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Research paper

Testing and manufacturing with numerical modeling of metal PTB orthosis

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Abstract

In this work, fiber glass as a reinforcement in composite material used for manufacturing ankle foot orthoses (AFO) PTB type of metal valve with vacuum molding technique fabricated. The material was depended on 8 layers of fiber glass. The mechanical properties of the AFOs' material were studied by tensile test, and fatigue test. The results showed that the tensile strength (Ϭult) for fiber glass are 224 MPa, yield strength (Ϭy) was 170 MPa and elongation at break 1.9mm.The gait cycle (ground reaction force (GRF)) and pressure distribution data were collected by using force plate and F-socket devices respectively for patient of age 29 years with height 185cm and weight 83kg .Heel contact time percent without PTBO equal to 5%, when wearing fiber glass PTBO equal to 59%. The midstance time percent for patient without PTBO equal to 12% when wearing PTBO equal to 34%. Solid work software program was used for PTPO modeling Also; the FEM (ANSYS ver.18.2) was used to compute the equivalent stress (Von-Mises), safety factor of fatigue and total deformation for fiber glass PTBO model. The obtained results from ANSYS gave the profile of safety factor of fatigue (1.1492).

Keywords: *Patellar Tendon-Bearing (PTB) Tensile; Fatigue; Fiber Glass; Modeling; Gait Analysis.*

1. Introduction

Orthoses are external appliances used to intercept or facilitate movement by supporting, aligning and Keep body parts. Orthotics can enhance the duty of dynamic body parts and prevent or correct deformation Orthoses can serve multiple functions, including controlling, correcting, facilitating, limiting, or inhibiting motion of the extremities or spine. Orthoses can also substitute for weak or paralyzed muscles and reduce muscle spasticity. These goals are not mutually exclusive; to maximize patient outcome, many clinical scenarios require complementary use of these functions. [1].
The PTBO was basically designed to support or off-load body weight for the below-knee part which is structurally inappropriate or causes pain fig show PTB orthosis [2]
In general the PTBOs part are manufactured usually of composite materials, due to their high strength to weight ratio specification, [3-4], therefore, the composite materials are modified through the years by adding of different components, variable number of laminated layers, [5-9]
H. Tanaka et. al, [10], estimated the unloading case effects of the patellar tendon-bearing (PTB) model for five healthy peoples using a dynamic plantar pressure system analysis. A method to enhance the unloading effect of the PTB, and tested this by using the same system. He concluded that the conventional PTB offers unloading of 30% of the body-weight while the part of the cast on the leg offered the most importance role in the unloading. It was also shown that when the depth of the space under the foot inside the PTB cast 1, 2 and 3 cm, the unloading effects were 60%, 80% and 98%, respectively.
The orthosis part investigation by many researcher with various parameters study, which investigation who to modifying the mechanical characterizations for its part, [11-20], or who to modifying the mechanical properties for materials using to manufacturing the orthosis part, [21-24]. Therefore, the best materials used to manufacturing the orthosis part is the composite materials, there, was to necessary the investigation of the composite materials properties and who can modified its properties and application for its materials. Then, various researchers studied the modifying ways of composite materials properties, [25-31], and different application for its materials, [32-40].
A wide range of materials are used in fabricating an orthosis and are frequently used in combination such as metals (are durable but are often considered unattractive and heavy), plastic (thermoplastic, thermoset….etc.) and fiber (fiber glass, carbon fiber…etc.) in this research a fiber glass has been used in the manufacturing of patellar tendon-bearing orthotic.

2. Experimental work

The experimental part is necessary work for engineering problem, which part given a good results of mechanical characterizations for its problem, which can be dependent on to investigation the behavior for its part, [41-43]. There, the experimental work including investigation for mechanical properties and characterizations for PTB orthosis part under various load condition. Therefore, its parts included manufacturing and testing of the composite materials using for orthsis part. Then, the following steps shown its steeping for manufacturing and testing materials orthsis part,

2.1. Materials

The materials of the PTBO needed in lamination for this study are as follows [44],

- Fiber glass and Lamination resins 80:20 polyurethane.
- Hardening powder.
- Polyvinyalcohol PVA bag.
- Materials for Jepson.

2.2. Preparing of samples for tensile, and fatigue tests

The preparing of samples for tensile and fatigue test, are as follows: Firstly Set the rectangular mold at the stand of vacuum pressure system. And Use the fiber glass stockinet as indicated by the overlaying lay-up. then Blend the overlay resin 80:20 polyurethane with the hardener. After that Maintain constant vacuum with pressure approximately (30-60 KPa) at room temperature. Until the laminations become cold cut according to the dimension of samples.

For tensile test three samples, [45-51], were prepared for lamination according to ASTM D638 type I. Fig. 1. shows the dimensions of tensile sample. Also, to evaluating the fatigue characterizations eight specimens are used, [52-55]. The dimensions of samples are length 100 mm and width 10 mm according to the fatigue device test while thickness various with the kinds of laminate, as shown in Fig.2.

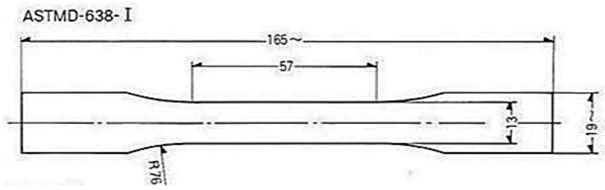

Fig. 1: The Dimensions of Tensile Sample According to ASTM D638.

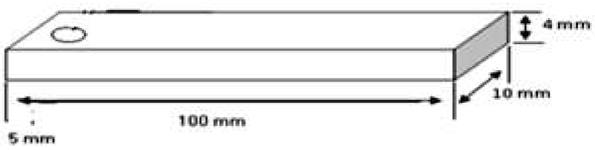

Fig. 2: Dimensions of Fatigue Samples.

2.3. Manufacturing procedure

The procedure of manufacturing metal PTB orthotic can be summarized as follows:

- Mounting the positive mold at the laminating stand.
- Putting the (8 fiber glass) layers and pulls the outer (PVA) bag.
- Mixing the Orthocryl lamination resin with the hardener about (800-900) ml of resin mixed with (2-3) part of hardener. The resulting matrix mixture is distributed homogenously inside the outside PVA bag.
- Maintaining constant vacuum and cut the resulting lamination in the shape of PTBO with required dimensions then placing Velcro closures with locating the place of the knee.
- Placing the side bars :The metal design consists of a metal structure shaped to the limb and upholstered with leather at the points where the device makes contact with a person's body, This orthosis consists of a rigid femoral stem and a calf foot part made of polyethylene or polypropylene, in some cases, leather can be used, A joint - locked or not - connects the two parts together, depending on the case, double-sided or single-sided high-rise, It is held with Velcro closures and the shoe, The most important step in this kind of orthosis is locating the place of the knee and determine Horizontal axis of the knee joint, Then modify the columns by meanders leg.
- Refining the trim lines and placing tapes: after cutting the shape of the orthosis, start to refine the edges and trim lines, placing the tapes on at the whole orthosis on the thigh area and calf and the foot.
- Alignment and Biomechanics: The alignment of the PTB orthosis is on the Adjust the horizontal axis of the ankle joint, let the patient wear it and walk with it and recognize the fixation of the deformity. Fig.3 shows the metal PTBO.

Then, testing patellar tendon-bearing by using the F-socket and gait cycle. Where, the Interface pressure test for patient wearing a metal PTB orthosis with age (29 years), height (185 cm) and weight (83 kg) suffered from left pain in the ankle and foot using sensor type (Mat Scan) which is acceptable for this type of dynamic load, as shown in Fig. 4.

Fig. 3: Metal PTB Orthosis.

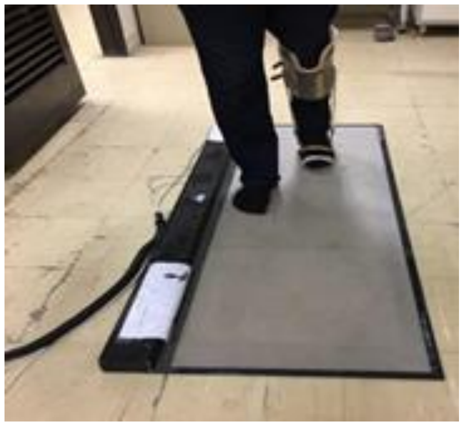

Fig. 4: Patient with Metal PTB Orthosis.

3. Numerical analysis

The PTB orthotic is drawing by using 3D SOLIDWORKS (version 2014) as shown in Fig. 5. SOLIDWORKS is a 3D mechanical CAD (computer aided design) program. ANSYS Workbench 18.2 software has been used as a numerical tool to illustrate the effect of the stress performance in a structure element. The analysis of PTBO's models for patient was established by FEM software to compute the equivalent (Von-Mises) stress, total deformation and safety factor of fatigue. According to the Von-Mises theory that considers the yield stress as criteria; ($\sigma e<\sigma y$, safe), ($\sigma e = \sigma y$, critical) and ($\sigma e>\sigma y$, failed). Where, (σe) is the equivalent stress, and (σy) is the yield stress. It is seen that the fatigue safety factor is safe in design applications if the safety factor is about or more than (1.25), [56-57].

Therefore, the numerical technique used to evaluated the mechanical characterizations for structure with various geometry and applied load conditions, [58-65]. In addition, the results for its technique can be depending to comparison with other techniques used, [66-74], to given the agreement for results were evaluated by analytical or experimental work.

Fig. 5: 3-D Modeling of the Metal PTB

4. Results and discussion

4.1. Tensile properties results

The mechanical properties of eight layers glass fiber with orthocryl lamination resin are listed in Table 1. Fig. 6 showed the stress-strain curve of fiber glass. Table 1 showed that there are large differences in the values of ultimate stresses, yield stress and modulus of elasticity between the glass fiber composite and polypropylene plastic materials, which were increased by more than 446%, 640% and 141% respectively as compared with Polypropylene.

Table 1: Mechanical Properties of Composite Material PTBO

PTBO Material	Thickness (mm)	Σy (MPa)	Σult (MPa)	E (GPa)
Composite fiber glass (8layers)	4.2	170	224	2.17
Polypropylene, [75]	4	23	28-41	0.9

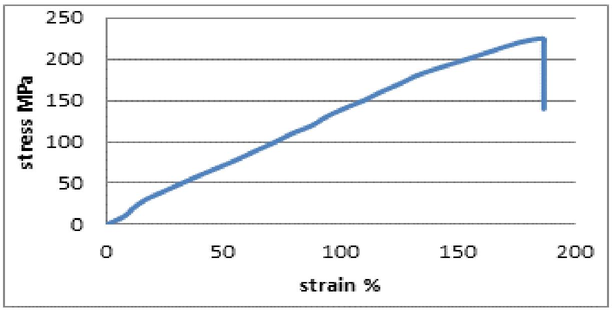

Fig. 6: Stress-Strain Curve for One Sample of Reinforced Composite with Fiber.

4.2. Fatigue test results

The result of fatigue test is shown in Fig. (7) show S-N curve for samples of lamination. The failure of fatigue of flat specimen can be occur when the specimen is fractured under periodic loading. The readings recorded by the fatigue tester machine, gave the number of cycles when the specimens were fractured. The failure stresses are decreasing and the numbers of cycles to reach to the failure are increasing at constant temperature.

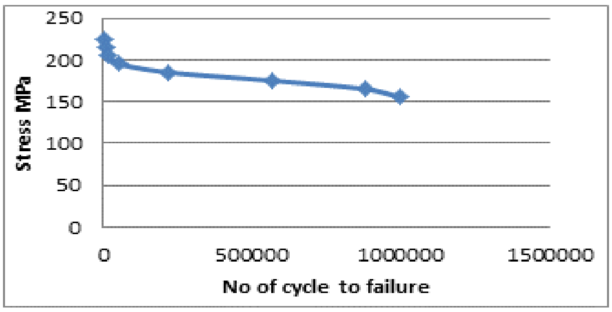

Fig. 7: S-N Curve for Composite Reinforcement with Fiber Glass.

4.3. Gait analysis with PTBO results

The ground reaction force (GRF) introduced under sole, due to biomechanical effects on leg during gait and stance cases walk over fixed plate where the force distribution is developed under sole due to patient gait. The test includes walking two main parts: before and after wearing PTB Orthosis . Fig.(8) shows the patients walking on force plate device with and without PTBO

Fig. 8: The Patient with and without PTBO.

a) Gait analysis without PTBO

Gait and gait cycle tables for patient without wearing PTBO results were shown in Tables 2 and 3 respectively. The main parameters describes the behavior of the gait cycle for patient separately as average data for one complete gait cycle from heel to heel strike. The force and the pressure distribution developed under sole due to patient gait for two feet are shown in Fig. (9), (10) restrictively.

Table 2: Gait Table for Patient without PTBO

gait table	patient without PTBO
Number of strikes	12
Cadence (steps/min)	47.6
gait time (sec)	10.08
Gait distance (cm)	368.9
Gait velocity (cm/sec)	36.6

Table 3: Gait Cycle without PTBO

gait cycle(sec)	patient without PTBO		
	Left	Right	difference
gait cycle time	2.06	2.98	0.93
Stance time	1.59	1.8	0.21
Initial double support time	0.50	0.42	-0.08
terminal double support time	0.42	0.50	0.08
total double support time	0.91	0.91	0.00
Heel contact time	1.12	1.17	0.05
Mid stance time	0.70	0.59	-0.12

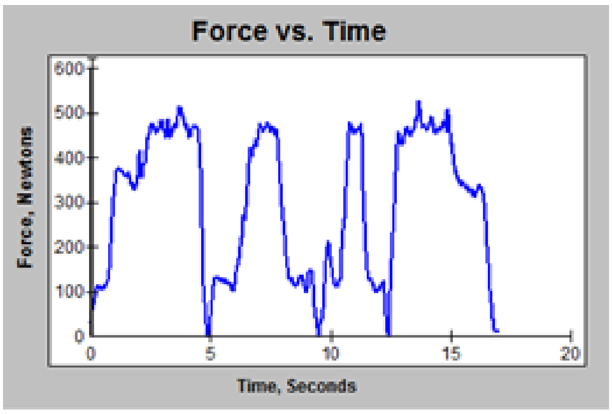

Fig. 9: Force vs. Time without PTBO.

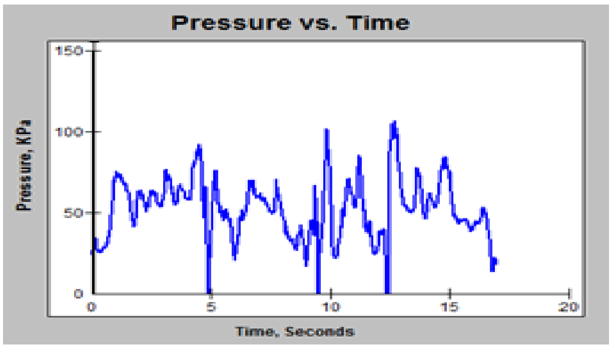

Fig. 10: Pressure vs. Time without PTBO.

b) 4.5. Gait analysis with metal PTBO

The main parameters describe the behavior of the gait cycle for patient wearing Metal PTBO separately as average data for one complete gait cycle from heel to heel strike. The results of the right were different from the left foot of the patient. Gait table and gait cycle table for patient with PTBO results were shown in Tables 4 and 5 respectively. The force and the pressure distribution developed under sole due to patient gait for two feet are shown in Fig. (11), (12) restrictively.

Table 4: Gait Table for Patient with PTBO

gait table	patient with PTBO
Number of strikes	11
Cadence (steps/min)	37
gait time (sec)	11.34
Gait distance (cm)	240.7
Gait velocity(cm/sec)	21.2

Table 5: Gait Table for Patient with PTBO

gait cycle	patient with PTBO		
	Left	Right	difference
gait cycle time	1.87	2.01	-0.14
Stance time	1.22	1.53	0.31
Initial double support time	0.1	0.22	0.13
terminal double support time	0.22	0.1	-0.13
total double support time	0.32	0.32	0.00
Heel contact time	0.38	0.97	0.59
Midstance time	0.94	0.61	-0.34

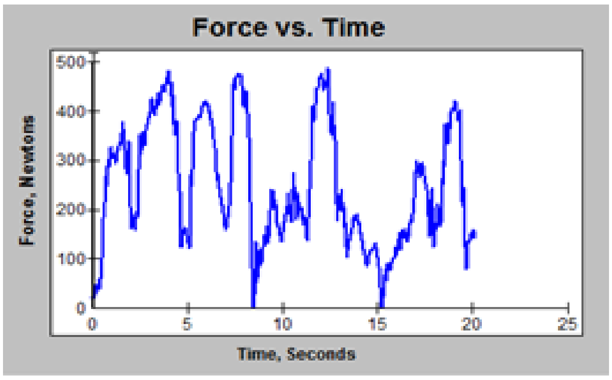

Fig. 11: force vs. Time with PTBO.

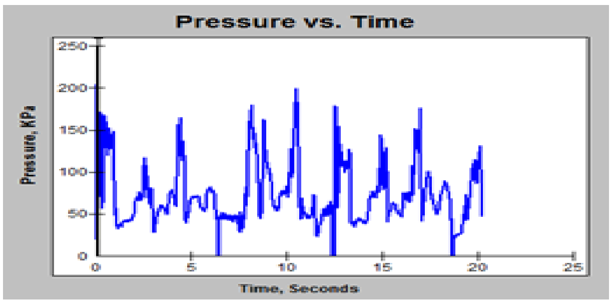

Fig. 12: Pressure vs. Time with PTBO.

The pressure distribution shows that at 50% of gait cycle the pressure reaches the maximum value because the ground reaction force is at maximum value in mid stance. The value of force with PTB Orthosis was 21.4 KN and the value of pressure with orthosis is 110 KPa that leads to better correction. The following result was obtained after achieving Gait cycle Test by using Force Plate device to determine the Ground reaction force GRF and interface pressure between the orthotics and the feet as shown in table 6.

From the comparison result obtained for the patient, as shown in the tables. The difference detected in the heel contact time and midstance time. heel contact time percent without PTBO equal to 5%, when wearing fiber glass PTBO equal to 59%. The midstance time percent for patient without PTBO equal to 12% when wearing PTBO equal to 34%. Reduction in the forces applied on foot after wearing orthotics and that is the main aim. the normal value of foot angle in men is 7 degrees and according to the above table it turns out that the angles of feet after wearing orthotics are increased and tend to be more normal so that's a good indication about orthotics well performance as shown in Fig. (13).

Table 6: Step Stride Comparison for the Case Study

Step Stride Table				
Step Stride Table	Case study Without PTB		Case study With PTB	
	right	left	right	Left
Step time (sec)	1.36	1.17	1.60	0.62
Step length(cm)	48.2	44	22.6	9
Step width(cm)	10.4	9.8	12.3	11.9
Step velocity (cm/sec)	35.8	37.6	14.1	14.5
Maximum force (N)	36.55	38.15	10.21	39.56
Maximum peak pressure (KPA)	236	206	172	225
Foot angle (degree)	0	2	-1	14

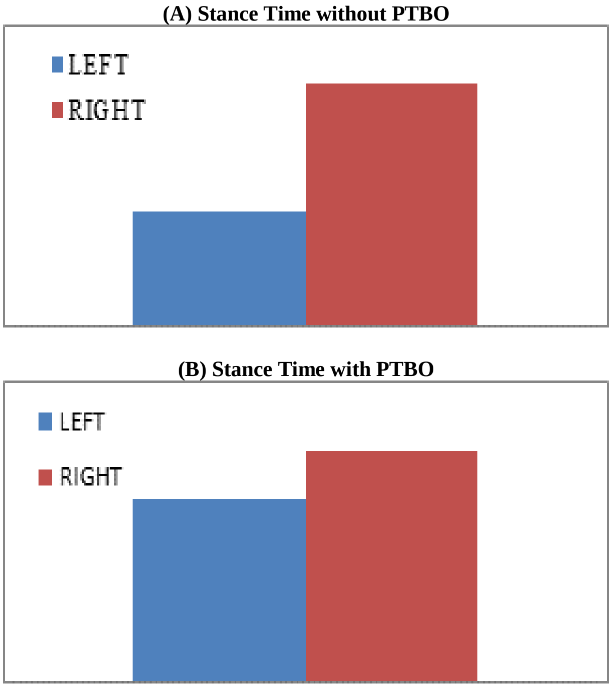

Fig. 13: Stance Time with and Without PTBO for Patient.

4.4. Interface pressure between the patient and PTBO

The alternating load between the calf and patient's leg, who was wearing the PTB, was measured as pressure. The sensor type (MatScan) is more acceptable for this type of dynamic load. The interface pressure was obtained by recording the output signal of the sensor through a multi-meter instrument which is interface with the computer and recording the data with the time. The pressures were only considered over the gait cycle by contact method between the patients and PTB at the calf reign. The data were normalized to 100 percent of gait cycle. The pressure for subjects was different at weight acceptance for as shown in Fig (14). The interface pressure between the stump of patient and socket can be measured using the F- Socket sensor. The sensor is driven by computer software (F-Scan) in order to measure the applied pressure curve. The sensor was put on the lateral region of the stump and it turns out that higher pressure is 226 KPa.

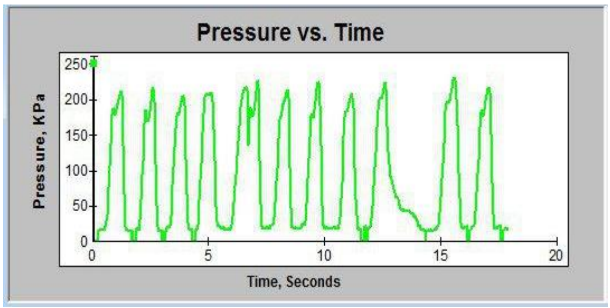

Fig. 14: Pressure vs. Time Percentage for Patient.

4.5. Numerical results

The analysis process and estimating of the Equivalent stresses, Total deformation and safety factor were done as shown below:

i) Equivalent stress (Von-Mises)

This stress is used to explain the fatigue S-N curve of the fatigue test taking into account the type of fatigue loading. Fig. (15) shows the overall distribution of the Von Mises stresses throughout the design and the approximate value and its location of the maximum Von Mises stress may be defined throughout the region of interest. The maximum stress was equal to 147.92 MPa.

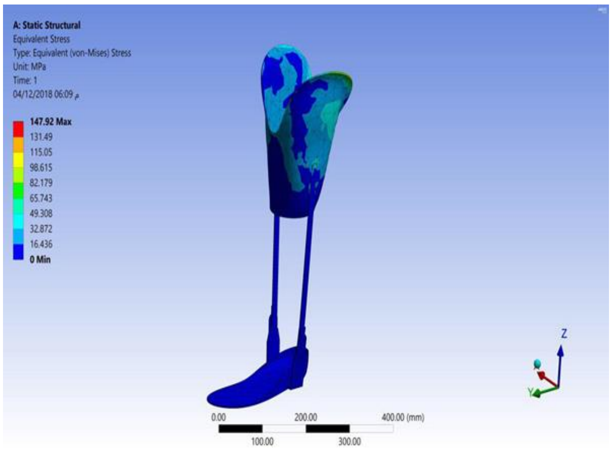

Fig. 15: Equivalent Stress (Von-Mises).

ii) Total deformation

Fig. (16) shows the maximum deformation for fiber glass lamination. The analysis process it has been found that the total deformation of Rigid Foot Orthosis is equal to 69.777 mm.

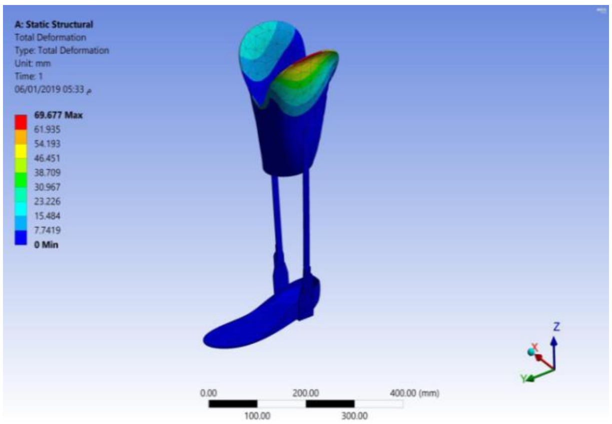

Fig. 16: Total Deformation.

iii) Safety Factor

The safety factor for polymer composite reinforced with fiber glass AFO model is passed in design as shown in the Fig. 17. The model of fiber glass material AFO showed that the fatigue safety factor for 8 layers of fiber glass is about (1.1492) which can be considered as safe as in design.

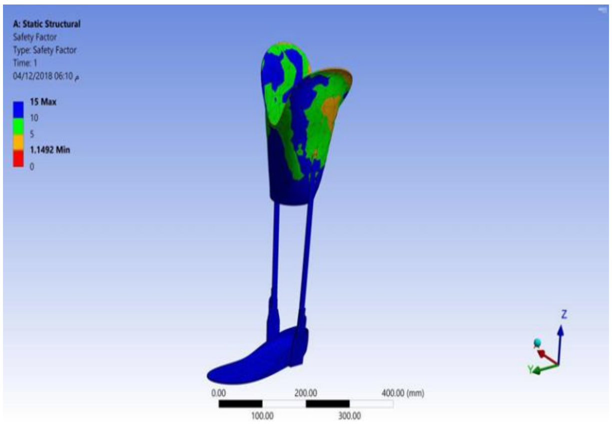

Fig. 17: The Safety Factor for Fatigue (Perlon).

5. Conclusion

This study gives a good database for manufacturing suitable lamination of an ankle foot ortheses suitable for patients. The conclusions of this work are as follows:

1) The results of the mechanical properties (σult, σy and E) showed that the KAFO made of 8 layers of glass fiber with orthocryl lamination resin were increased by 446%, 640% and 141% respectively as compared with that made of Polypropylene.
2) The model of material PTBO showed that the fatigue safety factor for (8 fiber glass) layers is equal to (1.1492) which is acceptable as safe as in design.
3) Maximum deformation is equal to 69.777 mm.
4) Higher interface pressure between the PTBO and patient is 226KPa at the calf region.

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