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Mechanical behavior of Perlon – Carbon fiber – Acrylic Materials of a new design of Ankle – Foot – Orthosis

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Abstract

In current work, manufacturing of a new Ankle – Foot Orthosis has been done that covers two parts, calf and sole, connected by movable aluminum neck joint which has high working strength to prevent failure at this region in additional to making leg and foot upright and then more control on drop foot during gait. The calf materials are (perlon – carbon fiber – acrylic) which layered to form the upper part of orthoses with lower coefficient of friction than the ordinary polypropylene calf with about ***19.93 %***, while sole was made from polypropylene material which represent lower part. The pressure device was also manufactured in present work to measure the interface pressure between calf and patient's leg using two sensors.

Static analysis were done by using " **ANSYS PROGRAM** ", static factor of safety was ranged between (*1.27 – 3.27*) for upper and lower parts of new orthosis. The new materials showed a reduction in deformation of calf to more than ***50 %*** compared to ordinary material.

Key Words

AFO, Perlon-Carbon fiber-Acrylic materials, FEM.

Abbreviation

AFO : Ankle Foot Orthosis.
PCA :Perlon – Carbon fiber – acrylic.
PP : Polypropylene.

1. Introduction:

A foot orthosis is designed to correct abnormal foot (mis-alignment condition) and lower extremity function. The ankle foot orthosis is a hard brace worn on the lower leg to support ankle and foot. This device keeps the ankle in a neutral position during walking and other daily activities.

Ankle foot orthosis are prescribed for insufficiencies in the movement of the ankle joint. Normally, they brace the ankle joint and compensate for instability of pareneus paralysis, weak ankle alignments, and stroke victims [1].

In the last 3-4 years a Scandinavia company has designed and produced an energy storing foot for amputees. The company then applied this approach to a design of AFO which they called a "Toe-off". The material used in a combined of glass, carbon and tefla fibers. It has some disadvantages. If you have a lot of instability, side to side, it does not control that. There is also a problem that the fibers of the Toe-off may be delaminated with usage [2]. J.Martin Carlson et al.(1992) [3] designed and provided an ankle-foot orthosis (AFO) that allows the client to walk comfortably and safely without bearing weight through the skeletal elements of the lower leg and foot has proven to be a daunting challenge.

Carmick and Middleton et al [4, 5], state that AFO must be weighed against the increased complexity of the design and the possibility of increased fabrication errors.Zachazewski et al. [6] reported favorable results in a single patient study in decreasing the positive support reaction in adult with traumatic spasticity. Sankey et al and Rosenthal et al [7, 8] state that if the amount of equines is small and the foot despite the equines, is capable of making a relation to the floor, a compensatory hyper extension of the knee is often present. In this case, a solid ankle AFO constructed either in 5 degrees of dorsiflexion or neutral ankle with a heel lift, will result in a flexion moment at the knee and improve the genurecurvature.

The 3 – dimensional FEM of the AFO system had been developed. The model results confirm the hypothesis that the peak stress occurred in the neck and the heel region of the AFO [9]. The FEM analysis for the calf-foot AFO model was performed under typical able-bodied gait loading and boundary conditions in order to evaluate the flexural response of the AFO. If the resulting value was found to be too high or too low, the cross – sectional areas (thicknesses) of the two struts were adjusted accordingly and a new simulation was performed [10].

In present paper, static solution for new manufactured design of AFO had been done with comparison of mechanical behavior of new and ordinary materials. The pressure device was constructed in present work to determine the internal pressure between patient's skin and calf. The dorsiflexion angle of new design had been determined by investigation of vertical deformation of sole under toe – off stance of patient.

2. Manufacturing

2.1 A New design of AFO

The manufacturing process steps for calf piece of ankle-foot-orthosis made from PCA materials can be listed in following steps :

1. Preparing the calf die made from gypsum according to patients lower leg size.
2. Covering the gypsum by first layer of PVA.
3. Laying the calf die by sheets of carbon fiber.
4. Adding perlon.
5. Covering the die by second layer of PVA.
6. Pouring down acrylic.

The sole piece was made from polypropylene due to it's ductility and it's ability to deflection in both dorsiflexion and plantarflexion. The necking position will be substituted by movable neck joint by connecting the two previous manufactured parts, calf and sole, which have option of multi-angles ability to turn (0, 15, 30, 60, 90, full range) that necessary to making load line passed through equilibrium position. The final form of new design of AFO can be shown in fig.1

Fig. 1 : New design of AFO.

2.2 Pressure device

In current work, the construction of AFO's pressure device is done due to necessary requirements of measured pressure between the leg and calf part of new design of AFO, which then used to estimate the deformations, stresses, strains,….etc developed in calf made from new materials (perlon - carbon fiber - Acrylic) and from usual material (polypropylene). The construction of a new device with its main parts can be shown in fig.2.

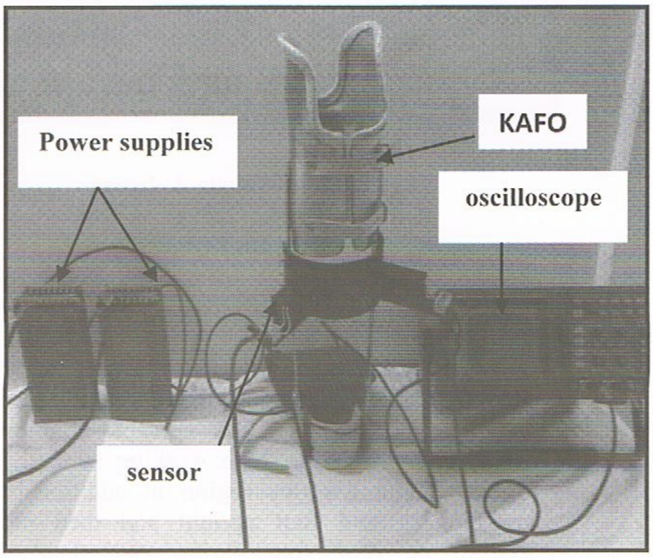


Fig. 2: Overall pressure measurement device.

3. Tests

3.1 Tensile test

The tensile test was done for both new and ordinary materials (PCA and PP materials) to determine their mechanical properties. The specimen's dimensions were taken in present test according to ASTM Standard [11], while investigated results can be shown in Table 1.

3.2 Calf pressure test

The pressure device measures the change in voltage which caused due to slight movement of sensor rod (1.5 mm in diameter) during test, and therefore change in alternative resistance of pressure sensor can be easily read from oscilloscope. The calibration of device had been done by applying gradually masses over sensor rod and then best fit curves can be constructed for sensor 1, sensor2, and average have the following polynomial equations respectively :

$$m = -39.4 + 0.182V - 6*10^{-5}V^2 \quad (1)$$

$$m = -15.79 + 0.069V - 2*10^{-6}V^2 \quad (2)$$

$$m = -26.59 + 0.113V - 2*10^{-5}V^2 \quad (3)$$

where m in gram and V in millivolt. The pressure can be determined from:

$$P = \frac{mg}{1000A} = \frac{4mg}{1000\pi d^2} \quad (4)$$

By substitution eqs. (1), (2), and (3) into equation (4); the interface pressure in calf part of AFO can be determined from the following final form of required polynomial pressure equations (in kpa) as shown in Table 2 :

$$P = -218.83 + 1.01V - 33.32*10^{-5}V^2 \quad (5)$$

$$P = -87.7 + 0.383V - 11.11*10^{-6}V^2 \quad (6)$$

$$P = -147.68 + 0.628V - 11.11*10^{-5}V^2 \quad (7)$$

Table 1 : Mechanical properties for PCA and PP materials.

Material	Young's modulus, E (GN/m^2)	Yield stress, σ_y (MN/m^2)	Ultimate stress, σ_u (MN/m^2)	Percentage of total elongation
PCA	1.634	32	33.75	2.2
PP	0.812	21	28.75	106

Table 2 : Interface pressure in calf part of AFO.

Case		Pressure (kpa)		Average Pressures (kpa)
		Sensor 1	Sensor 2	
Stance phase	Mid-stance	146.6	33.72	69.47
	Toe - Off	115.3	36	59.61
	Heel strike	131.9	50.24	76.16
Swing phase		101.6	30	50.23
Up stair		124.4	51	74
Down stair		161.1	26.2	69.47

3.3 Friction test

The friction rig was manufactured to measure or calculate the static coefficient or friction between two surfaces in contact, patient's skin and calf, and then can be deduced the preferred material of calf that making smooth contact (less coefficient of friction) with patient's skin by making comparison between new and ordinary materials readings.

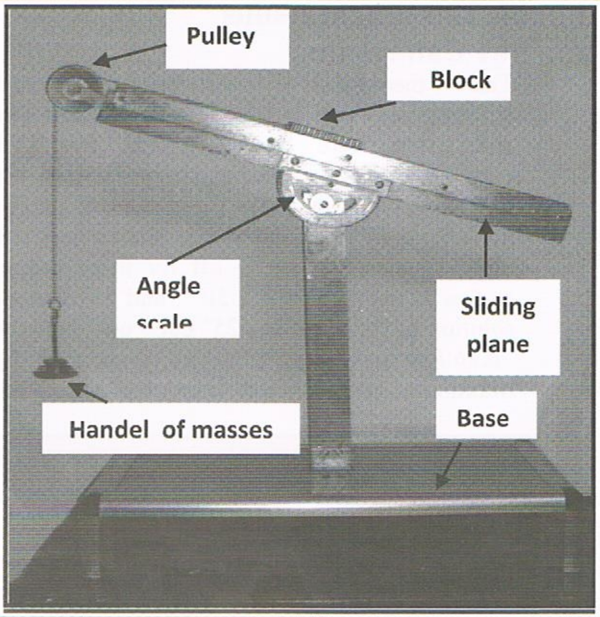


Fig.3 : Friction device.

The whole device was made from aluminum except to handle of masses which made from steel and wood for vertical rod and base respectively. Sliding block and handle of masses have 167.6 and 24.3 gm respectively. Main parts that present friction device have been constructed, as shown in fig.3. Determination of coefficient of friction for new and ordinary materials can be done on friction rig by fixing the tensile load on cord, 85 gm in addition to handle weight, and then gradually tilted sliding plane until initiation of motion was begin at angle of inclination shown in Table 3. By using elementary equilibrium friction of mass over inclined plane; coefficients of friction can be determined.

Table 3 :Friction coefficients for new and ordinary materials.

Material	Total mass (gm)	Angle of inclination (degree)	Friction coefficient
PCA	109.3	12	0.454
PP	109.3	5	0.567

4. Theoretical results

4.1 Calf results

The theoretical investigations including deformation, Von – Misses stress, shear stress, and strain were carried – out by ***ANSYS PROGRAM*** using mechanical properties which are investigated in Table 1 and internal pressures in Table 2 for different stance phases heel strike, mid – stance and toe – off for three proposed angles of cut – out 25° , 30° , and 35°.The static solution of PCA calf has 25° cut – out angle under ***76.16 kpa*** internal pressure can be shown in fig.4. Maximum induced deformations and Von – Misses stresses results for new and ordinary materials for all cut - out angles can be shown in Table 4 and for only new PCA materials calf included maximum deformations and Von – Misses stresses were developed along path AB (along free cut – out edge) and path CD (distance between fixed holes for strap) for mid – stance and toe – off phases as shown in Tables 5 and 6 respectively. The calf main dimensions have been used in present work are ***5.885, 4.365, 19,*** and ***0.22 cm*** for upper diameter, base diameter, calf height, and thickness respectively.

Table 4 : Maximum deformations and stresses develop in calf under heel strike loading.

Cut – out angle (degree)	Max. deformation (mm)		Max. Von – Misses stress (N/mm^2)	
	PP	PCA	PP	PCA
25	1.2494	0.6502	9.71	12.54
30	1.2380	0.6530	10.38	13.78
35	1.0311	0.5550	14.20	19.01

Table 5 : Maximum deformations and stresses develop in PCA calf and their paths under mid - stance loading.

Cut – out angle (degree)	Max. deformation (mm)			Max. Von – Misses stress (N/mm^2)		
	calf	Path AB	Path CD	calf	Path AB	Path CD
25	0.5931	0.5751	0.1480	11.44	4.102	4.246
30	0.5957	0.5766	0.1658	12.57	3.607	4.335
35	0.5063	0.5062	0.1557	21.90	2.627	4.165

Table 6 : Maximum deformations and stresses develop in PCA calf and their paths under toe- off loading.

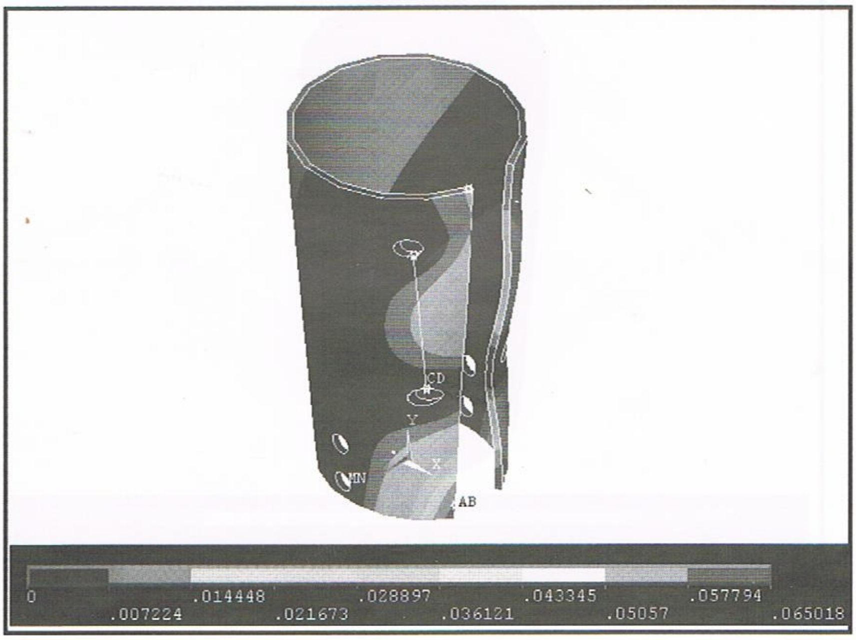
Cut – out angle (degree)	Max. deformation (mm)			Max. Von – Misses stress (N/mm^2)		
	calf	Path AB	Path CD	calf	Path AB	Path CD
25	0.5089	0.4934	0.1410	9.815	3.414	3.687
30	0.5111	0.4948	0.1527	10.79	2.929	3.885
35	0.4344	0.4343	0.1358	18.79	2.254	3.574

4.2 Sole results

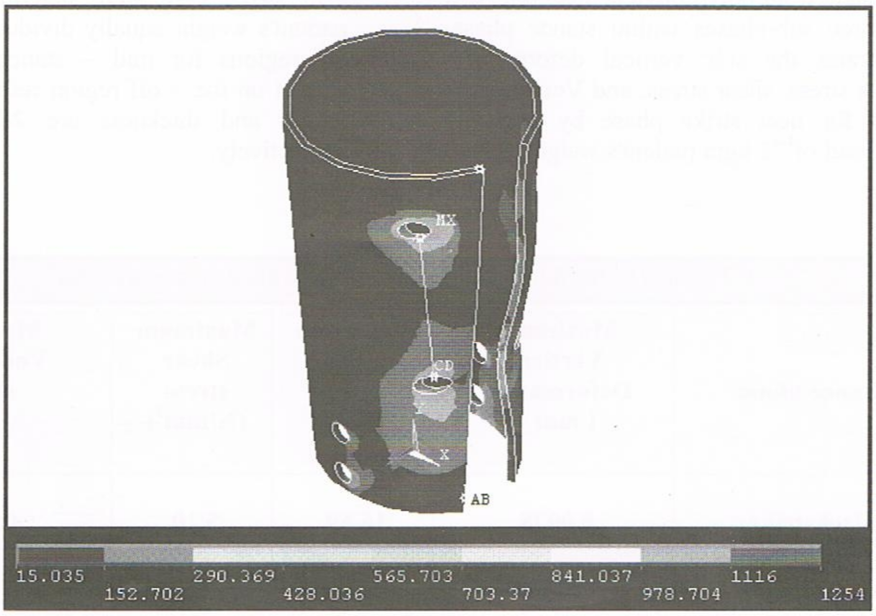
The static solution for lower part of orthosis which are made from polypropylene material was done for three sub-phases within stance phase. Fig.5 illustrates the sole vertical deformation, Von- Misses stress, shear stress, and Von- Misses total strain for heel strike phase by applying distributed load of 72 kgm patient's weight atheel region. Table 7 was illustrates the static results for mid – stance and toe – off phases in addition to heel strike case were determined by applying patient's weight equally divided on heel and toe-off regions for mid – stance phase and total weight on toe – off region respectively. The sole length and thickness are ***28.75*** and ***0.5 cm*** respectively.

Table (7) : Static result items for sole under stance phases.

Stance phase	Maximum Vertical Deformation (mm)	Maximum Von-Misses Stress (N/mm^2)	Maximum Shear stress (N/mm^2)	Maximum Von-Misses strain
Heel strike	0.0978	16.59	5.10	0.0338
Mid - stance	2.130	8.89	1.23	0.0370
Toe - off	5.812	6.43	2.64	0.0792



(a)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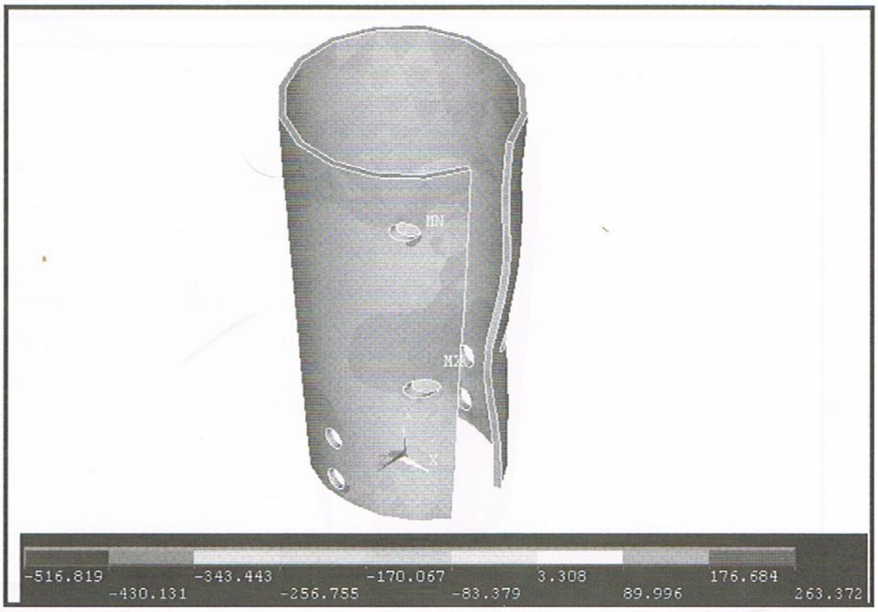
(b)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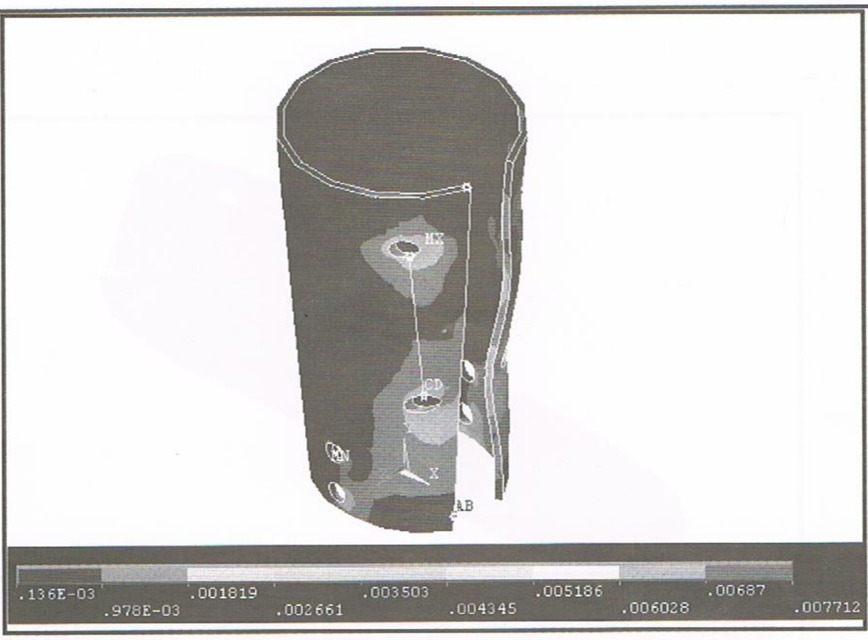
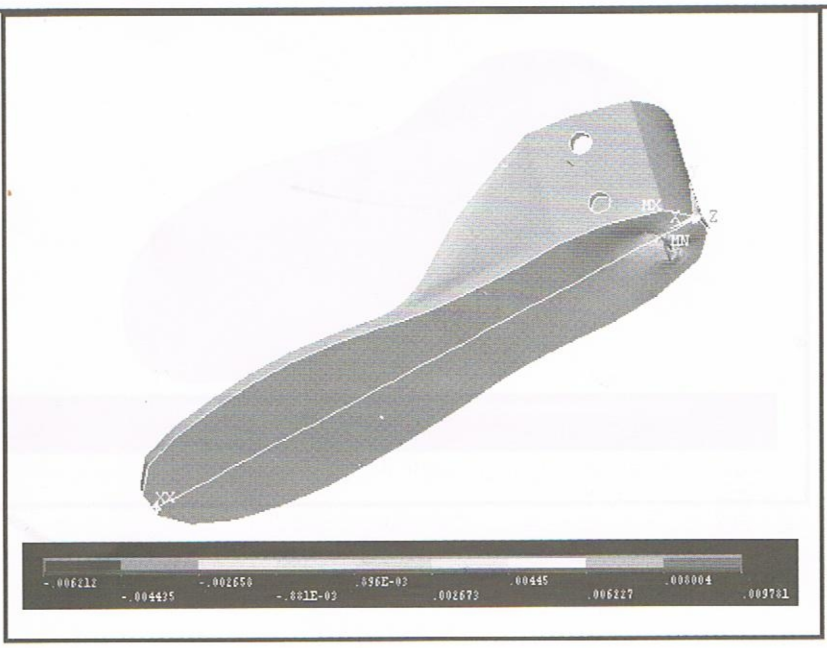


(d)

Fig. 4 : Static results for 25° calf under heel strike phase; (a): deformation (cm), (b): Von – Misses stress (N/cm^2), (c): shear stress (N/cm^2), and (d): Von – Misses strain.



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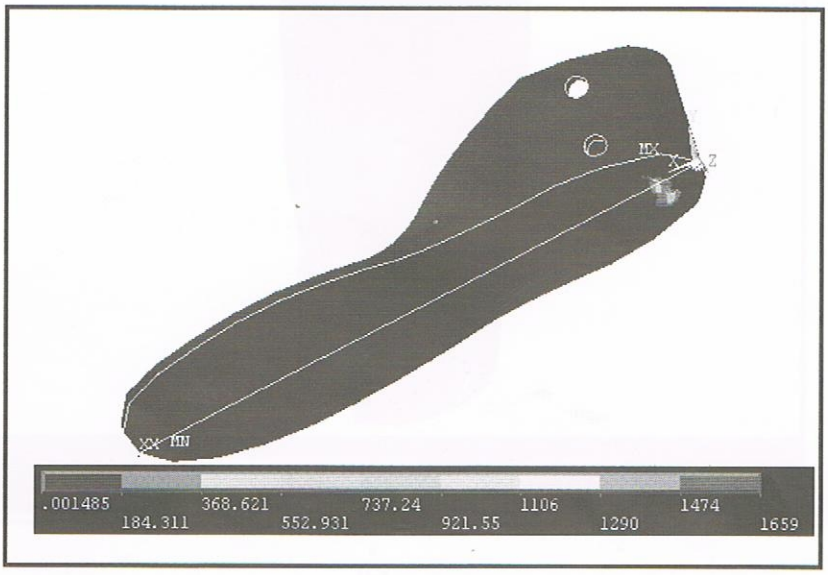
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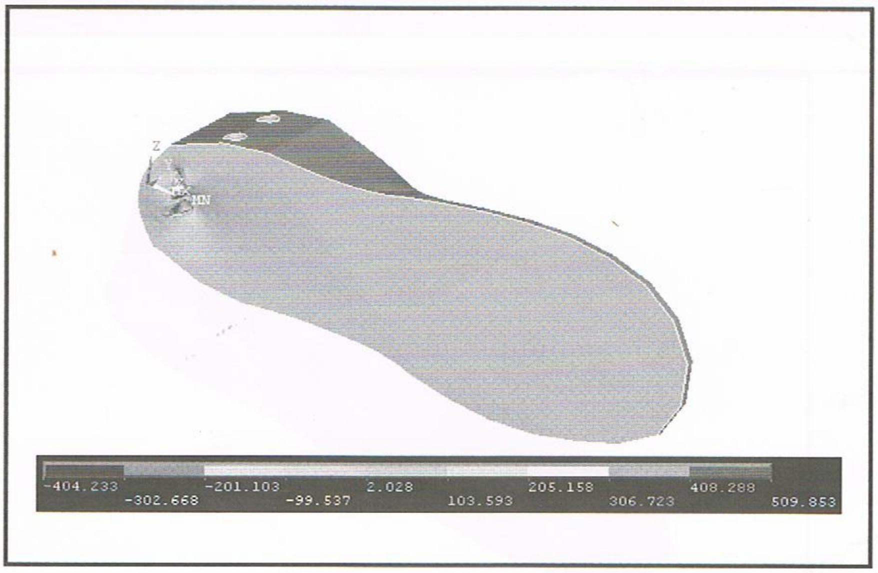
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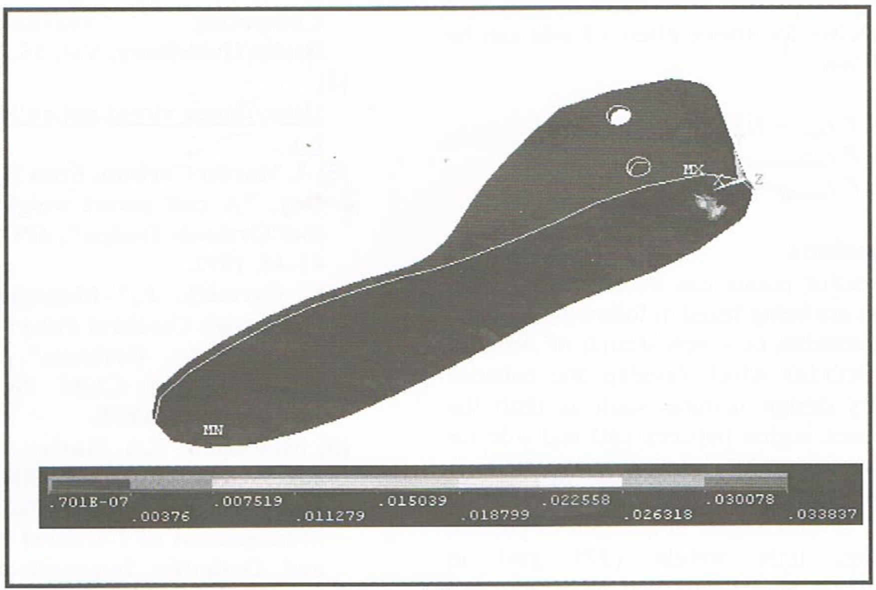
(c)



(d)

Fig. 5 : Static results sole under heel strike phase;
(a): deformation (cm), (b): Von – Misses stress (N/cm^2),
(c): shear stress (N/cm^2), and (d): Von – Misses strain

5. Discussion

The new AFO design offers excellent control to foot during gait cycle where maintain neck joint at fixed 90° in addition to other advantages like simplicity, easy fit to foot, and lower weight (*575 gm*) than other designs like pneumatic artificial muscles ankle foot orthoses which has **1.7 kg** weight with complexity in design and required duration maintenance of its artificial muscles. Friction coefficients for new as shown in Table 3; therefore the new and ordinary materials were ***0.454*** and ***0.567*** respectively material was made a significant reduction in friction (***19.93 %***) between patient's skin and calf and then red regions had been reduced. Usually, patient was worn ordinary AFO used cushion padded between calf and patient's leg required to minimize red regions, but this additional material led to make leg bulky in appearance with difficulty in worn.

Table 3 shows that the maximum deformation were ***0.65018*** and***1.24939mm*** for PCA and PP materials respectively located at free lower edge for calf, that means new materials serve to lower the maximum deformation developed in calf part of AFO to approximately half of that made from ordinary PP material. The maximum Von – misses stresses were ***12.54*** and ***9.71 N/mm^2***for PCA and PP materials respectively; by dividing the yield stresses for two materials **σ_{pca} = 32 MPa**and **σ_{pp} = 21 MPa** which already investigated from tensile test to its maximum Von – Misses stresses gives static factor of safeties are ***2.55*** and ***2.16*** for new and ordinary materials respectively with ***15.3 %*** increment was obtained from using PCA materials.From Tables 4 and 5 it can beconcluded that heel strike developed higher deformation in calf and stress than mid – stance and toe – off phases. The 35° cut – out of calf was gave lower deformation but higher Von – Misses stress than other two phases.

Table 6 shows the maximum deformations, stresses and strains of three phases of sole stance heel strike, mid – stance and toe – off. Maximum deformation was occur at toe – off phase among phases under study ***5.812 mm*** reduced to ***2.13 mm*** in mid – stance before became minimum at heel strike phase, the clarification of their results coming from that the foot bent at toe-off phase leads to sole deformed in greatest amount at this phase among others.

Maximum Von – Misses stress was induced in heel strike reduced to lower amounts at *8.89* and *6.43* N/mm^2 for mid – stance and toe – off phases respectively because the stance contact area of sole with ground would be minimum in heel case in comparison with other phases. The factor of safeties for stance phase of sole can be listed as follows:

$$(S.F)_{heel} = 1.27.$$
$$(S.F)_{mid\text{-}stance} = 2.36.$$
$$(S.F)_{toe\text{-}off} = 3.27.$$

6. Conclusions

The major points can be concluded from present work are being listed in following points :

1. Manufacturing of a new design of Ankle – Foot Orthosis which develop and enhance ordinary design features such as omit the weak neck region between calf and sole for ordinary design by replacing it in aluminum movable neck joint which has ability to be turn to several angles in addition to prevent buckling, light weight (*575 gm*) in comparison with heavy and more complex designs, do not required maintenance, good control on patient's leg during cycle due to existence of rigid neck joint, and easy in packing.
2. The strength to weight ratio of new PCA materials equal to (*6.35*Gpa/N) higher than against ordinary PP material which equal to (*4.73 Gpa/N*).
3. Static factors of safety have been determined in our study are *2.55* and *2.16* for calf made from PCA and PP materials under heel strike phase, while for sole these factors are to be*1.27, 2.36* and *3.27* for heel strike, mid – stance, and toe-off phases respectively.
4. New PCA materials reduce the deformation of calf to approximately *50 %*, with good improvement in factor of safety.
5. Higher stresses and deformation were developed at heel strike phase like about *8.78 %* and *21.7 %* increment than mid-stance phase for 25° cut-out calf, but lower deformation was determined for sole under same phase.
6. Higher reduction in friction between patient's skin and PCA calf has been obtained in compared to that developed with PP calf by about *19.93 %* and therefore less red regions had been observed after orthosis has been worn-off and then no need to used bulky cushion pad.

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التصرف الميكانيكي لمواد البيرلون – شرائح الكاربون – اكريلك المستخدمة في تصنيع مسند قدم – كاحل جديد

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هيئة التعليم التقني

الخلاصة

في هذا البحث, تم تصنيع مسند قدم- كاحل جديد والذي يشتمل من جزئين(العلوي والسفلي) بربطهما بمفصل عنق متحرك من الالمنيوم والذي يمتلك متانة عالية قادرة على منع الفشل عند هذه المنطقة من المسند بالاضافة الى جعل الساق مع القدم بشكل عامودي وبالتالي سيطرة اكثر على القدم الساقطة خلال المشي. ان الجزء العلوي للمسند يصنع من مواد (البيرلون – شرائح كاربونية – اكريلك) على هيئة طبقات وبمعامل احتكاك اقل من معامل احتكاك للمادة المستخدمة سابقاً(البولي بروبلين) بنسبة (19.93%), بينما الجزء السفلي للمسند يصنع من مادة البولي بروبلين. تم في هذا البحث ايضاً تصنيع جهاز لحساب الضغط المتولد بين الجزء العلوي للمسند وبطانة الساق للمريض باستخدام متحسسين اثنين. تم اجراء التحليل الستاتيكي على المسند باستخدام برنامج "ANSYS" وبمعامل امان ستاتيكي يتراوح بين (1.27-3.27) للجزئين العلوي والسفلي للمسند. قلصت المادة الجديدة من التشوهات المتولدة للجزء العلوي للمسند الجديد عن المادة السابقة باكثر من 50 % .