CHAPTER VI
COMPARISON AND ANALYSIS OF EXPERIMENTAL AND FEM RESULTS

6.1. Analysis and Comparison of mechanical properties with Titanium alloy and Stainless Steel

The most commonly used biomaterials are titanium and stainless steel, the purpose of this chapter is to make a comparison of the results obtained in Chapter 2 with the results obtained by a student of Mechanical Engineering, here at UDLAP.

He compared these two alloys in their versions Ti-6Al-4V for titanium alloy and 316L for stainless steel, now it will be compared with Vitallium Co-Cr-Mo alloy.

6.1.1. Hardness

The results of the former penetration test are:

Table 6.1. Hardness results of common biomaterials[98]

Ti-6Al-4V (ASTM grade 5) (HRC)	316L Stainless Steel (HRC)
31	27
31	26
32	27
33	28
32	26
31.8	26.8

The results of this test are:

Table 6.2. Hardness Results of Vitallium alloy

Vitallium Co-Cr-Mo (HRC)
37
35
36
37
35
36

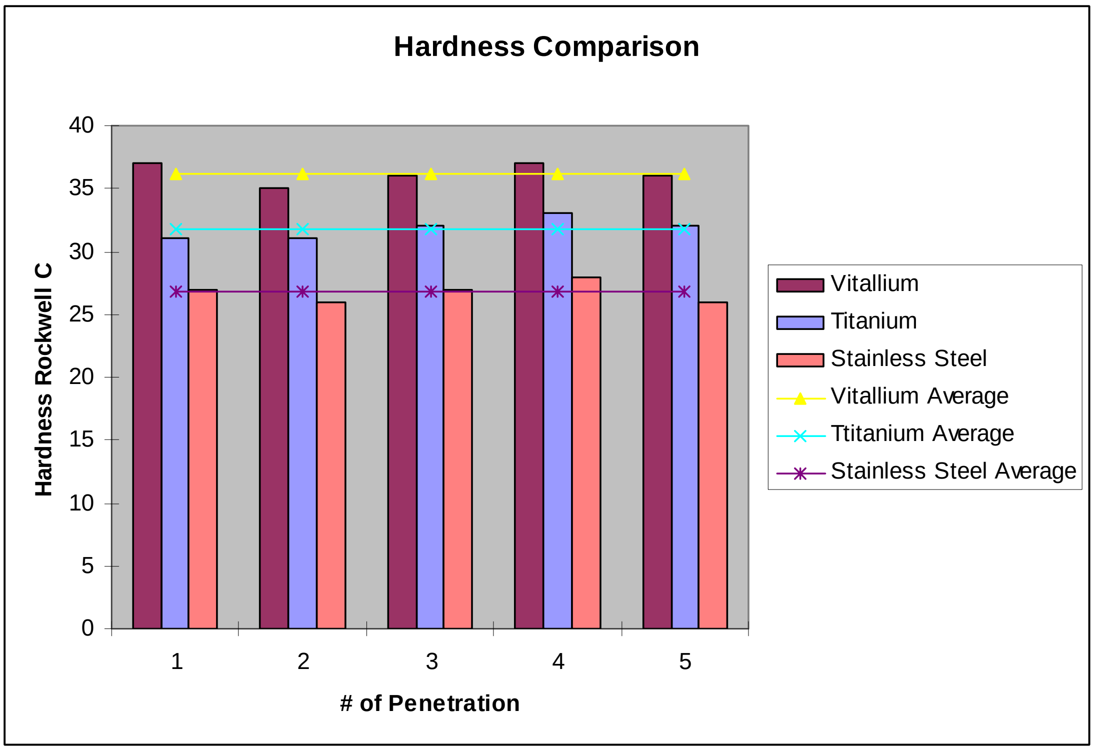


Fig. 6.1. Hardness Comparison Chart

Vitallium implant is 13% harder than the most popular material, the Ti-6V-4V titanium alloy, and 35% harder than 316L Stainless Steel.

6.1.2. Impact

In the previous study, the impact results were: [98]

For Ti-6Al-4V, Charpy energy absorbed = 228.9284 N ^{x} m.

For 316 L SS, Charpy energy absorbed = 201.5032 N ^{x} m.

In Chapter 2 vitallium results were:

For Co-Cr-Mo, Charpy energy absorbed = 76.46 N ^{x} m.

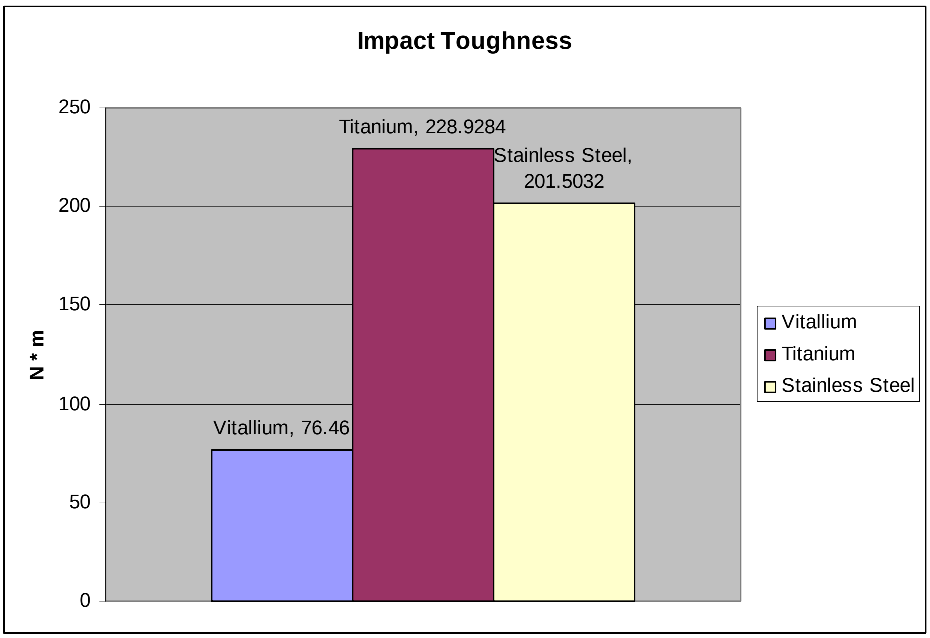


Fig. 6.2. Comparison of Impact Test

It is not possible to compare the materials because of the difference in geometry of the samples, while Vitallium sample had a standard impact test shape, titanium and stainless steel samples were cylinders bigger in volume than the standard sample.

6.1.3. Fatigue

Recalling to fig 2.8, page 23; it is possible to see that the maximum load resisted by the chrome-cobalt-molybdenum alloy is of 170 ksi or 1.1 GPa for 10,000 cycles. And, again according to the same figure, it is possible to assume that the endurance limit of the alloy is near the 105 ksi or 720 MPa.

These results are close to the theoretical results obtained for orthopedic alloys in “The wear pattern in metal on metal prostheses” by Anissian HL (2001) shown in table 6.3.

Table 6.3 Properties of Materials used in prosthesis

Material	Young Modulus (GPa)	Elastic Limit (MPa)	Ultimate Strength (MPa)	Fatigue Strength (MPa)	HVN (kg/mm)	Elongation at fracture
Stainless Steel	190	792	930	241-820	130-180	43-45
CoCrMo	210-253	448-841	655-1277	207-950	300-400	4-14
TiCaP	110	485	760	300	120-200	14-18
Ti-6AL-4V	116	897-1031	965-1103	620-689	310	8

According to the fatigue strength obtained by Smith and compared to the theoretical ultimate strength, it is possible to see that the experimental results still fit in the range before rupture of the material. There is a gap of values that do not fit in the elastic range of the material.

6.2. Analysis of Knee Joint without Medical Implant.

Human bone fracture is presented when the bone is subjected to a stress of around 250 GPa in a healthy middle age person, this stresses may be presented because of an external impact in most of the cases. Next the objective of this chapter is to analyze how safe is to walk taking into account this information.

6.2.1. Minimum Principal Stress Results

FULL FOOT STRIKE	TOE OFF	MID SWING

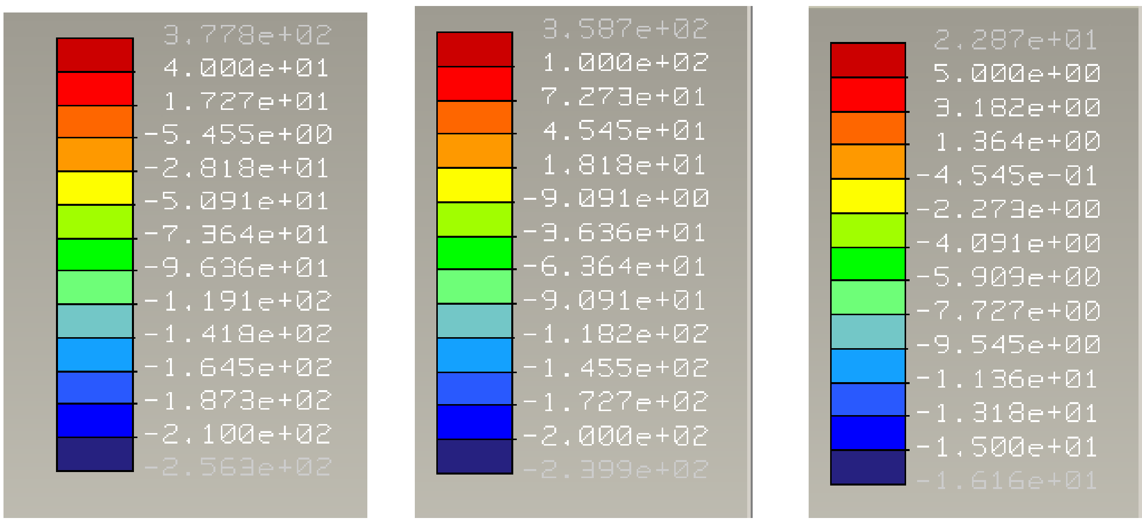


Fig.6.3. Minimum Principal Stress Results

These are the minimum principal stresses since the main force is an axial compressive force; these values presented are shown in figure 6.3, the units of these results are in MPa. These results can prove the difference between the first and second phase of the gait is not too big. The maximum compressive stress is of 210 MPa for the full foot strike phase; meanwhile the toe off phase presents 200 MPa. For the maximum tension stresses, there is a little more difference since the first part of the gait presents 40 MPa and in the second shows 100 MPa, but we can neglect this positive stress since there is no element in the knee joint that presents these values in our analysis.

As it was expected, the third phase, mid swing, presents the lowest values, since the forces acting on the joint at this stage are very low. The reason for the mid swing phase to have stresses from 5MPa to –15MMPa.

6.2.2. First General View

FULL FOOT STRIKE	TOE OFF	MID SWING

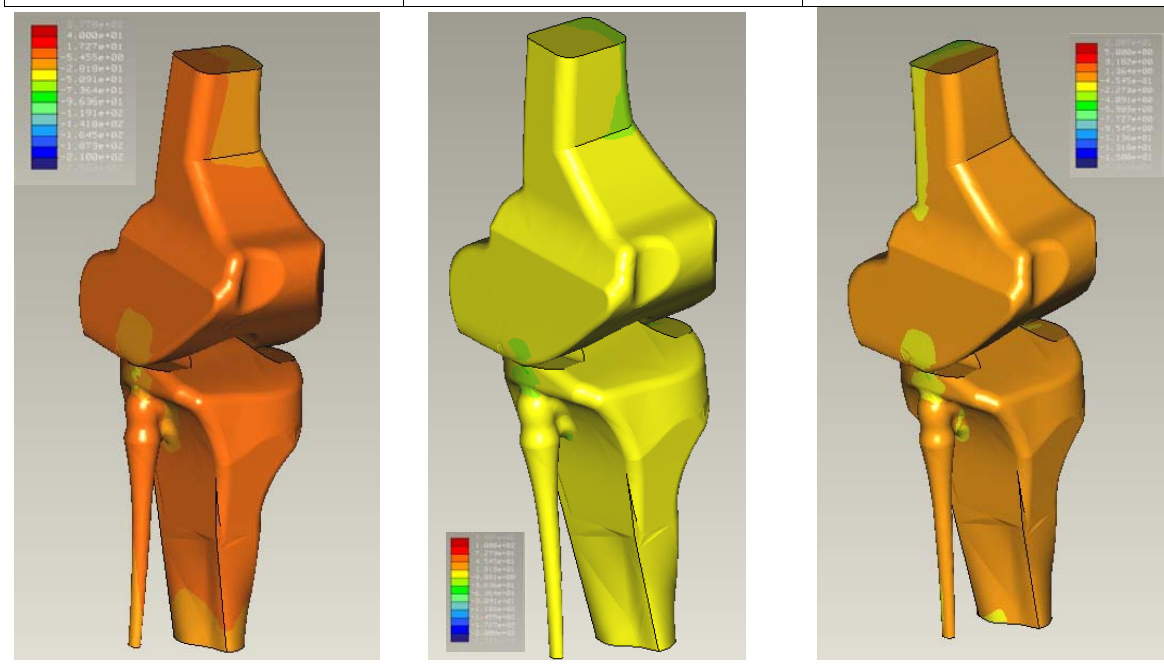


Fig.6.4. First General View

In general, we can see that most of the bone in the tree conditions is subjected to a minimum stress value since the most of the model is in one color. Each one of them represents the gap between the negative and positive values, which makes us think that maybe, most of the bone is very close to negligible stresses during the gait cycle.

Starting from the top in figure 6.4, the first that can be seen in these stages of the gait is that in the first two the initial concentration of stress is focused to sustain the moment produced in the x axis while the foot is in contact with the ground; this, by showing difference of stresses at the top left position. Meanwhile in the last picture in the mid swing phase the difference of stresses is shown along the back of the bone which is also understandable since at this time the knee is totally flexed at its highest angle and getting ready to start the forward movement.

It is also interesting to notice how the stresses are distributed in the full foot strike and toe off phases. Since in both of them the higher amount of stresses are presented in the left part, at the full foot strike stage the stresses are increasing from the center of the left side to the edges in a mostly linear way. In the toe off the stresses grow from the front to the back of the bone, this can be explained since the moment exerted in this phases in not only different in magnitude but also in direction, since for the first phase the moment is negative and in the second one the moment is positive. This distribution is not shown in the third phase because at this point, the moment is 0.

6.2.3. Second General View

FULL FOOT STRIKE	TOE OFF	MID SWING

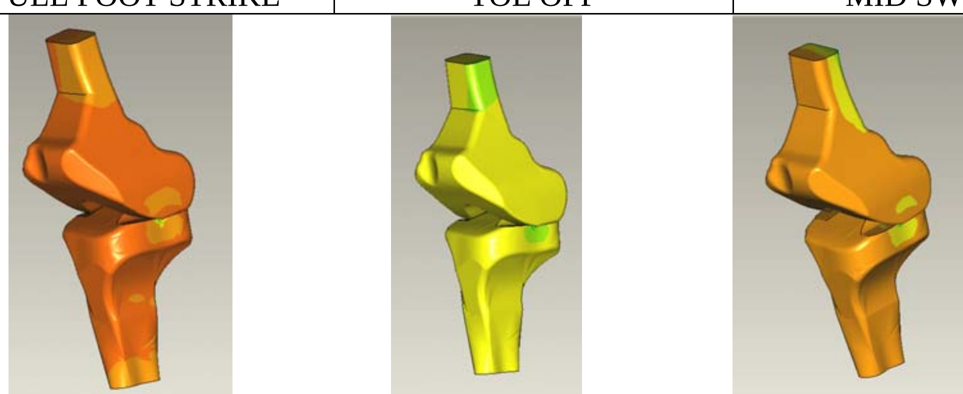


Fig.6.5. Second General View

In figure 6.5, it is possible to see what was discussed previously, about the difference in the distribution of stresses at the top of the femur caused by the difference in the direction of the moment, and also how only the first part presents a little more stresses in the bottom part were the axial force was directly applied. But in the other two stages the higher amount of stresses is almost the same at this point than in the majority of the bone.

It is also possible to discuss the critical points at each stage of the gait, at the first part, the full foot strike; the main concentration is the contact point between the femur and tibia. It can be thought that the tibia is this critical point; because even though the point were the tibia and femur have contact also presents high higher amount of stresses, the value of these is not as high as the concentration shown for the second phase, the toe off. This only at this view, when we look into next views the conclusions will change; it can be said that the critical point at the toe off phase is the point of contact between the two bones too. And the critical point for the third stage, the mid swing, is the back of the femur, mainly because this part supports the weight of the bone and the anterior posterior force at the maximum angle presented during the gait cycle.

6.2.4. First Detailed View

FULL FOOT STRIKE	TOE OFF	MID SWING

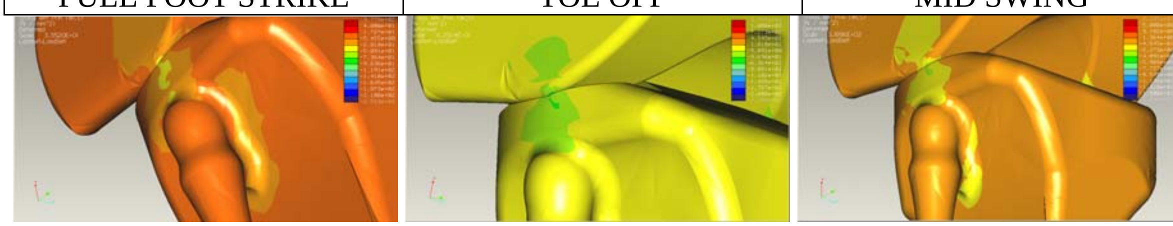


Fig.6.6. First Detailed View

In this detailed view shown in figure 6.6, it can be seen a very similar stress distribution, but of course with different values, the main characteristic here is the major concentration in the contact point what by the way is obvious, after this point with the major stress value this extends mostly towards the femur, despite the fact that the length of the higher stresses is higher in the full foot strike phase. This does not necessarily means that these stresses are higher at least than the toe off stage because of the color pallet distribution. For the first case, when the higher amount of stresses is longer, this color means stresses from 28 to 50 MPa, while in the second phase the length of the section where the color indicates higher stresses is shorter, but this section implies stresses from 36 to 63MPa. This may represent the difference in direction of the moment, and that is why there is a little bit more stresses in this side than in the first phase. But this only can be implied if the in the other side the stresses are higher in the first case than in the second, i.e. the other way around that what is shown in this side.

The second higher stresses grow also from the contact point mostly through the femur and across the union with the fibula with almost the same shape, but again with different values. It is difficult to estimate the difference with the color gap presented in these results, but since the first, second and third stage present almost the same distribution in the majority, we can assume that the distribution is the same but the magnitude of the stresses are different. We can assume this same thing of the stresses that grow along the tibia, same shape of the stress distribution but different magnitude.

6.2.5. Second Detailed View

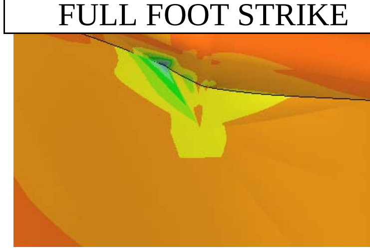
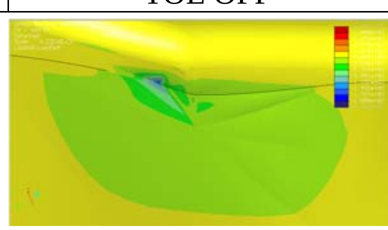
FULL FOOT STRIKE	TOE OFF	MID SWING
		

Fig.6.7. Second Detailed View

The first thing to notice in this detailed view shown in figure 6.7, is the previous comment about the difference of higher amount of stresses between full foot strike and toe off phases, we mentioned that the higher stress distribution in the second stage of the gait was caused due to the difference in direction of the moment between first and second point of gait cycle. But, in this view, we can see that despite the fact that the stress values gap between colors is now higher for the first part the higher amount of stresses are again higher in the toe off stage. With this we can conclude that the main factor at this point for the higher amount of stresses is the magnitude of the moment applied, since the absolute value of the moment exerted in the second phase is higher in magnitude than the applied in the first one. The axial force is not such an important factor for the concentration point here mainly because the magnitude of this vector is almost the same for the two cases but higher in the full foot strike than in the toe off.

In the case of the stresses distribution, we can see that the shape of the change of sections is almost the same in the three cases, even though the difference in magnitude of these stresses. For example in the third case, where the maximum stress we can see it is as in the other cases a little dark blue spot, but this one meaning a maximum stress of 15MPa, while the first and second case we are taking of about 200MPa, more than 10 times the previous value. Taking into account the third stage, the mid swing, we can imply that the shape of the stress distribution does is a matter of the axial and anterior-posterior forces, since for the mid swing phase there is no moment exerted in the knee but even though the shape of the distribution is very similar.

6.2.6. 45% Cut. Axis XZ

FULL FOOT STRIKE	TOE OFF	MID SWING

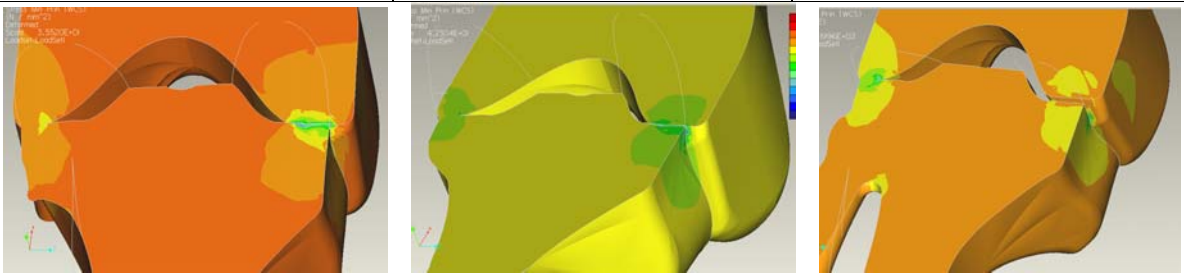


Fig.6.8. 45% Cut. Axis XZ

In figure 6.8 it is possible to see a cut along the X axis shows the distribution of stresses in the contact point, which has been described before as the critical point of the first two stages of the gait cycle. It grows from the contact point trough the ends in an arc distribution.

6.2.7. 41% Cut. Axis YZ

FULL FOOT STRIKE	TOE OFF	MID SWING

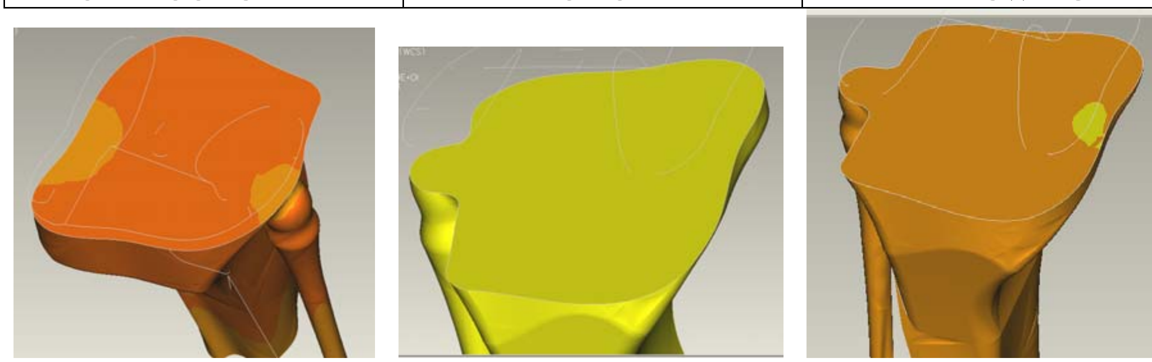


Fig.6.9. 41% Cut. Axis YZ

Figure 6.9 is only a view obtained trying to find the most critical contact point between the tibia and femur and while scaling the bone trying to get a point we obtained this view.

6.2.8. 45.5% Cut. Axis YZ

FULL FOOT STRIKE	TOE OFF	MID SWING

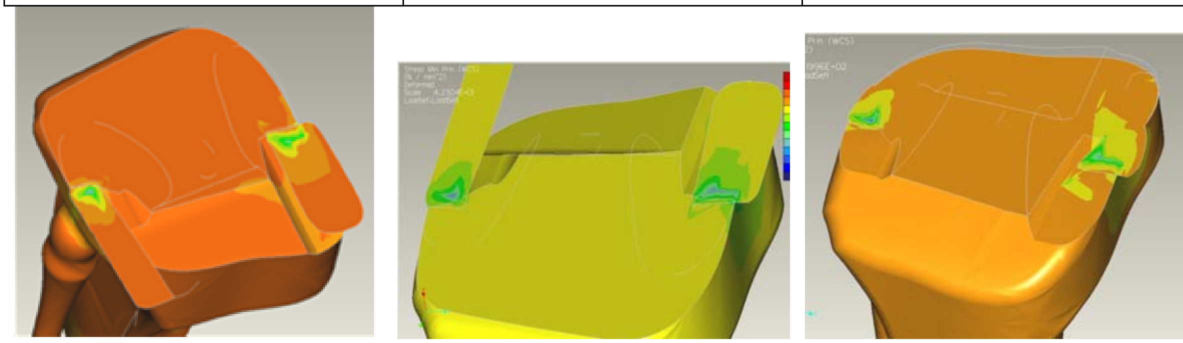


Fig.6.10. 45.5% Cut. Axis YZ

Here, in figure 6.10, it is shown what has been said before, the critical point of stresses in the knee joint, the contact point between the two bones, it can be seen in this view how the concentrations of stresses is higher in value and quantity than in the rest of the knee, next will be made a more detailed analysis of these views.

6.2.9. Right Detail Cut 45.5%. Axis YZ

FULL FOOT STRIKE	TOE OFF	MID SWING

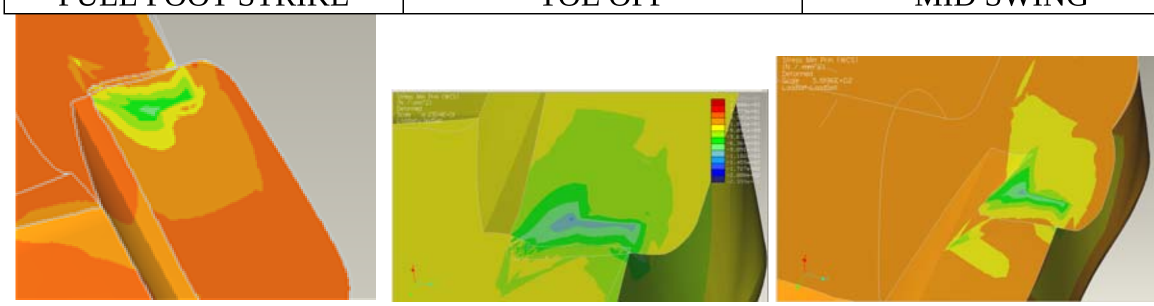


Fig.6.11. Right Detail Cut 45.5%. Axis YZ

Here we can clearly see that in deed, the stresses are higher in the toe off stage than in the full foot strike stage because even tough axial force is lower in a 5%, the moment is higher in a 400% and of contrary direction. The right contact point of the knee shows stresses up to 120MPa for the full foot strike, and 150MPa for the toe off stage. Despite the fact that the moment is 400% higher, the difference of the stresses is not that big, is of 25%.

The third phase, the mid swing, again does not show any additional information but the fact that the stresses are significantly lower and that the stress distribution is very similar in the three cases.

6.2.10. Left Detail Cut 45.5%. Axis YZ

FULL FOOT STRIKE	TOE OFF	MID SWING

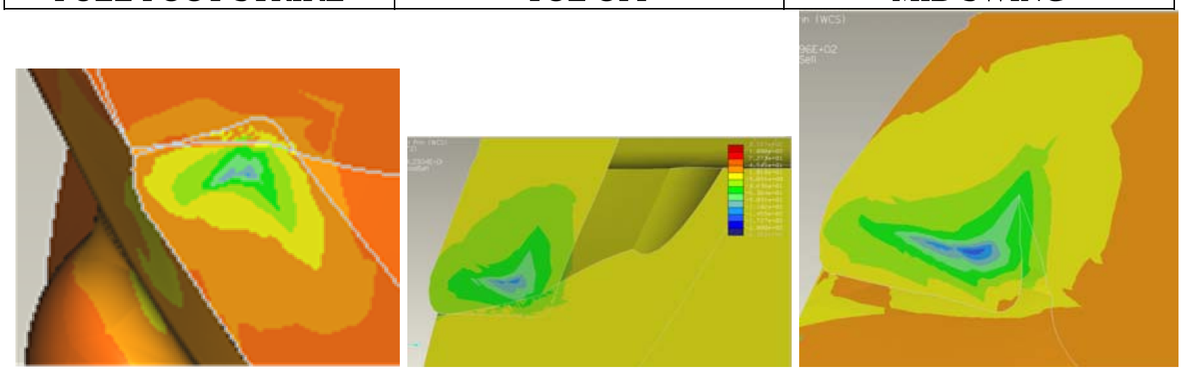


Fig.6.12. Left Detail Cut 45.5%. Axis YZ

This side of the knee showed a little higher stresses, this, caused by the difference in size of both parts of the femur that exhibits the contact points, the left side is a bit smaller in comparison with the right side. This may explain why there are more stresses in this side than in the other. The first stage presents a point with higher stresses than the first one, a small dot of a gage between 140 – 165 MPa, while the toe off stage exhibits a bigger area of stresses with a gage between 120 – 150 MPa. The third phase shows a maximum stress of 15 MPa.

6.3. Analysis of Knee Joint with Vitallium Biomedical Alloy Implant.

The results of this analysis are the principal shear stresses, since the principal type of load that the screws are subjected to, is precisely this. The stresses presented in the bone may look very alarming taking into account the colors of the result, but the gap of stresses for this analysis is only the needed to see how was this loading acting in the screw. In Fig 6.11 we can see the color gap for stresses in this result.

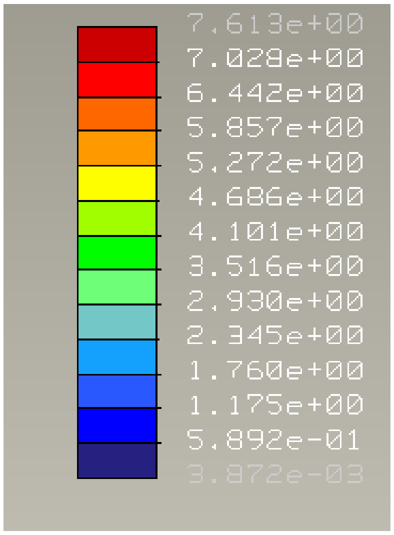


Fig. 6.13. Stresses color gap

In figure 6.12, we can see a cut in the xy axis at 50% of the drawing, where the screw was placed to see half of the screw and half of the bone.

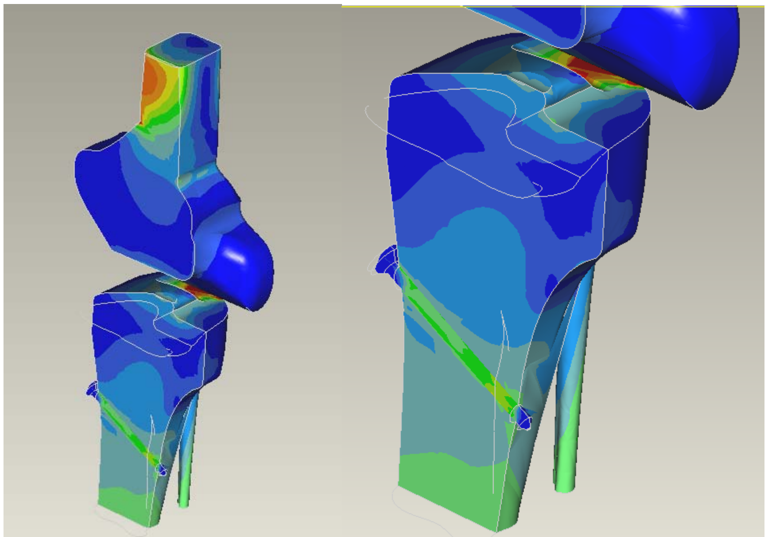


Fig. 6.14. XY Cut at 50%

Hiding the first element (bone) now it is possible to see only the screw and the stresses presented on it after the application of forces. From the literature the yield shear stress that vitallium alloy can resist is up to 25 MPa; in these results, shown in fig 6.13, 6.14 and 6.15, we see that the maximum higher amount of stresses is presented almost at the finish of the subjection with a maximum stress value of 7 MPa.

The head and bottom of the screw exhibit low but different from zero shear stresses, and in the contact points are shown higher concentrations of low stresses from 590 KPa to 2.34 MPa, in a very low length increase the shearing stresses almost 400%.

After that most of the screw shows a constant shear force of between 3.5 – 4 MPa. As expected, the stresses grow from the bottom to a point where the stresses are maximum at the beginning of the fixing. The first threads support the most of the force and eventually become constant shearing higher amount of stresses.

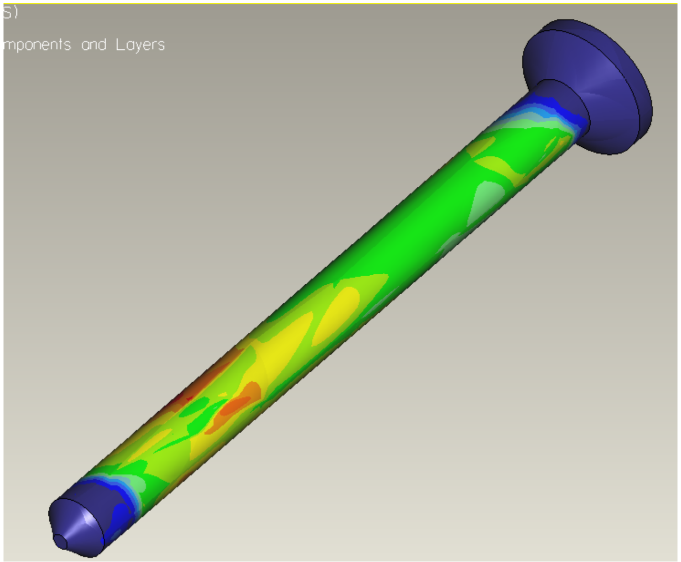


Fig 6.15. Vitallium screw applied in knee. Main view

Inside the screw, at a 50% cut we can see that this maximum shearing stresses are mainly superficial. The inside of the screw shows a more soft distribution of stresses from the top of the contact point to the inside in a wavy way and in the bottom again it is presented the slow growing of stresses to a main point where the stresses begin to decrease. Again, it is possible to see that the most of the screw has stress values between 3.5 – 4 MPa with some ranges of up to 4.6 – 5.2 MPa in the higher stress distribution area.

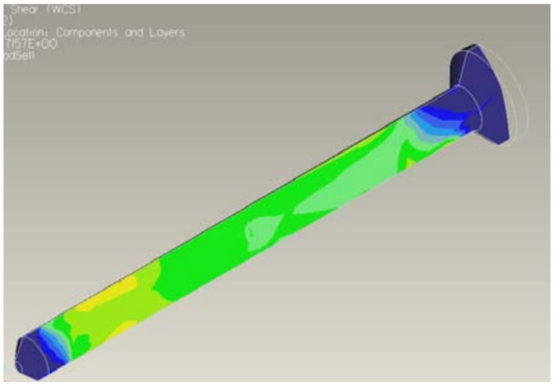


Fig. 6.16. Vitallium screw applied in knee. XY cut at 50%

The main concentrations are presented in 3 points, 2 at the top of the screw, or where the screw is in contact with the superior part of the hole produced in the bone and one at almost 180^{o} from the first critical point. In these areas stresses are softly distributed to the center where at this point the principal stresses go from 4.1 – 4.6 MPa.

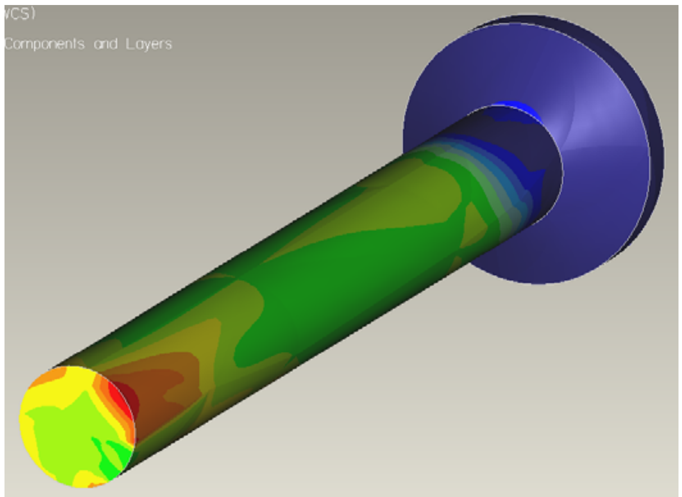


Fig 6.17. Vitallium screw applied in knee. 3 points view at 33%