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Design and Analysis of a Modified BK Prosthetic Socket

A Thesis
Submitted to Council of College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

By

Bassam Assad Alwan

(B. Sc. Mechanical Engineering, 2014)

Supervied by

Prof. Dr. Muhsin J. Jweeg　　Dr. Zaid S. Hammoudi

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بسم الله الرحمن الرحيم

يَا أَيُّهَا النَّبِيُّ إِنَّا أَرْسَلْنَاكَ شَاهِدًا وَمُبَشِّرًا وَنَذِيرًا (45) وَدَاعِيًا إِلَى اللَّهِ بِإِذْنِهِ

وَسِرَاجًا مُّنِيرًا (46) وَبَشِّرِ الْمُؤْمِنِينَ بِأَنَّ لَهُم مِّنَ اللَّهِ فَضْلًا كَبِيرًا (47)

وَلَا تُطِعِ الْكَافِرِينَ وَالْمُنَافِقِينَ وَدَعْ أَذَاهُمْ وَتَوَكَّلْ عَلَى اللَّهِ وَكَفَىٰ بِاللَّهِ

وَكِيلًا (48)

صدق الله العظيم

سورة الاحزاب

عن ابي هريرة رضي الله عنه: ان رسول الله صلى الله عليه وسلم ، قال:

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We certify that we have read the thesis titled **(Design and Analysis of Modified BK Prosthetic Socket)** and we have examined the student **(Bassam Assad Alwan)** in its content and what is related with it, and in our opinion, it is adequate as a thesis for the degree of Master of Science in Mechanical Engineering.

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Asst. Prof. Dr. Dhia Ahmed Salal, ...……… (Head of Department)

The thesis was ratified at the Council of College of Engineering / University of Diyala.

Signature…………………...
Name: Prof. Dr. Abdul Monem Abbas Karim
Dean of College of Engineering / University of Diyala
Date:

Dedication

In the Name of ALLAH, the most Merciful, the most Compassionate.

The current study is dedicated to My great teacher and messenger, Mohammed (May Allah bless and grant lime).

*To My Shikhi (**Hazrat Al- Sheikh Mustafa Al - Sheikh Hashem Al - Khashali Al –Muski**) and My Family {**My Father, My Mother, My Brother, My Sisters, My Wife and My Child**}*

***All-Sincere** and **Good People** where they are in the world.*

My Lovely Country Iraq.

Bassam Assad Alwan 2018

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Special thanks and appreciation to Abu Muhannad, Abu Mahmoud, Teacher Mahdi and all my friends.

Bassam Assad Alwan 2018

Supervisor's Certification

We certify that this thesis entitled **"Design and Analysis of a Modified BK Prosthetic Socket''** was presented by **(Bassam Assad Alwan)** under my scientifically supervision, therefore, it is suitable for debate by the examining committee.

Signature:	Signature:
Name: Prof. Dr. Muhsin J. Jweeg	Name: Dr. Zaid S. Hammoudi
University of Telafer	University of Diyala
Scientific Affairs Department	Mechanical Engineering Department
Date / / 2018	Date / / 2018

In view of the available recommendation, I forward this thesis for debate by the examining committee.

Signature:

Name: Asst. Prof. Dr. Diaa Ahmed Salal
Chairman of the Department of Mechanical Engineering.

Date: / / 2018

Linguistic Certification

I certify that this thesis entitled **"Design and Analysis of a Modified BK Prosthetic Socket'' was presented by (Bassam Assad Alwan)** under my linguistic supervision. Its language was revised to meet the style of the Technical English language.

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Date: / / 2018

Scientific Certification

I certify that the thesis entitled **“Design and Analysis of a Modified BK Prosthetic Socket''** was presented by **(Bassam Assad Alwan)”** has been evaluated scientifically, therefore, it is suitable for debate by the examining committee.

Signature:

Name: Asst. Prof. Dr. Ayad M. Takhakh

Address: Al-Nahrain university , College of Engineering

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COMMITTEE DECISION

We certify that we have read the thesis entitled **"Design and Analysis of a Modified BK Prosthetic Socket"** and we have examined the student **(Bassam Assad Alwan)** in its content and what is related with it, and in our opinion, it is adequate as a thesis for the **Degree of Master of Science in Mechanical Engineering**.

Examination Committee Signature

The thesis was approved by the Council of College of Engineering/ University of Diyala

Signature:

Name: Prof. Dr. Abdul Monem Abbas Karim

Dean of College of Engineering/ University of Diyala.

Date: / / 2018

ABSTRACT

The terrorist operations, the wars and the incidents led to an increase in the number of amputations in Iraq. Prosthetic limbs are manufactured to compensate for the missing parts of the human body. However, the most common type of lower limb is Trans-tibial (Below Knee).

In this work, design and analysis of below knee BK Prosthetic Socket is discussed with the aim of selection of material, and manufacturing of socket. Four groups Composite materials used for manufacturing BK prosthetic socket by using vacuum molding technique with various volume fractions are studied. The first group consists of eight layers (2-layers of carbon and 6-layers of perlon with Vf=0.409) with acrylic resin, the second group consists of eight layers (2-layers of carbon and 6-layers of perlon with Vf=0.24) with acrylic resin, The third group consists of twelve layers (4-layres of carbon and 8-layers of perlon) with acrylic resin, and four group consists of acrylic resin only. The study was conducted experimentally, analytically, and numerically.

The experimental work involves determination of physical, mechanical and fatigue properties of composite material used for manufacturing below knee prosthetic sockets. Two models Trans-Tibial prosthetic sockets with (3) mm thickness were manufactured from Composite material (12-Layers) and subjected to Force Plate testing and F-socket testing to determine ground reaction force and pressure interface at socket/stump region.

The analytical work discusses the friction effect on normal stress at interface. A simplified lower limb model was applied to analyze the effect of frication. MATLAB Program was utilized to calculate the pre-pressure, pressure and shear stress at stump/socket region by solving the equations.

The finite element method (ANSYS-15) was utilized for the analyzing and evaluating of the fatigue properties by observing the, maximum principal stress, the total deformation and safety factor.

The results showed the mechanical properties (ultimate strength and Young’s modulus) are increasing with the increasing volume frication at constant perlon and carbon fiber layers.

The results showed that the composite materials achieve a large increment in mechanical properties such as (ultimate strength, Young’s modulus, Flexural strength and flexural modulus) which were increased to a percentage of (124%), (7.2%), (95.9%), and (83.87%), in composite material (12-Layers) as compared with composite material(8-Layers with volume fraction=0.409). However, The ultimate tensile strength and the modulus of elasticity of composite materials (12-Layers) are higher than those of the composite materials (8-Layers with volume fraction=024) by 100% and 185% respectively, and by 444% and 274% for pure acrylic lamination. The fatigue limit for 12-Layers (perlon and carbon) is 63 MPa. Result of F-socket apparatus, four specific areas of the BK prosthetic socket which experienced pressures in excess of 100 kPa were identified. The highest pressure at socket/stump region was 200 kPa in patella tendon area for long socket.

The results show that the maximum principal stress, deformation and safety factor are equal to 37 MPa, 8.48 mm and 1.7 respectively for long socket and 26 MPa, 4.59 mm and 1.83 respectively for standard socket.

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LIST OF ABREVIATIONS

Abbreviation	Definition
BK	Below Knee
ANSYS	Finite Element Method Commercial Software
PTB	Patellar Tendon Bearing Socket.
HST	Total Surface Weight Bearing Socket.
HST	Hydrostatic Design Socket
SLS	Selective Laser Sintering.

CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
FGP	Fiberglass Reinforced Polyester.
RE	Ramie Fiber Reinforced Epoxy Composite

List of Key Symbols

Symbols	***Definition***	***Unit***
M1	*Moment of force*	***N.mm***
AB	*The force applied by the body to the prosthesis .*	***N***
CD	*The counter force applied by the floor to the Prosthesis.*	***N***
d1	*The perpendicular distance from **(O)** to the line of action Of force **AB***	***mm***
d2	*The perpendicular distance from **(O)** to the line of action of force **CD.***	***mm***
K_N	*Perpendicular Spring Constant*	***N/mm***
K_S	*Parallel Spring Constant*	***N/mm***
E	*Young's modulus of soft tissue*	***MPa***
G	*Shear modulus of soft tissue*	***MPa***
A	*the area of supporting surface of skin*	***mm***
L	*the length limb contacts with socket*	*mm*
W	*Weight of Body*	*kg*
t	*the average thickness of soft tissue*	*mm*
D1	*Upper Diameter of the support surface*	*mm*
D2	*Lower Diameter of the support surface*	*mm*
Ө	*Conical Angle*	*Deg.*
H	*the vertical distance over which the limb makes contact with the socket*	*mm*
K	*Vertical Stiffness*	*N/m*
dSo	*Pre-Compressed Parallel Displacement*	*mm*
dNo	*Pre-Compressed Normal*	*mm*

	Displacement	
N	*Normal Force*	N
S	*Shear Force*	N
σo	*Pre-Compressed Stress*	MPa
τ	*Shear Stress*	MPa
σ	*Normal Stress*	MPa
Vf	*Volume Fraction of Fiber*	
Vm	*Volume Fraction of Matrix*	
vf	*Volume of Fiber*	cc
vm	*Volume of Matrix*	cc
vt	*Total Volume*	cc
ρ_{ex}	*True density*	g/cc
Wd	*Dry weight of sample*	g
Ws	*weight of the sample, a commentator and submerged in water*	g
Wn	*weight of the sample is statured with water*	g
D	*Density of water*	g/cc
$\rho\mathbf{c}$	*Theoretical Density*	g/cc
$\rho\mathbf{ex}$	*Experimental Density*	g/cc
Ef	*Stiffness from Bending Test*	GPa
Q	*Correction Factor*	
δ	*Specimen Deflection*	mm
σ_a	*Stress amplitude*	MPa
l	*Specimen Length*	mm
$t1$	*Specimen thickness*	mm

CHAPTER ONE

INTRODUCTION

CHAPTER ONE

INTRODUCTION

1.1 Background

At recent years, the use of the prosthetic socket increased significantly in the world due to terrorist operations and war barbaric which resulted in millions of amputees and more urgent need for artificial limbs, especially lower-limb prostheses due to injuries inflicted by landmines. There have been several reports of poor service life of lower-limb prostheses in Iraq which emphasize the need to investigate their design of socket. This urges the researchers to examine the materials, design and manufacturing of socket. Therefore, this research investigates the trans-tibial prosthetic socket when subject to loading during standing and walking.

Amputation is the removal of a limb (arm or leg) or other body part because of injury or disease. It may include the upper and lower extremities or both. Lower amputation is subdivided into five types: hip disarticulation, above knee, through knee, trans-tibial (below knee), and Sym's amputations [1]. A prosthetic component is an artificial tool which mimics the function and appearance of a lost body part. Prosthetic of below knee consist of several parts include socket, pylon or shank, ankle, and foot. The prosthetics socket provides a contact area between the prosthetic component and stump of leg which is sketched for preparation the comfort for patients, transmission of the appropriate weight from the human body to the prosthesis, and effective locomotion control [2]. Socket prosthetic covers the stump and enables the patient to stand-up, sit-down, walk, and move freely.

The prosthesis socket can be subdivided into three regions as shown in figure (1-1) [3].

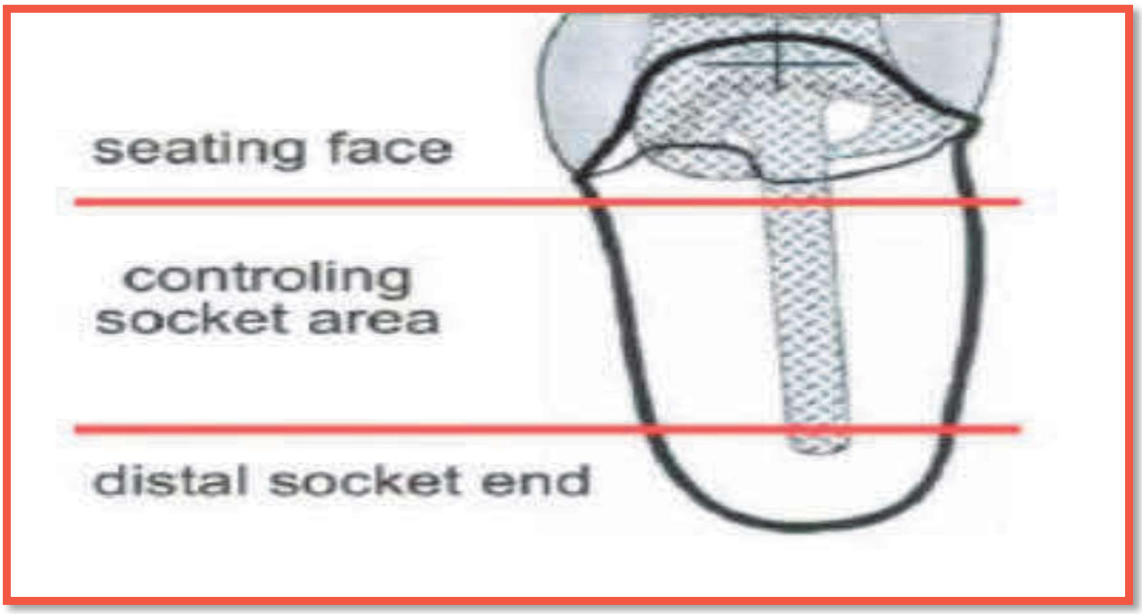

Fig. 1-1. Socket regions [3].

1.2 Types of Socket Interface

The socket interface designs can be classified by respective weight bearing characteristics into three types: specific area weight bearing or patellar tendon bearing (PTB), total surface weight bearing (TSB), and hydrostatic design (HST) [4].The first type is patellar tendon bearing (PTB). This type involves anatomy such as the patella tendon in anterior side, popliteal fossa in posterior region, and the medial flair for weight bearing. Patellar tendon bearing socket explains a specific relationship between anterior and posterior regions as shown in figure (1-2a). The total surface bearing socket (TSB), provides a uniform distribution of the weight (weight of body) over the full stump. This type reduces the amount of pressure applied to the skin due to the regular distribution of weight (1-2b). Gel sleeve is utilized to help redistribute notorious normal stress (pressure) regions in the lower limb [5].

The last type is hydrostatic socket which is also so-called as pressure cast, includes chamber for compression the fluid to obtain a suitable distribution of pressure in socket/stump interface as shown in figure (1-2c).

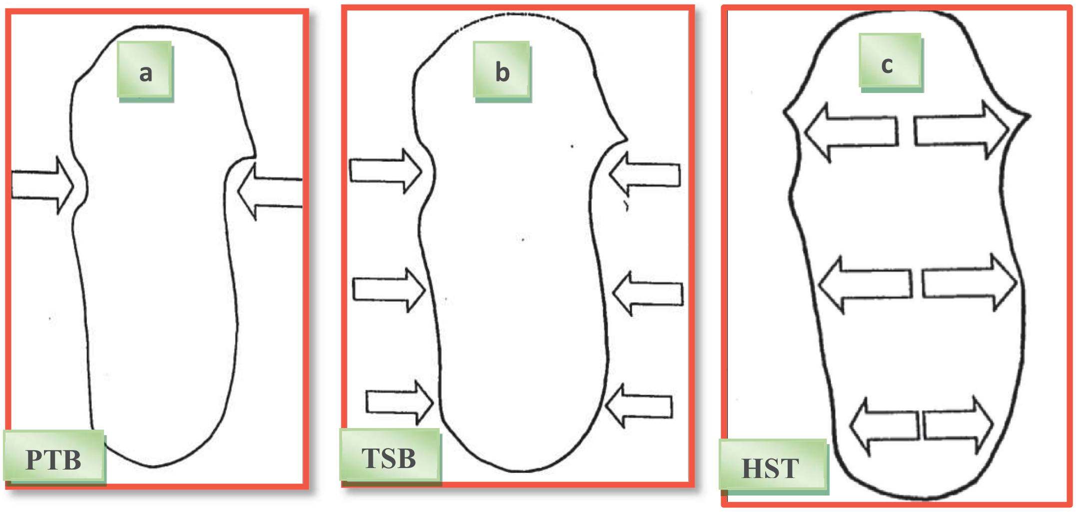

Fig. 1-2. Types of socket interface [4].

1.3 Materials Used in Manufacturing Socket

The selection of suitable material used in prosthetic limbs industry is very important. The material is of direct relationship with the patient's comfort. There are properties that should be taken into consideration when choosing a material such as weight, durability, low density and high strength.

The prosthetic socket may be manufactured from thermoplastic material or composite material [6]. Polyethylene (PE), polypropylene (PP), modified polyesters, and epoxies classified as thermoplastic [7].

Composite materials consist of two components, one of them is called the matrix and the second is known as material reinforcement. Properties required for the reinforcement material should be lightweight, high strength under tension and pressing, stiff to resist bending and shear stresses, a strong resistance to fracture under shock, easy to apply and cost effectiveness [8]. There are several types of fiber and the matrix used to build a composite materials is shown in Table (1-1) [9].

Table (1-1) Types of composite materials [9]

Material		Characteristics
Fiber	Glass	High strength, low stiffness, high density, lowest cost;
	Carbon	Available as high modulus or high strength; low cost; less dense than glass; sometimes used in combination with carbon nanotube
	Aramids (Kevlar)	Highest strength-to-weight ratio of all fibers; high cost
	Other fibers	Nylon, silicon carbide, silicon nitride, aluminum oxide, boron carbide, boron nitride, tantalum carbide, steel, tungsten، molybdenum
Matrix	Thermosets	Epoxy and polyester

1.4 Methods of Manufacturing Socket

There are many different kinds of fabrication methods available to depending on their individual clinical needs. Vacuum technique, modular socket system, selective laser sintering, and computer aided design and manufacturing may all be classified a ways used to manufacture the socket.

1.4.1 Vacuum Forming Method

The prosthetic sockets have been manufactured by Vacuum technique by following steps [10]:

1. Negative mold preparation: this is done by wrapping gypsum bandage around the stump to capture the basic shape of the stump. Once dried, it is removed from the stump.
2. Positive mold preparation: the negative mold is filled with gypsum, then rectification of positive mold is done at pressure sensitive and pressure tolerant areas.

3. Socket preparation: the positive mold is sealed in polyvinyl alcohol bag PVA and filled with resins. Once this hardens, the positive mold is broken and the socket is obtained.

1.4.2 Modular Socket System Method

Modular socket system is one of the fabrication methods that is different from the traditional methods. When this method is used, direct lamination on the residual limb of the patients and manufactured time does not exceed two hours [11].

1.4.3 Selective Laser Sintering Method

Prosthetic socket is manufactured in selective laser sintering method by adding material instead of removing material using directed energy beam [12].

The use of SLS to manufacture socket is due to several reasons; creating the socket directly, eliminating the needed mold, handing lamination and modification process, manufacturing complex shapes and designing new sockets [13].

Selective sintering laser (SLS) helps to connect the prosthetic component into socket, such as installation the pylon is very simple [14].

1.4.4 Computer-Aided Design and Manufacturing (CAD/CAM)

CAD/CAM techniques are utilized in the design and manufacture of socket [15]. CAD/CAM method includes several steps to fabricate the prosthetic socket: finding a way to create the optimal prosthetic socket shape according to the information of stump, finding easy and simple way to fabricate the prosthetic socket, and checking the socket on stump before modifying process [16].

Computer-aided manufacturing and computer-aided design (CAM/CAD) can reduce the time and cost of manufacturing prosthetic socket for patients. [17].

1.5 Finite Element Analysis

Finite element method (FEM) is a method widely utilized in bio-engineering to measure static and dynamic properties in complex systems. It has been selected as a useful tool for socket design [18]. To study the pressures at stump/socket interface region during gait cycle for patients with Trans-tibial amputation, stump and socket models were drown by Ansys software [19].

1.6 Research Objectives

The objectives of this research is to design, analyze and manufacture prosthetic trans-tibial socket (Patellar Tendon Bearing). The work is divided into three main parts: experimental, analytical, and numerical using the finite element method (FEM). To achieve the above objectives the following steps are followed:

1. Reviewing the types, design, and manufacture of trans-tibial prosthetic socket.
2. Investigating the possibility of using proved materials for manufacturing sockets
3. Designing and fabricating sockets based on a proposed materials. CAE design and analysis techniques are to be used.
4. Experimentally testing the fabricated sockets on real persons and studying their efficiency.

1.6 Layout of the Thesis

Five detailed chapters cover the general theme of this thesis:

Chapter 1: This chapter includes a background about the prosthetic socket, types of socket interface, materials and methods of manufacturing of socket. It also introduces the main objectives to be achieved, layout of the thesis.

Chapter 2: This chapter presents a review of the types of materials, testing of materials and finite element method to analyze the socket.

Chapter 3: This includes the general analytical model for studying the effect of friction at interface stump/socket. Also, a numerical simulation of the trans-tibial socket is presented in this chapter using FEM software (ANSYS workbench version 15).

Chapter 4: This involves the experimental works including material part describing the method of manufacturing socket from different lamentations. This chapter also describes testing of these materials to calculate the mechanical properties and fatigue characteristics. It also includes designing and manufacturing prosthetic socket. Interface pressure technique for the trans-tibial socket is also described in detail and applied to determine the pressure in the socket of trnas-tibial prosthetic amputee.

Chapter 5: presents and discusses of the results of physical, mechanical and fatigue properties of composite materials.

Chapter 6: presents the basic conclusions and recommendations that can be drawn from this work. It also presents some recommendations for future work.