MODELING ANALYSIS ON BLOOD FLOW INTO THE MAIN ARTERY AROUND KNEE JOINT OF HUMAN LEG DURING SPORTS ACTIVITIES

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ABSTRACT

Vascular injuries are a wide variety of traumatic and nontraumatic injuries to lower limb especially at knee joint. Nowadays, athletes are facing to the vascular injuries that attack to knee joint. The vascular injuries most commonly affect the popliteal artery followed by the common femoral artery through knee joint. The objective of this project is to develop the three dimensional modeling of the knee and investigate the blood flow through human leg. The researcher has been done simulate the model from Fluid Structure Interfaces (FSI) software for blood flow through human leg. In this setup, the values of blood velocity for different gender male and female at range 20-30 years old are been analysis. The different blood velocity during exercise, running and cycling give different result with different gender. Next, normal blood pressure for male and female at 120 mmhg are applied and results were shown the pressure of human after 60 seconds. Besides, variations force are applied to knee joint such as from 250 N, 500 N, 750 N and 1000 N in order to get the result of displacement and stresses on knee joint after impact. Human legs were considering with and without kneepads for analysis the stresses on knee after impact. By using different materials of kneepads such as PVC, ABS, polycarbonate, coconut fiber, oil palm trunk fiber and kenaf fiber the effects of absorption stresses will notice. In three design of artery through knee joint, the 2nd design gives the highest velocity for three conditions during exercise, running and cycling. The blood velocity after 60 seconds during exercise is 75.3 cm/s and 73.3 cm/s, running is 90.1 cm/s and 87.8 cm/s, cycling is 85.1 cm/s and 84.8 cm/s for male and female respectively. Six materials of kneepads are simulated and the kenaf fiber is the most suitable kneepad to protect knee. The stress exerted on kenaf fiber of kneepads is 7.94 MPa at 1000 N for thickness 0.5 cm. After that, the researcher have been applied the kenaf fiber as kneepads for three condition human leg at same angle but different blood flow pattern. The result represent, for 3rd condition human leg give the peak velocity blood flow is 77.13 cm/s and 98.5 cm/s for with and without kneepads. The 3rd condition gives the lowest change rate of displacement, thus the value with and without kneepads are 0.5113 mm and 11.81 mm respectively. In three models of artery with knee joints give three different values of velocity and pressure. Thus, can be prove that, artery for all human are different and doesn't give the same blood flow velocity through artery. Besides, for three condition of leg shows the different pattern blood flow in human leg for straight, with bones and artery condition.

ABSTRAK

Kecederaan vaskular adalah kecederaan trauma dan nontraumatic terutama pada anggota badan iaitu sendi lutut. Kini, atlet menghadapi kepada kecederaan vaskular yang menyerang sendi lutut. Kecederaan vaskular yang sering terjadi telah menjejaskan arteri popliteal diikuti oleh arteri femoral biasa melalui sendi lutut. Objektif projek ini adalah untuk membangunkan tiga model dimensi lutut dan menyiasat aliran darah melalui kaki manusia. Penyelidik telah melakukan simulasi model dari Antaramuka Struktur Bendalir (FSI) perisian untuk aliran darah melalui kaki manusia. Dalam persediaan ini, nilai halaju darah untuk berlainan jantina lelaki dan perempuan pada jarak lama 20-30 tahun akan menjadi analisis. Halaju darah yang berbeza semasa latihan, berlari dan berbasikal memberikan hasil yang berbeza dengan jantina yang berbeza. Seterusnya, tekanan darah yang normal bagi lelaki dan wanita di 120mmHg digunakan dan keputusan yang ditunjukkan tekanan manusia selepas 60 saat. Selain itu, daya variasi digunakan untuk sendi lutut seperti dari 250 N, 500 N, 750 N dan 1000 N untuk mendapatkan hasil daripada anjakan dan tekanan pada sendi lutut. Kaki manusia telah dipertimbangkan dengan dan tanpa kneepads untuk analisis tekanan pada lutut selepas kesan. Dengan menggunakan bahan-bahan yang berbeza kneepads seperti PVC, ABS, polikarbonat, kelapa serat, serat batang kelapa sawit dan kenaf serat kesan tekanan penyerapan akan berbeza. Dalam tiga reka bentuk arteri melalui sendi lutut, reka bentuk kedua memberikan halaju tertinggi bagi tiga keadaan semasa latihan, berlari dan berbasikal. Halaju darah selepas 60 saat semasa senaman adalah 75.3cm / s dan 73.3 cm / s, berjalan adalah 90.1 cm / s dan 87.8 cm / s, berbasikal adalah 85.1 cm / s dan 84.8cm / s untuk masing-masing lelaki dan perempuan. Enam bahan kneepads ynag terlibat dalam simulasi dan hasilnya serat kenaf adalah kneepad yang paling sesuai untuk melindungi lutut. Tekanan yang dikenakan ke atas gentian kenaf daripada kneepads adalah 7.94 MPa pada 1000 N untuk ketebalan 0.5 cm. Selepas itu, penyelidik telah menggunakan gentian kenaf sebagai kneepads untuk tiga keadaan kaki manusia pada sudut yang sama tetapi corak aliran darah yang berbeza. Hasilnya mewakili, bagi keadaan yg ketiga kaki manusia memberikan aliran darah halaju puncak 77,13 cm / s dan 98.5 cm / s untuk dengan dan tanpa kneepads. Keadaan ketiga memberikan kadar perubahan terendah anjakan, dengan itu tekanan menyerap semasa dengan dan tanpa kneepads adalah 0,5113 mm dan 11.81 mm masing-masing. Dalam tiga model arteri dengan lutut sendi memberi tiga nilai yang berbeza halaju dan tekanan. Oleh itu, boleh membuktikan bahawa, arteri untuk semua manusia adalah berbeza dan tidak memberi sama halaju aliran darah melalui arteri. Selain itu, selama tiga keadaan kaki yang berbeza menunjukkan aliran corak darah di kaki manusia untuk lurus, dengan tulang dan keadaan arteri.

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A	Cross sectional area
P	Pressure
E	Young's modulus elasticity
σ	Stress
m	Mass
V	Velocity
t	Time
F	Force
V	Kinematic viscosity
ρ	Density
%	Percentage

LIST OF ABBREVIATIONS

FSI   Fluid Structure Interaction

3D   3 Dimensional

UMP   University Malaysia Pahang

CHAPTER 1

INTRODUCTION

1.1   INTRODUCTION

This chapter will describe about the background, problem statement, objectives and scope of the study. From the background of the study, it comes out the problem statement and from the problem statement; the purpose of this study can be identified. This study will be based on the objective that have been determined and is limited by the scopes.

1.1.1   BACKGROUND OF STUDY

Human body is made up by a head, neck, torso, two arms and two legs. In order to stabilize body to stand strong, there is a part named knee joint that lower limb extremities above the upper limb body. The knee joint is consists important parts of femur, tibia, meniscus, cartilage, patella and ligament. The part of the knee joint is surrounded by blood vessel such as artery and veins. The aim of blood vessel is to supply the blood through the veins and artery by the pumping of blood from human heart.

In this study, the blood flow through human leg at knee joint will beinvestigated. The pattern of blood flow via human leg during sports activities will be determined. Beside, in human leg consists of arteries to the knee joint and surrounding structures are supplied by the large femoral and popliteal arteries. Femoral artery is located in upper thigh bones, while popliteal is located behind the knee joint. In this research, the blood

flow through femoral and popliteal are investigated with different velocity of blood flow depending on human's activity of human do for male and female.

Nowadays, athletes are susceptible to a wide variety of traumatic and nontraumatic vascular injuries to the lower limb. However, this case is least familiar among people because they see the effect of injuries comes from other parts of the knee joint such as meniscus, ligament, patella and cartilage. The vascular injuries are much related to sports especially at the knee joint of human legs. This is because the main blood vessel of knee joint is located in the upper thigh and behind of the knee is femoral and popliteal artery respectively. Retirement from sports may occur, if the both arteries are injured and the lower limb can loss function.

Football, rugby, kayaking, windsurfing and cycling are famous sports activities among people and athletes. However, injury may occur both through the arteries of femoral and popliteal when the impact of external force is coming in contact directly to the knee. Those the compression effects to the both artery and the disruption of blood flow is occurring. This vascular injury will be explained more in the study.

Next, the researcher also develops the modeling of kneepad on human leg especially on knee, in order to protect the knee for being injured seriously. Then the researcher also, needs to compare the material of kneepad that going to be used for determines the less stress on knee after using kneepads.

1.2   PROBLEM STATEMENT

Vascular injuries are a wide variety of traumatic and nontraumatic injuries to lower limb especially at the knee joint. Nowadays, athletes are facing to the vascular injuries that attack to the knee joint. The vascular injuries most commonly affect the popliteal artery followed by the common femoral artery through the knee joint. The effects to the athletes during gets the injury are receiving pain, swelling and deficits due to occlusion, dissection or aneurysm of the involved by both arteries. Thus, this may be due to the flow of blood flow from both arteries will affected serious injuries to the athletes such as during cycling, running, and jumping.

"Popliteal artery injury is a well-documented complication of trauma to the knee. The popliteal artery is relatively immobile as it is tethered between the adductor hiatus and the soleus arch, which increases its susceptibility to injury during trauma" (Casey et al., 2009)

Cycling sports activities also involve injury of artery especially to the common femoral artery. This can be described, the compression impact to the common femoral artery at knee occurs during the cyclist fall from the bicycle. However, these injuries are low because the external iliac and femoral arteries are protected by the bony pelvis and femoral sheath. "The incidence of trauma to the external iliac artery or common femoral artery has been reported to be as low at 0.4%-7.0% of all vascular injuries. These injuries are rare because the external iliac and femoral arteries are generally well protected by the bony pelvis and femoral sheath." (Casey et al., 2009)

1.3   OBJECTIVES

The objective of this project is to develop the three dimensional modeling of the knee and investigate the blood flow pattern through human leg.

1.4   SCOPE

The scopes of this study are:-

i.   3D modeling of blood flow via femoral and popliteal artery.

ii.   The blood is assumed as incompressible and Newtonian flow.

iii. Focus for athletes' condition during running and cycling.

iv.   Simulate five different materials of kneepads.

v.   Applying with and without kneepads on leg with fixed velocity of blood flow during cycling.

CHAPTER 2

LITERATURE REVIEW

2.1   INTRODUCTION

In this chapter, the basic knowledge of human artery of popliteal and femoral artery will be discussed in it. Besides, simple explanations of blood flow in artery will presented. Next, popliteal and femoral artery disease in athletes is will be explained. The simple explanation of fluid flow theory and the fundamental engineering theories also will be described which is related to the blood flow of the artery during simulation study.

2.2   BLOOD FLOW IN ARTERY

In human blood circulation, the blood flows from the heart to arteries, which branch narrows into the capillaries and arterioles. After the tissue being hit, capillaries join and widen to become venules and then widen more to become veins, which return blood to the heart.

The function of heart is to pump and supply the blood to the entire body, through the artery blood vessel. Arteries are normally carrying oxygenated blood, exceptions made for the pulmonary and umbilical arteries. In the circulatory system, the arterial system is the higher pressure portion and arteries are more muscular than veins. During heart contraction or also called systolic pressure the artery condition is the peak pressure while at the minimum, or diastolic pressure between contractions, when the heart expands and refills (Casey et al., 2009).

All arteries consist of three distinct layers, media, intima and adventitia, but the proportion and structure of each varies with the size and function of the certain artery. The Figure2.1 below shows the arterial layers of a human body:
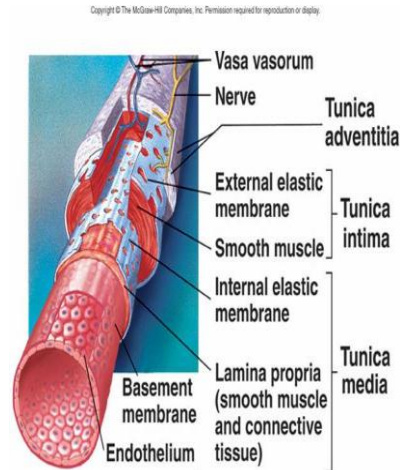
Figure 2.1: The arterial layers of a human body

Source: Ku (1997)

Besides, the knee joint is a second important part of body after the heart. Knee joint is located at lower limb extremities of body which is supported the top of body for stability. This includes parts of the femur, tibia, cartilage, ligament and meniscus between bones. The bones and parts of the joint are surrounded by arteries for blood supply through lower limb body. Knee joint is surrounded by the important arteries of larger femoral and popliteal. Figure shows the artery of femoral and popliteal artery around knee human leg.
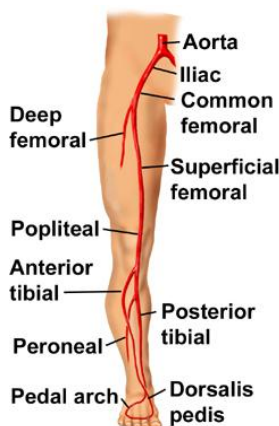
Figure 2.2 : Popliteal and femoral artery

Source : http://primumn0nn0cere.wordpress.com

According previous study blood flow in arteries is dominated by unsteady flow phenomena. The system of cardiovascular is an internal flow loop with multiple branches in which a complex liquid circulates. The normal arterial flow is laminar with secondary flows generated at curves and branches. In hemodynamics conditions, arteries can adapt to change the flow in many variations (Ku et al., 1997).

The previous research of the arteries will supplying blood, must respond to local changes in the end organs while maintaining overall homeostasis of the circulatory system. In the normal condition, the arteries can adapt to changes blood pressure. However, the arteries may unable to provide blood to important organs because unable to respond for imposing forces (Taylor et al., 1998).

2.3   POPLITEAL ARTERY

Popliteal artery is the main artery of knee joint. This artery is located at the behind of the knee joint in the popliteal fossa and is a direct extension of the superficial femoral artery after it passes through the adductor hiatus, an opening in the tendinous slip of the great adductor muscle of the thigh. The popliteal artery lies posterior to the femur and anterior to the popliteal vein. The popliteal artery and vein are normally located between the two heads of the gastrocnemius muscle (Wright et al., 2004)

2.4   FEMORAL ARTERY

The femoral artery is one of the arteries in the human body which is often afflicted by atherosclerosis (Hoogstraten et al., 1996). These arteries are continued from the external iliac artery after passes under the inguinal ligament. The oxygenated blood is carried away from the heart through the femoral arteries by supplying to lower limb of the leg.

2.5   POPLITEAL AND FEMORAL ARTERIES DISEASES

2.5.1   External Iliac Artery Endofibrosis/ Common Femoral Artery

External iliac artery endofibrosis is one of the most commonly described lower extremity vascular conditions in competitive athletes. External iliac and femoral artery is rare injuries because the arteries are well protected by the bony pelvis and femoral sheath. When the external iliac travels between the superior pubic ramus and the inguinal ligament and femoral artery within the femoral artery then the injury may occur because the portion of the external iliac is least protected. From the several reports of sports medicine the blunt trauma may occur in the common femoral artery, most often due to the bicycle handlebar trauma. The mechanism of the injury occurs by the compression of the artery against underlying osseous structures, leading to intimal disruption, luminal fibrosis, subintimal fibrosis or intramural hematoma (Taylor et al.,1998).

2.5.2   Popliteal Artery Entrapment Syndrome

This is the common effect of the popliteal artery entrapment syndrome through the knee joint. This syndrome has occurred when the compression occurs in the popliteal artery by surrounding the musculotendious structure. The popliteal entrapment syndrome occurs in common activities such as basketball, football, rugby, and martial arts (Jaff et el ,.2010).

In popliteal entrapment syndrome it can be classified two types of entrapment such as anatomy and functional. In anatomic cases syndrome when the popliteal artery in abnormal displacement with the head of the gastrocnemius muscle. The Figure 2.3 shows graphic illustrations of normal anatomy of popliteal fossa and common variants responsible for arterial entrapment. Besides, the functional popliteal entrapment syndrome occurs when the positional compression of the popliteal artery in the absence of anatomic abnormalities. Rignault et al (1985) state in their study for the functional artery syndrome is attack to athletes because the hypertrophied gastrocnemius muscles, sometimes coinciding with the use of anabolic steroids. In neutral positions of foot, there a no symptoms but compression of the popliteal artery may occur during active plantar flexion or with passive dorsiflexion show in the Figure 2.4.
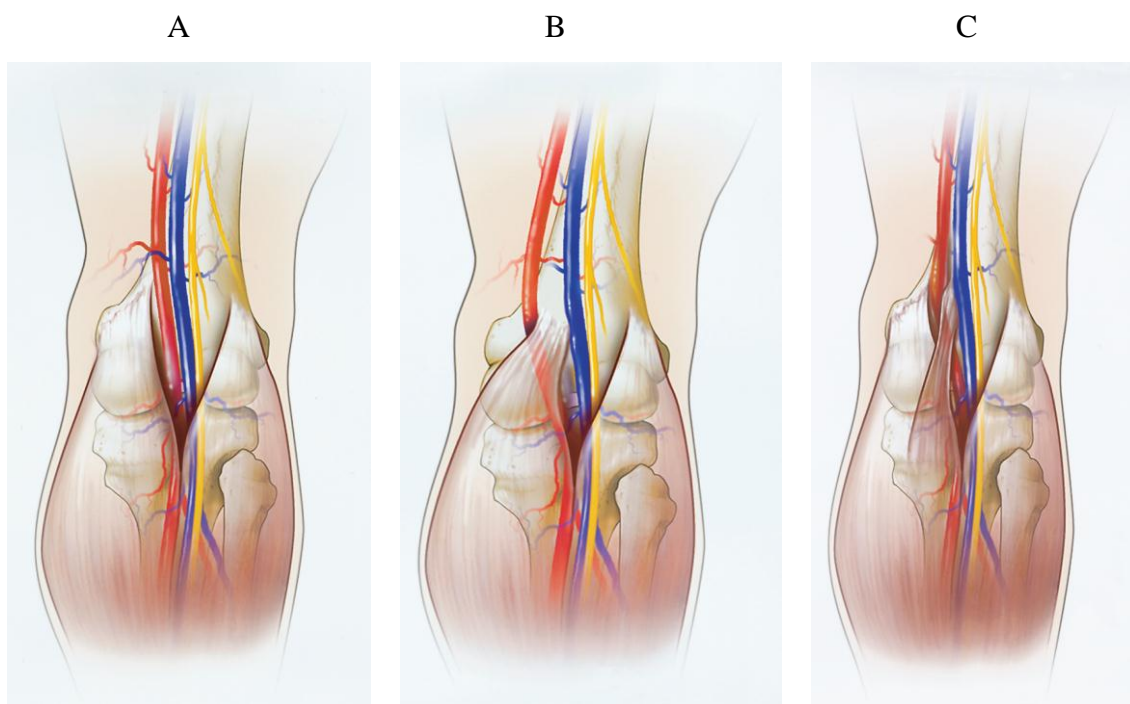
A   B   C

Figure 2.3: Graphic ilustration show normal anatomy of popliteal fossa and common variants responsible for arterial entrapment. (A) Normal Popliteal artery, (B) Abnormal Embryologic and (C) Anamalous Muscle

Source : Thanila A.Macedo et.al (2003)

Figure 2.3 shown the three different of arteries in knee joint. In figure A represent the normal popliteal artery is adjacent to and laterals to medial head of gastrocnemius muscle, which is normally attached just superior to medial femoral condyle. Next, in figure B is abnormal embryologic development can result in numerous anomalous popliteal fossa relationships responsible for entrapment. For example, medial head of gastrocnemius muscle may be attached more laterally than is normal. Lastly in figure C is anomalous muscle band may be responsible for abnormal attachment.
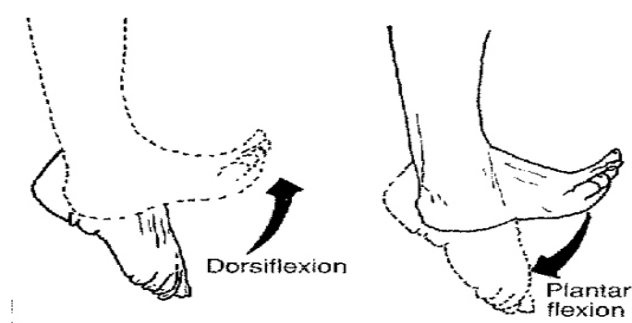
Figure 2.4: Compression popliteal artery during dorsiflexion and plantar flexion

Source : http://sheltonstevens.com/

2.5.3   Cystic adventitial disease of the popliteal artery

Cystic adventitial disease occurs at popliteal artery and commonly effect for males and athletes. This disease occurs when the popliteal artery wall is formed cyst. The cyst is formed with abnormal character and containing fluid. The cyst can cause the affected artery to become blocked or narrowed. The symptoms of this disease are calf cramps and leg pains (Jaff et al., 2010). Figure 2.5 below shows the normal anatomy of popliteal artery and the cyst are form.

a) Normal anatomy of popliteal artery   b) Cyst formation

Figure 2.5: Normal anatomy of popliteal artery and cyst formation

Source : Rector and Visitors of the University of Virginia (2012)

2.6   SPORTS ACTIVITIES RELATED TO ARTERY INJURY

Nowadays, athletes are vulnerable get the vascular injuries to lower limb especially at knee joint. From the literature review, many of vascular injury are effect to the main artery of knee such as popliteal and femoral artery. These both of artery are very important in order to supply blood around knee joint. The retirement from sports may occur, if the vascular injury attacks to the lower limb leg and leg may loss function.
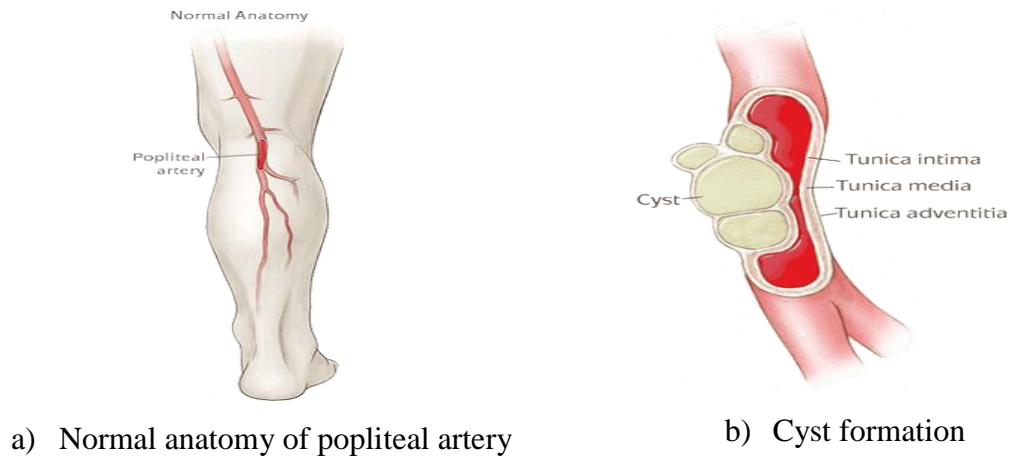
In the literature review, traumatic arterial injuries may occur to the common femoral artery. Cycling is a famous sports activity because this sport is not heavy. However, vascular injury may occur to the femoral artery during a fall from a bicycle. This incidence is rare effect to the common femoral artery because artery is generally protected by the bony pelvis and femoral sheath (Casey et al., 2009).

Besides, football is the activities very related to the lower limb body especially in the knee joint. In previous study, vascular injury entrapment syndrome to the popliteal artery may affect to a footballer. The effect popliteal artery injury to the footballer is blunt trauma, hypertension, dislocation, periarticular fractures and ligament rupture. Thus the injury cause flow interruption in the popliteal artery and the patients

may complain of pain, parethesias, or loss of sensation or motor function distal to the knee (Casey et al., 2009).

2.7 GOVERNING EQUATION

Governing equation is the equation of the dynamic fluid flow theory that used to describe the behavior of blood flow. The governing equation is consisting of continuity equation, momentum equation and energy equation. It is used to perform simulation of fluid dynamics to obtain the result of iteration. The derivation of equations based on physical law such as mass conservation, Newton's second law and first law of thermodynamics (Jiyuan et at., 2008)

2.7.1 Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{2.1}$$

Equation 2.1 above is the three-dimensional continuity equation that is derived from the conservation of mass. The illustration of the conservation of mass in an infinitesimal control volume of a fluid flow between two stationary parallel plates are analyzed to form the flow field in direction of *u, v and w* (Jiyuan et al., 2009). Since the fluid is assumed to be incompressible fluid flow then the density ρ can be constant and there are no changes in mass and volume. In 3 dimensional simulations of blood flow in main arteries, the velocity profiles can be represented by velocity component u, v and w where the *u* velocity component is related to *x* coordinate direction, *v* velocity components is related to *y* coordinate direction and *w* velocity components is related to *z* direction.

2.7.2 Momentum Equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{p}\frac{\partial p}{\partial x} + v\frac{\partial^2 u}{\partial x^2} + v\frac{\partial^2 u}{\partial y^2} + v\frac{\partial^2 u}{\partial z^2} \tag{2.2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{p}\frac{\partial p}{\partial y} + v\frac{\partial^2 v}{\partial x^2} + v\frac{\partial^2 v}{\partial y^2} + v\frac{\partial^2 v}{\partial z^2} \tag{2.3}$$

$$\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{p}\frac{\partial p}{\partial z} + v\frac{\partial^2 w}{\partial x^2} + v\frac{\partial^2 w}{\partial y^2} + v\frac{\partial^2 w}{\partial z^2} \tag{2.4}$$

Equations 2.2, 2.3 and 2.4 above are the *x-*, *y- and z-*components respectively of the momentum equation. Since the fluid in 3-dimensional flow, the all components of *x, y* and *z* need to be considered in simulation part. The three equations above need to derive in Newton's second law in order to represent the v as kinematic viscosity of fluid, μ as viscosity of fluid and ρ as density of fluid. Thus, the symbol of u, v and w is represent the velocity components in the x, y and z coordinated direction while ρ is used as pressure applied. The Equation 2.5 below represents the kinematic viscosity formulation. Since, in simulation of blood flow considered the constant viscosity and density of fluid properties setup, then the kinematics viscosity can be calculated by using Equation 2.5. In a Newton's second law of motion defined as the forces acting on the body of fluid element is equals to product between mass of fluid and acceleration of the element. Navier Stokes equation can be described by the conservation of momentum in the fluid flow (Jiyuan et al., 2009).

$$v = \frac{\mu}{\rho} \tag{2.5}$$

2.7.3 Energy Equation

As known the energy conservation is derived from the first law thermodynamics. First law thermodynamics Equation 2.6 defined as the time rate of change energy is equal to sum of the net rate of heat added and net rate of work done (Jiyuan et al., 2009).

$$Time\ rate\ of\ change\ of\ energy = \sum \dot{Q} + \sum \dot{W} \tag{2.6}$$

$$\frac{dT}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial x^2} + \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} + \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial z^2} \tag{2.7}$$

Equation 2.7 above is the energy equation in 3dimensional, which derived from the thermodynamics law. Since the working fluid is blood to be analyzed, then the energy fluid is defined as the sum of the internal energy, and gravitational potential energy. In the study of 3 dimensional simulations, the fluid of blood is assumed as incompressible, thus it can be neglecting the kinetic energy, the enthalpy h can be reduced to C_pT, where C_p is the specific heat and is assumed to be constant.

2.8   FLUID FLOW THEORY

2.8.1   Newtonian Fluid

Newtonian fluids defined as fluids for which the shear stress is linearly proportional to the shear strain rate. Most common fluids such as air and other gases, water, kerosene, gasoline, and other oil-based liquids are Newtonian fluid. The viscosity of a fluid is a measure of its resistance to deformation. Since in Newtonian fluid, then the viscosity of the fluid can be assumed constant when constant temperature and constant pressure are applied. These are because the viscosity is only depends on the temperature and pressure, not on the force exert upon it while Newtonian fluids (Cimbala et al., 2010). In the simulation, blood can be constant viscosity if fluid is assumed to be Newtonian.

2.8.2   Incompressible Flow

Incompressibility is an approximation, in which the flow is said to be incompressible if the density remains nearly constant throughout. Thus, the volume of every portion of a fluid remains unchanged over the course of its motion when the flow is approximated as incompressible. The Equation 2.8 of condition for incompressible flows is given by the equation below, where V is the speed of flow and c is a speed of the fluid, if the Mach number, Ma of the flow is small, and then the fluid density changes could be neglected (Cimbala et al.,2010).

$$Ma = \frac{V}{c} < 0.3$$

(2.8)