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FLOW DYNAMICS IN PARTIALLY BLOCKED TIBIAL ARTERY

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ABSTRACT

Tibial artery comprises of two branches, anterior and posterior sides of the subject. These arteries are often obstructed due to plaque formation. They are also affected by several other conditions like hypertension, diabetes, smoking, drinking. In the present paper, peak wall shear stresses and velocities are computed for seventy percent blocked bifurcated tibial artery at varying postures. Three postures sitting, erect and supine positions are considered for the analysis and on the other hand, the artery is assumed to be affected by diabetes and hypertension. In normal arterial flow, the maximum velocity is noticed at supine posture. In contrast, the maximum wall shear stress is observed in a diabetic affected artery when compared to a normal arterial flow. In anterior and posterior tibial arteries, the peak velocities in normal and diabetic arteries are observed at 45-degree bifurcation. In contrast, peak stresses in normal and diabetic affected arteries at the anterior and posterior tibial arteries are noted at 60-degree bifurcation. The study presents the effect of artery bifurcation when subjected to comorbidities at various postural changes.

KEY WORDS: Tibial Artery, Postures, Bifurcated artery, comorbidity, hypertension, diabetes, stenosis

1. INTRODUCTION

Peripheral artery disease (PAD) is a circulatory disease, in which blood flow in the limbs is restricted due to narrowing. This problem is most common among senior people and records show that 14 to 29% of them are above 70 years of age. Comorbidities like smoking, age, diabetes, high blood pressure is the leading problem that is associated with PAD. It is observed that 50% of the PAD patient's exhibit pain in the lower extremities and 40% of them suffer with asymptomatic symptoms [1]. PAD could increase the risk of death in patients by 25%. From the studies, it is observed that 80-90% of CVD (cardio vascular disease) are due to the involvement of diabetes, hypertension, smoking and hyperlipidemia [2]. PAD is observed more commonly in men than women [2]. However, PAD affects women more severely. Approximately 3 to 29% of the adult females between the age groups 45 to 93 suffer with PAD [4]. PAD can be evaluated using an ankle brachial index and based on the specific ranges, the severity of disease can be determined. PAD and tobacco abuse have a stronger association than ischemic heart disease and tobacco abuse. Thus, the risk for PAD is sixteen times greater in smokers and seven times greater in ex-smokers. Even though hypertension is a risk factor for PAD to occur, diabetes and smoking affect PAD more than hypertension [2]. The other risk factors include the raised levels of C-reactive protein (CRP), homocysteine, fibrinogen, lipoprotein and plasma viscosity [3]. Symptoms of PAD include intermittent claudication which is otherwise pain, cramping, aching in the calves and thighs. In addition to this, extremity PAD indicates critical limb ischemia, which includes tissue loss, rest pain and limb-threatening manifestations [3]. Lower limb amputation occurs mainly due to diabetes and PAD. In addition, diabetic PAD increases the risk of morbidity and mortality from cardiovascular diseases [5]. Tibial arteries play a

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major role in supplying the right amount of blood flow to the feet. If one of the tibial arteries is compromised, the other tibial artery can compensate the total blood flow velocity to the feet [6]. A tibial artery in the lower extremity is subjected to peripheral ischemias and it is important to treat them by revascularization [7]. Hence the present work is based on peripheral artery disease in tibial artery when subjected to several comorbidities.
Exercise technique is a common recommendation for PAD patients but it is really important to understand the consequences when the patient is suffering with diabetes or anemia. 70 to 80% PAD patients suffer with claudication over a ten-year cycle. To improve the quality of life and decrease stroke and cardiovascular death, exercise programs and revascularization techniques should be performed [8]. Diabetes on the other hand causes atherosclerotic occlusive disease in the lower extremities. A clinical study was conducted on patients to observe the occlusion lesions in different arteries when blood flow is affected by diabetes. The study shows more than 10cm occlusion lesions in anterior and posterior tibial arteries than in iliac artery [9]. Diabetes patients could also cause coronary artery disease. This can be identified from a quantitative clinical study on stiffness and impaired blood flow in lower arteries of the leg [10]. The volume of blood flow, average velocity and peak systolic velocity decreases in the lower limb arteries when they are subjected to postural changes. These variations are observed in patients with intermittent claudication when posture changes from recumbency to sitting [11]. Postures also affect the systolic blood pressures in middle aged adults. A change in magnitude and direction of posture affects the social demographics, cardiovascular comorbidities and cigarette smoking. Clinical studies were conducted with men and women from several countries to observe the effect of comorbidities along with postural changes [12].

Previous studies indicate the correlation of PAD, posture changes and its effect on cardiovascular variables. The present study mainly focuses on analysis of bifurcated blocked tibial artery when subjected to high blood pressure and diabetes at various postures. Bifurcated arteries with a blockage cannot be treated with stents for patients with 70 years of age. Some patients use physiotherapy as a means for exercise and therapists should have knowledge on blood flow patterns in PAD patients with diabetes and blood pressure. This study provides therapists details of velocities and shear stresses in PAD patients with comorbidities at varying postures.

3. METHODOLOGY

3.1 Computational Analysis

A two-dimensional tibial artery is modeled with seventy percent blockage at the bifurcation (Fig.1). Tibial artery is divided into anterior tibial artery and posterior tibial artery. The dimensions of the artery are provided in table 1. In the present analysis both the segments are modeled with seventy percent blockage at the bifurcation. The blockage percentage was defined based on the reduced arterial dimensions. Computational fluid dynamic analysis is conducted by meshing the model at high density with uniform interval size and mesh independency was checked. Blood flow in the artery is defined with mean pressure inlet and it leaves the artery as pressure outlet.

Table 1 Geometry of Tibial Artery [13]

Artery	Length (mm)	Radius (mm)
Peroneal Artery	159	1.3
Anterior Tibial **(AT)**	25	1.3
Posterior Tibial **(PT)**	161	1.8

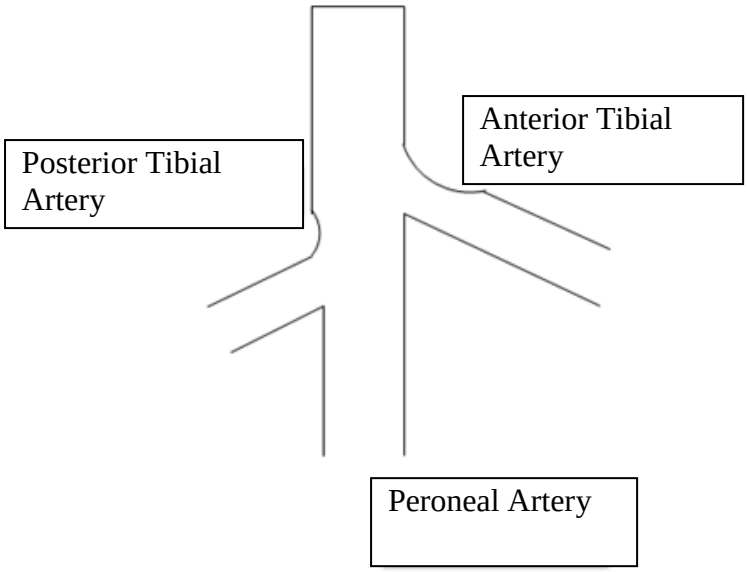


Fig.1 Anterior and Posterior Tibial Artery Model

The present analysis compares healthy blood flow conditions with diabetic blood. The properties vary with respect to both the blood flow conditions which are indicated in Table 2 [14]. Blood is assumed to flow in the cell zone. The density of blood is 1050kg/m^3 and an unsteady blood flow is defined using a C-program. The blood flow in the artery is affected with diabetes and this study analyzes, anterior and posterior tibial arteries at three different postures. A clinical study has determined the systolic and diastolic pressures at sitting, supine and erects position of the human body [Table 3]. The mean arterial pressures inlets of the tibial arteries at three different postures are defined based on the systolic and diastolic blood pressures [Table 2].

Table 2 Viscosities of Normal and Diabetic Artery with Varying Mean Arterial Pressure Inlets [14]

Normal Artery (Viscosity) Pa.s Material Property	**Diabetes Mellitus (viscosity) Pa.s Material Property**
0.0035	0.00802

Table 3 Diastolic and Systolic Pressures at Varying Postures [15]

Position	**Systolic Pressure (mm of Hg)**	**Diastolic Pressure (mm of Hg)**	**Mean Arterial Pressure (mm of Hg)**
Erect	140	112	121.33
Sitting	160	115	130
Supine	170	120	136.66

3.2 Governing Equations

The flow inside the femoral artery is considered to be incompressible and blood is considered a non-Newtonian fluid. The continuity and Navier-Stokes equation for a two-dimensional cylindrical coordinate (r, z) can be written in a differential conservation form which is shown below.
Continuity Equation for two-dimensional arterial flow is given by:

$$(1/r*(\partial(ru_r)/\partial r)) + \partial u_z/\partial z = 0 \quad (1)$$

Momentum equation in r-direction is given by

$$\partial u_r/\partial t + u_r \partial u_r/\partial r + u_z \partial u_z/\partial z = -1/p\partial p/\partial r + \mu/\rho[\partial/\partial r(1/r\partial(ru_r)/\partial r + \partial^2 u_r/\partial z^2)] \quad (2)$$

Similarly, momentum equation in z-direction is given by

$$\partial u_z/\partial t + u_z \partial u_z/\partial r + u_z \partial u_z/\partial z = -1/p\partial p/\partial z + \mu/\rho[1/r\partial/\partial r(r\partial u_z/\partial r + \partial^2 u_z/\partial z^2)] \quad (3)$$

Where u is the velocity with which blood flows, t is the time taken, ρ is the density of the blood, (r and φ) are direction of blood flow and p is the pressure.

Boundary Conditions:
The boundary conditions used in the present analysis are

<u>For Unsteady Flow Condition:</u>

A periodic velocity boundary condition can be applied to the inlet of the normal and stenosed artery using User Defined Function (UDF). The general equation obtained from FLUENT is given by

$$P_z = P_0 + A\sin\omega t \text{ [16]} \quad (4)$$

Where P_0 is the initial pressure, P_{avg} is the average systolic and diastolic pressure
At the outlet of the artery, the pressure with which blood exits is given by:

$$\partial p_r/\partial z = \partial p_z/\partial z = 0 \quad (5)$$

At the wall surface of the artery:
No slip flow condition is assumed: $u_z=0$

4. RESULTS AND DISCUSSIONS

In this chapter, two branches (anterior and posterior ends) of tibial artery were modeled and analyzed. When the anterior and posterior tibial arteries are seventy percent blocked, the maximum wall shear stress and velocities at the blockage were analyzed at three different postures. In addition to this, the bifurcation angles of the anterior and posterior tibial arteries were varied in a healthy and diabetic artery. In a blood vessel, when viscosity increases, the velocity in the blood vessel decreases. In anterior tibial artery, the maximum velocity in a blocked bifurcated artery is observed in a 45-degree bifurcated artery [Fig.2].

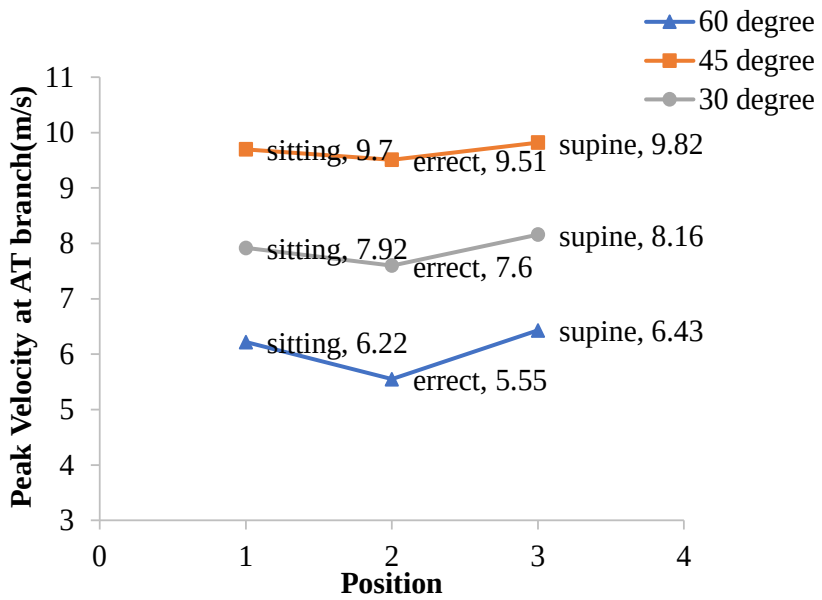


Fig. 2 Effect of Posture & Angle on Velocity in Blocked AT Artery with Healthy Arterial Flow

Maximum velocity in a 45-degree anterior tibial artery bifurcation is exhibited at the supine position in healthy arteries. In both healthy and diabetic arteries, the supine position exhibits higher velocity than the sitting and erect positions. In a 60-degree bifurcated artery, the maximum velocity in a healthy artery at supine posture is 6.43, whereas the maximum velocity in a diabetic artery at supine posture is 6.3. In posterior tibial artery, the velocity in a blocked bifurcated artery is high in a 45-degree bifurcated artery.

Similarly, peak velocity in a 60-degree posterior tibial artery bifurcation is observed at supine position. The analysis shows that erect position has a lower velocity when compared to sitting position. At 60 degrees bifurcated arteries, the velocity is observed in a posterior tibial artery, when compared to the anterior tibial artery. In contrast, velocities in Anterior and Posterior tibial arteries in a 45-degree bifurcated artery are 9.82m/s at all the three postures and under the same health condition. This case is validated with another research article written by author Ku.D in which higher velocities are noticed at supine position in anterior and posterior tibial artery[17]. In addition to the postures in tibial artery, this research differentiates blood flow patterns in the diabetic and healthy artery with different bifurcation angles.

When blood flow in a blocked bifurcated anterior tibial artery is affected with diabetes, the maximum velocity is observed in a 45-degree bifurcated artery at supine position [Fig.3]. Similarly, under the same blood flow conditions in a posterior tibial artery, velocity is high at the 45-degree blocked region [Fig.4].

Velocities in an anterior tibial artery are same as the velocities in posterior tibial artery in a 30-degree bifurcated artery at all the three postures. However, the velocity among the three different bifurcations is observed at the supine position in a 45-degree bifurcated artery. 45-degree angle has a sharp curve when compared to 30 and 60 degree bend. The sharp curve and the blockage can cause increase in velocity of the blood.

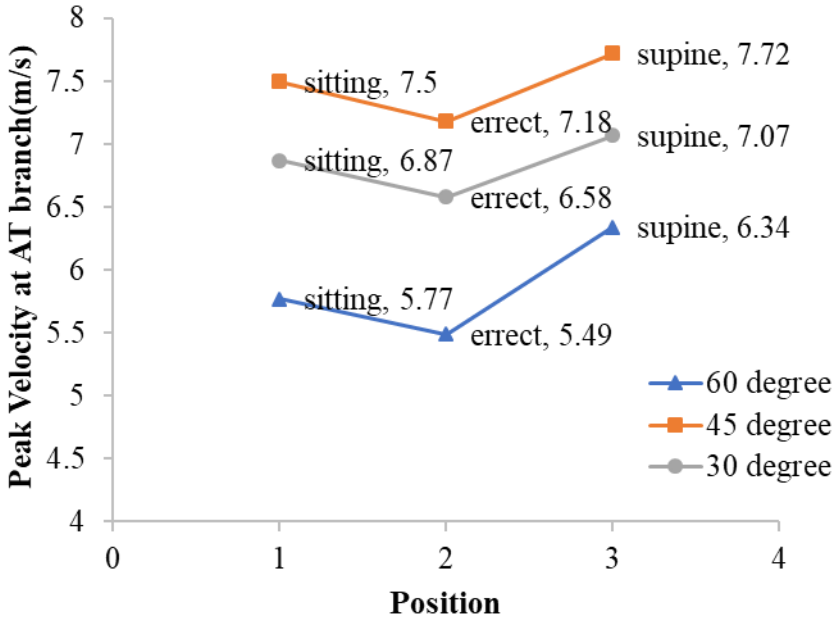


Fig.3 Effect of Angle & Posture in Diabetic Effected Blocked Bifurcated AT Artery

The minimum velocity among the three-different bifurcation is observed at 60 degrees bifurcated anterior tibial artery at erect position. Stress, on the other hand plays an important role when the viscosity changes in healthy and diabetic effected arteries. In an anterior tibial artery, the stress is higher in a 60-degree bifurcated artery than 30 and 45 degrees. Among the three postures, supine posture exhibits high stress values with normal arterial blood flow. Similar results are exhibited in a posterior tibial artery; however, the stress in anterior tibial artery is higher than posterior tibial artery by 5% due to the change in stenosis locations at the bifurcation. Fig.5 and Fig.6, indicates graph for diabetic effected anterior and posterior tibial arteries at three different postures. The bifurcated blocked anterior and posterior tibial arteries indicate that the stress is high at 60-degree bifurcation. At supine position, maximum stress value is observed in a diabetic affected anterior tibial artery compared to diabetic affected posterior tibial artery.

In a 60-degree bifurcated anterior and posterior tibial arteries, the maximum stress is observed at the supine posture of the anterior tibial artery. The diabetic affected artery has high stress effects than a healthy artery which relates to viscosity and shear stress theory of increase in viscosity increases shear stress. When diabetic affected anterior and posterior tibial arteries are bifurcated at 45 degrees, maximum stress is exhibited in supine posture. Similarly, at supine position, maximum stress occurs in a diabetic effected artery at 30-degree bifurcation. In addition, the low stresses are noticed in a 45-degree bifurcated artery at erect posture with the normal arterial flow. The present research analysis on bifurcation angles and shear stresses correlates with the experimental results obtained by authors Cacho A.O et al which shows high shear stresses in 60-degree bifurcation angle and low shear stress in 45 degree bifurcated angle [23]. Several studies were conducted by different authors to determine the correlation of bifurcation and shear stress. A proper conclusion was not obtained but similar correlations were observed by most studies. These observations can help doctors and therapists draw conclusions on how to handle individual patients with multiple health conditions.

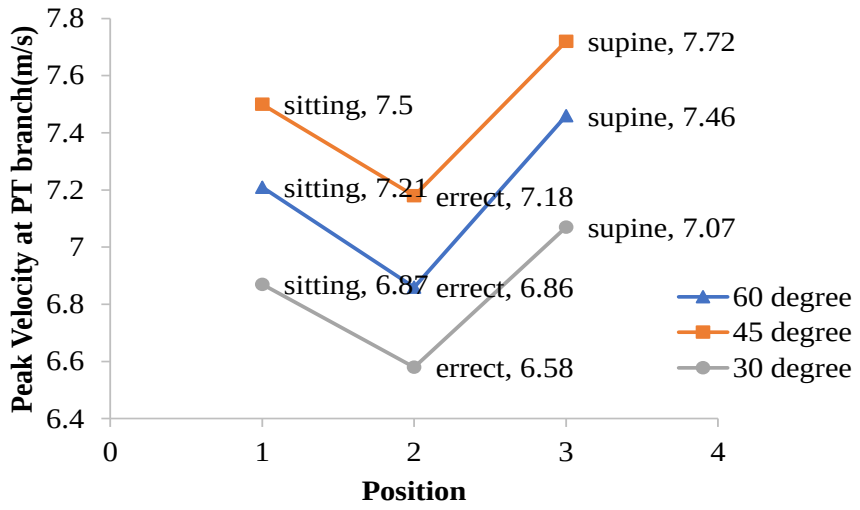


Fig.4 Effect of Angle & Posture in Diabetic Effected Blocked Bifurcated PT Artery

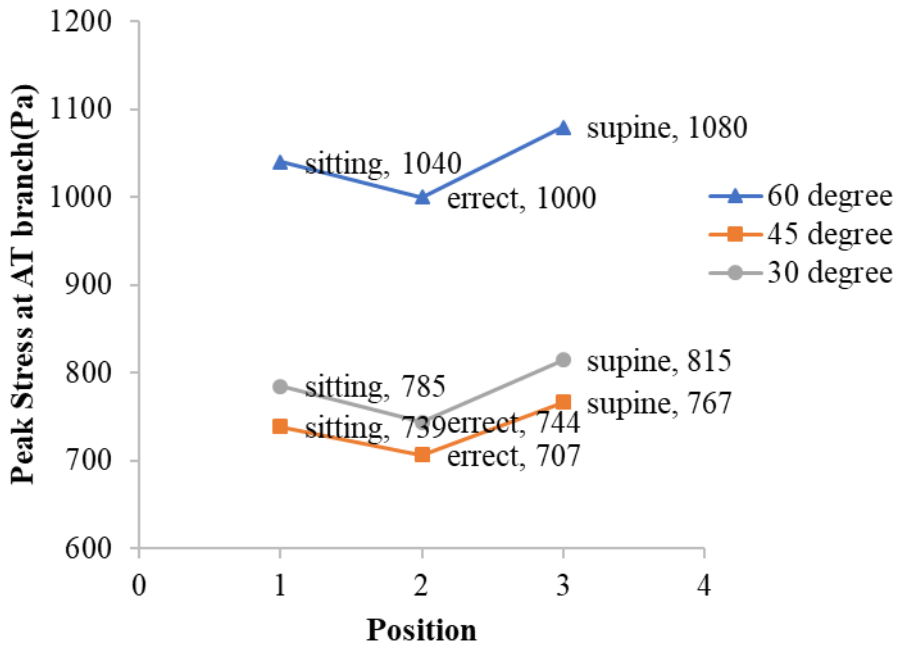


Fig.5 Effect of Angle & Posture on Stress in Diabetic Effected Bifurcated AT Artery

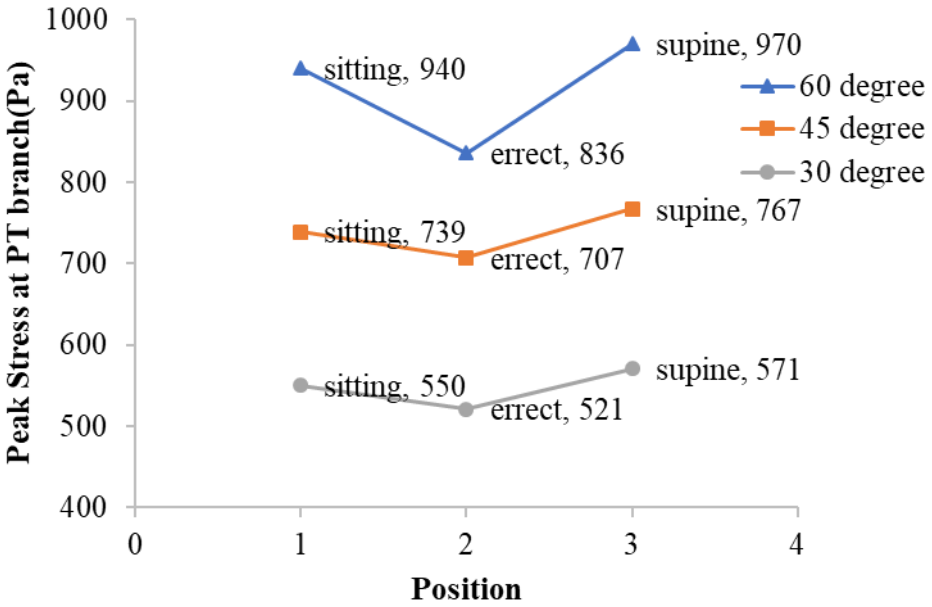


Fig.6 Effect of Angle & Posture on Stress in Diabetic Effected Bifurcated PT Artery

4.1 Clinical Aspects

Two set of angles are compared with respect to their stress effects in healthy and diabetic affected stenosed arteries. The maximum stress difference in healthy and diabetic artery is higher in 60 degree bifurcated artery at sitting and standing postures from Table 4. This shows that while exercising, patients with 60 degree bifurcation AT artery have more arterial stress.

Table 4 Percentage Difference in stress values between healthy and Diabetic AT Artery at Varying Postures

Diabetic	Max Stress at AT branch-60	Max Stress at AT branch-45	Max Stress at AT branch-30	% diff btw Healthy and Diabetic artery at 60	% diff btw Healthy and Diabetic artery at 45	% diff btw Healthy and Diabetic artery at 30
sitting	1040	739	785	96.96	53.95	57.95
erect	1000	707	744	98.02	52.04	56.96
supine	1080	767	815	77.63	54.95	57.95

Table 5 Percentage Difference in velocities of Healthy and Diabetic AT Artery at Varying Postures

Diabetic	Max Velocity at AT branch-60	Max Velocity at AT branch-45	Max Velocity at AT branch-30	% diff btw Healthy and Diabetic artery at 60	% diff btw Healthy and Diabetic artery at 45	% diff btw Healthy and Diabetic artery at 30
sitting	5.77	7.5	6.87	7.23	22.68	13.25
erect	5.49	7.18	6.58	1.08	24.5	13.42
supine	6.34	7.72	7.07	1.4	21.38	13.35

Table 5 presents percentage difference in maximum velocities in healthy and diabetic AT artery. The comparative analysis in velocities shows that standing position in diabetic patients can cause difficulty in blood flow to the heart. Physiotherapy exercises involve sitting and standing and hence therapists should analyze the patients' health condition and artery structure before assigning them with specific exercises.

Table 6 Percentage Difference in stress values between healthy and Diabetic PT Artery at Varying Postures

Diabetic	Max Stress at PT branch-60	Max Stress at PT branch-45	Max Stress at PT branch-30	% diff btw Healthy and Diabetic artery at 60	% diff btw Healthy and Diabetic artery at 45	% diff btw Healthy and Diabetic artery at 30
sitting	940	739	550	64.91	53.95	58.05
erect	836	707	521	49.02	52.04	56.93
supine	970	767	571	67.82	54.95	58.17

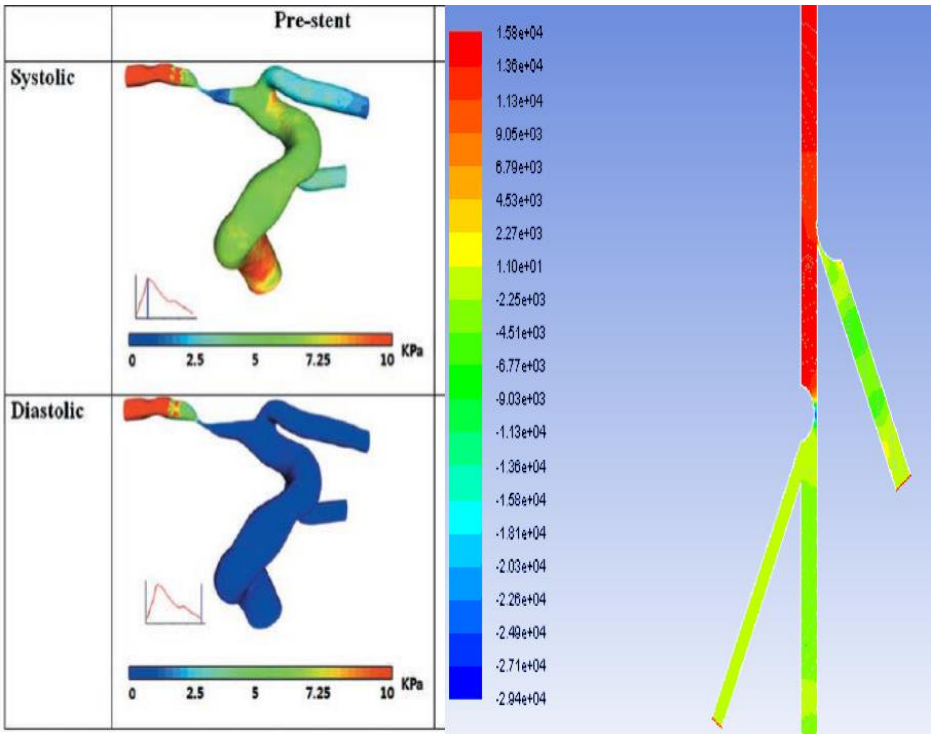
Table 7 Percentage Difference in velocities of Healthy and Diabetic PT Artery at Varying Postures

Diabetic	Max Velocity at PT branch-60	Max Velocity at PT branch-45	Max Velocity at PT branch-30	% diff btw Healthy and Diabetic artery at 60	% diff btw Healthy and Diabetic artery at 45	% diff btw Healthy and Diabetic artery at 30
sitting	7.21	7.5	6.87	18.9	22.68	13.25
erect	6.86	7.18	6.58	19.67	24.5	13.42
supine	7.46	7.72	7.07	18.74	21.4	13.36

Similarly, Table 6 and 7 presents percentage difference in shear stresses and velocities in a healthy and diabetic posterior stenosed tibial artery. Consistent results in shear stress and velocities were observed in a normal artery and stenosed artery which shows increase in blood pressure to heart. PAD can be treated in four stages. Stage 1 is where patients notice pain in the leg and identify the problem and try to get treatment from the clinic. Stage 2 is where patients take help from physiotherapists, increase exercise and try to reduce the pain due to PAD. Stage 3 is where patients definitely need endovascular revascularization and stage 4 is where they need limb amputation [18]. Research proves that exercise therapy has the potential to reduce PAD affects on patients and reduce cardiovascular events [19]. However, the European Society for Vascular Medicine suggests individual analysis on each patient suffering with PAD [18]. General suggestions for PAD patients like exercise therapy may not be suitable if they have other complications like anemia and diabetes. They suggest PAD patients should be treated conservatively in specialized centers. The present study computationally proves that patients should be treated individually based on their arterial anatomy and health condition to receive the right treatment. A generalized treatment method cannot be suggested to PAD patients.

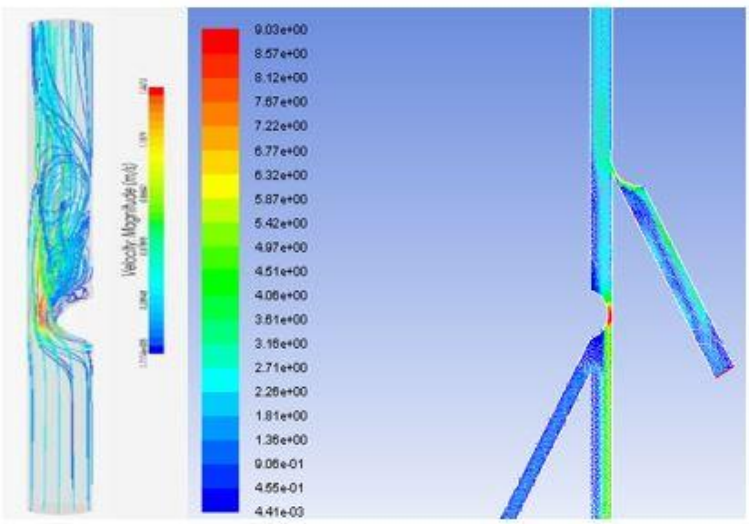
5. VALIDATION OF RESULTS

A bifurcated intracranial stenosed artery [Figure 7a] from a previous study is compared to the bifurcated tibial artery [Figure 7b] in the present study. Fluid structure interactions are applied to the bifurcated stenosed artery, which results in wall shear stress interaction, pressure drop and velocity of the artery. The pressure drop of the blocked tibial artery is higher due to the high percentage stenosis and postural changes.



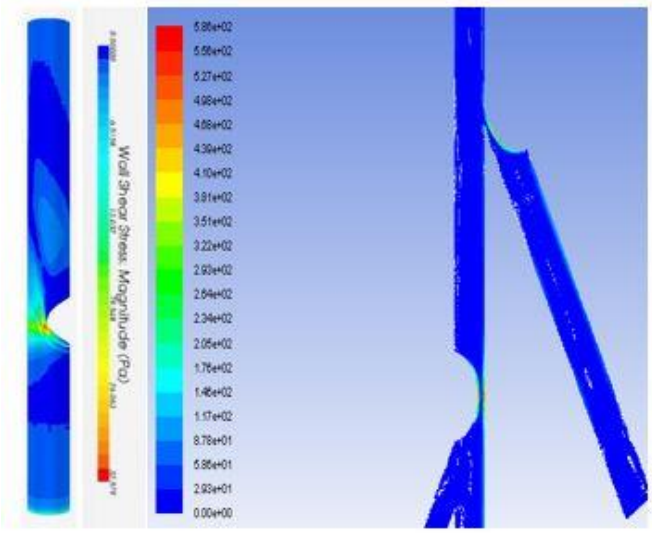
(a) Previous Study Intracranial stenosed artery [20] (b) Tibial Artery Present Study

Figure 7 Comparision of Arterial Pressure Drop From Intracranial Stenosed Artery & Tibial Artery with hypertension



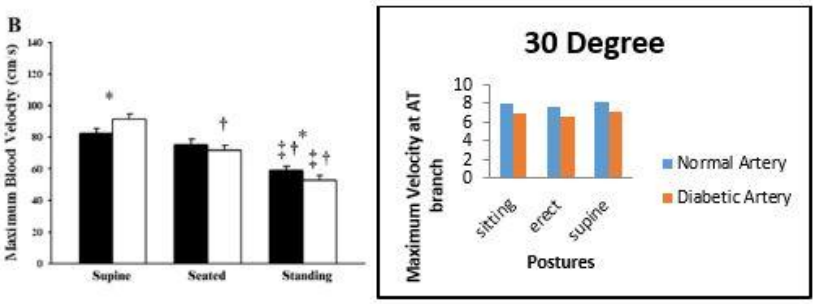
(a) Carotid Artery(Previous Study) [21] (b) Tibial Artery (Present Study)

Figure 9 Comparision of Arterial Velocities From Carotid & Tibial Arteries with hypertension



(a) Carotid Artery Previous Study [21] (b) Tibial Artery with diabetes [Present Study]
Figure 10 Comparision of Arterial Shear Stress From Carotid & Tibial Arteries

A previous study modeled a carotid artery with seventy percent blockage in the artery. A computational fluid dynamic analysis was conducted to obtain the velocity and wall shear stresses in the carotid artery. The velocity and wall shear stresses obtained from the previous study [Figure 9a & Figure 10a] are different when compared to the present study tibial artery [Figure 9b & Figure 10b]. The slight difference in the results are due to the dimensions of the artery, the plaque at the bifurcation and different arterial blood flow conditions.
A superficial femoral artery was investigated at varying postures to observe the effect of postures on the artery [Figure 11a]. A Doppler ultrasound technique was used to study the femoral artery hypothesis. The results show that maximum blood flow velocity was observed in supine posture, followed by sitting and erect posture. The present work also resulted a maximum blood flow velocity in supine posture [Figure 11b]. However, the obtained velocities are higher in tibial artery due to the high stenosis and comorbid arterial blood flow conditions.



(a) Arterial Velocities at Different Postures in Femoral Artery (Previous Study) [22]
(b) Arterial Velocities at Different Postures in Diabetes affected Tibial Artery (Present Study)
Figure 11 Comparision of Arterial Velocities From Femoral & Tibial Arteries

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NOMENCLATURE

P_0	initial pressure	mm Hg
u	velocity of blood flow	m/s
Pavg	average systolic and diastolic	pressure mmHg
t	time	s
ρ	density of the blood	kg/m^3

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