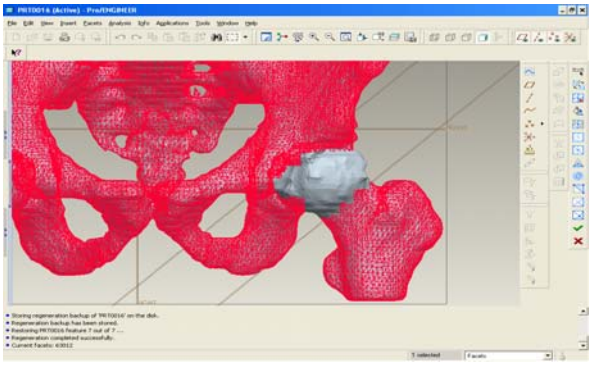


Figure (11): The forces acting on the designed hip structure.

Although the direction of applied weight load can vary by as much as 30°, it was assumed that the weight load direction is vertical and centered on the stem. [6] The second force that affect the hip is the muscular force in the hip region, it is assumed that the muscular force is 0.5 times the user's body weight, and in a direction that is shown in Figure (11). [4] The stress that acts on the femur depends on the moment and the geometry of the beam as in formula (1) below:

$$\sigma = M * Y / I \qquad (1)$$

where:
σ: is the yield stress of the material
M: is the moment (N.m)
I: is the moment of inertia
Y: is the radius of the cross section

After calculation, the length was found to be 6.37 cm. Then, a full assembly of the hip was determined as shown in Figure (12). The cup (socket) design is also of a great importance to facilitate the movement of the hip. The dimensions of the socket were determined from the diameter of the femur and the space available in the body of the diseased man (Figure 13). The material of the socket was chosen to be UHMWPE based on Pramanuk et al. [1]

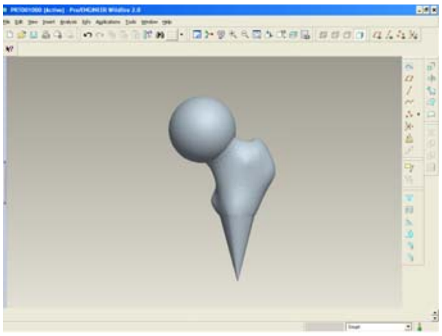


Figure (12): The final Hip assembly.

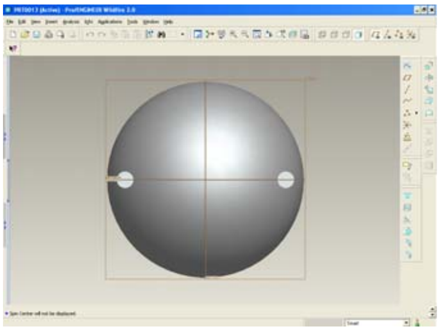


Figure (13): The final shape of the socket.

The manufacturing stage: The manufacturing process of the designed hip comprises the following steps:

1. The file of the designed part was converted into STL format using Pro Engineer software to be understood by the 3D printing rapid prototyping machine in the Industrial Engineering department at the University of Jordan.
2. The verification of the STL file was achieved by using the software Catalyst which is built in the prototyping machine. This was done to make sure that the STL file can be fabricated without errors.
3. The supports were generated and the slice thickness was determined to be 0.3302 mm automatically by the prototyping machine.
4. The process of fabrication was simulated as shown in Figures (14) and (15).
5. The fabrication took place using plastics of ABS type which can be changed to Ti-6Al-4V material or any material of interest. The final product after fabrication is shown in Figure (16). The used 3-D printer is shown in Figure (17).

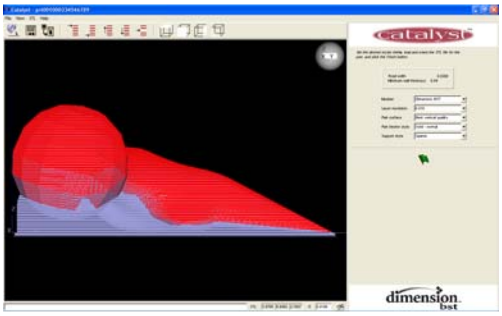


Figure (14): The fabrication of the hip.

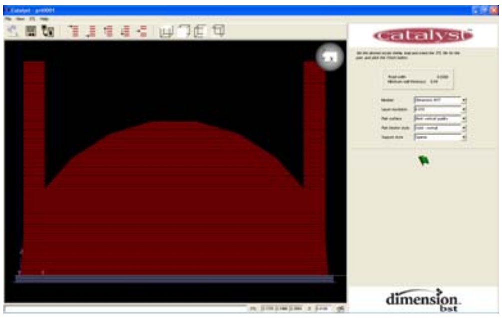


Figure (15): The fabrication of the cup.

Figure (16): The final shape after manufacturing.

Figure (17): The used 3D printer for manufacturing.

Conclusions

1. Rapid Prototyping proved to be a useful and capable technology in the field of biomedical engineering and surgery.
2. Rapid Prototyping model facilitates the pre-operative planning of an optimal surgical approach and enables selection of correct or appropriate implants.
3. Rapid Prototyping enables the manufacturing of a typical bio-parts
4. The integration of technologies such as medical imaging, software such as pro engineer and modern fabrication processes such as RP is important in the medical field. With wider practice by smaller institution, it is possible to reach small, isolated community hospitals. This could help minimize the problem of long waiting list and congestion in 'big' hospitals by reducing referral cases.

References

1. Pramanuk S, Agarwal AK, and Rai KN. Chronology of total hip joint replacement and materials development. Trends Biomater. Artif. Organs 2005; 19 (1): 15-26.
2. Fisher J. Biomedical Applications. Modern Tribology Handbook, Vol. Two: Materials, Coating and Industrial Applications, edited by Bharat Bhushan. Florida: CRC Press, Boca Raton, 2001; 1593-1609.
3. Kalpakjan S, Scmid SR. Manufacturing processes for engineering materials, 4th edition: Prentice Hall, 2003; 610-619.
4. Walker JH, Meswania J, Muirhead-Allwood SK, and Catterall T. The role of 3D image reconstruction and rapid prototyping models in total hip arthoplasty, Phidias-EC Funded network project on rapid prototyping in medicine, 1988; 1.
5. Callister WD. Materials Science and Engineering: An Introduction, 7th edition: McGraw-Hill, 2006; 728-735.
6. Hamrock BJ, Schmid SR, and Jacobson B. Fundamntals of Machine elements, 7th edition: Prentice Hall, 2004.

استخدام طريقة النمذجة السريعة في حقل الجراحات التأهيلية وخاصة الترقيعية منها

عصام جلهم،[1] زياد حوامده، [2] بسام عماري [3]

[1]–مساعد عميد كلية الدراسات العليا لشؤون الكليات العلمية؛ 2– نائب عميد كلية علوم التأهيل؛ 3– عميد كلية التأهيل،

الجامعة الأردنية، عمان، الأردن

الملخص

إن لتكامل التقنياتِ مثل التصوير الطبِي والبرامج الحاسوبية الاحترافية وطرقِ التصنيع الحديثةِ مثل النمذجة السريعة أهمية كبرى في الحقلِ الطبِي. فقد مكنتنا هده الدراسة مَنَ حَلّ بَعْض المشاكلِ الطبيةِ خصوصاً تلك التي تعنى باستبدال الأطراف في الجراحات الترقيعية، بالاضافة الى اقتراح منهج يمكن اتباعه في مثل هده الحالات لاستِبدال اجزاء الجسم البالية بمُنتَج حيوي بنفس الأبعادِ، والحجم، والشكل.

الكلمات الدالة: إعادة التأهيل، تصنيع، الجراحة الترقيعية، النمذجة السريعة، عظم فخذ، ورك.