Design and Analysis of Knee Ankle Foot Orthosis (KAFO) for Paraplegia Person

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ABSTRACT

Knee ankle foot orthoses (KAFOs) are prescribed to paraplegic patients with low level spinal cord injury and with good control of the trunk muscles. Three types of KAFOs were used in this work (plastic-metal, metal-metal and composite materials), the composite materials were depended on the number of perlon layers (13 layers & 9 layers) with one layer of carbon-fiber and (6 layers) without carbon-fiber. The mechanical properties of most of the KAFOs' materials were tested by tensile test and fatigue machines.

The data of gait cycle (Ground Reaction Force (GRF), and pressure distribution) were collected from one patient with poliomyelitis (wearing brace type KAFO) and one normal subject. In this paper, the FEM (ANSYS) was used to compute the safety factor of fatigue for all types of KAFOs' models and the equivalent stress (Von-Mises). The interface pressure between the patient's leg and the brace was tested by using a piezoelectric sensor.

The results obtained from ANSYS gave the profile of safety factor of fatigue, for metal-metal KAFO (3.69), plastic-metal model (0.88). While, the (13) layers for composite material was about (1.4), but (1.07) & (0.41) for (9) layers and (6) layers, respectively. The value of safety factor increased with the composite material for the suggested design.

Keywords: KAFO, Fatigue, interface pressure, acceleration, GRF, poliomyelitis.

تصميم و تحليل رياضي لمسند صناعي نوع (قدم - كاحل - ركبة) لمعوقي الاطراف السفلى

الخلاصة

توصف المساند نوع (قدم كاحل ركبة) KAFO لمرضى شلل الاطراف السفلى لذوي الاصابات الطفيفة في الحبل الشوكي وتحكم جيد في عضلات الجذع. تم استخدام ثلاثة انواع من المساند (بلاستيكي – معدن, معدن – معدن, مواد مركبة) و تم أجراء فحص الشد والكلال على مواد KAFO لدراسة الخواص الميكانيكية. تم اجراء قياس قوة رد الفعل (GRF) بمساعدة مريض مصاب بشلل الاطفال (يرتدي مسند نوع KAFO) وحالة سليمة لكل من الاختبارات

المذكورة . في هذه البحث تم اجراء حسابات عامل الامان للكلال ولكل نماذج (KAFO) والاجهاد المكافئ (Von-mises) بالاعتماد على برنامج التحليل الهندسي (ANSYS). التصميم المقترح لنموذج (KAFO) المكون من المواد المركبة قد تميز بتبديل مواقع (Perlon's layers) الفخذ والساق, نموذج (13-9) طبقة, (13-6) طبقة, (9-6) طبقة للمسند (KAFO) . اعتمد قياس ضغط التداخل بين ساق المريض و المسند باستخدام متحسس نوع (Piezoelectric). النتائج المستحصلة من برنامج ANSYS اعطت توزيع عامل الامان للكلال واوضحت للنموذج (معدن – معدن) كان عامل الامان (3.69) و(بلاستيك –معدن) (0.88) اما للمواد المركبة (13 طبقة) فكان حوالي (1.4) و (1.07) و(0.41) للطبقات 9 و 6 على التوالي , و نلاحظ ان قيمة عامل الامان ازدادت في المواد المركبة للتصميم المقترح.

GENERAL

One of the major problems faced by modern society is integration of people with any kind of deficiencies for daily activities. Frequently, it is not noticed in most people any difficulty in performing simple tasks as opening a door, hearing and answering a telephone call, stand up, walking or even drink a cup of coffee [1]. The knee ankle foot orthosis has became a part of the patient's life. previous studies dealt with conventional KAFO, stance control KAFO as new design, pneumatic braces and carbon-composite KAFO, for studying the gait cycle, kinetics and ground reaction force.

T. SUGA et al, 1998, [2], discussed newly designed computer controlled knee-ankle-foot orthosis (Intelligent Orthosis). A knee-ankle-foot orthosis had been developed with a joint unit that controls knee movements using a microcomputer (Intelligent Orthosis). Irby et al, 1999, [3], was studied Optimization and Application of a Wrap-Spring Clutch to a Dynamic Knee-Ankle-Foot Orthosis. On the same device, Irby et al, 1999, [4], A dynamic knee-brace system (DKBS) has been designed which provides stance phase stability and swing phase freedom. the Automatic Control Design for a Dynamic Knee-Brace System was studied , a self-contained electronically controlled dynamic knee-brace system (DKBS) has been designed and tested allowing for knee flexion during swing phase. Terris Yakimovich et al, 2005, [5], discussed Design, Construction and Evaluation of an Electromechanical Stance-Control Knee-Ankle-Foot Orthosis, A new electromechanical Stance-Control Knee-Ankle-Foot Orthosis (SCKAFO) was designed to provide improved gait for people with knee-extensor weakness. Andrew H. Hanson, 2007 [6], investigate the effect of ankle-foot orthosis (AFO) on Roll-over shape (ROS) in adults with hemiplegia following stroke. Gregory S Sawicki, 2009, [7], studied pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation. Priya Chantal et. al, 2010, [8], researched the effect of stance control orthoses (SCOs) on gait characteristics and energy expenditure in knee-ankle-foot orthosis users.

Braces are devices which hold the extremities in a stable position. The goals of bracing are to increase function, prevent deformity, keep the joint in the functional position, stabilize the trunk and extremities, facilitate selective motor control, decrease spasticity and protect the extremity from injury in the postoperative phase. [9].

THE INFORMATION OF THE SUBJECTS (PATHOLOGICAL & NORMAL)

The kinetics data were collected via the young subject, his age was about (18 years) with height (165 cm) and weight (51 Kg). The subject was wearing plastic—metal orthosis type KAFO with knee cap for his right lower extremity, his case was Poliomyelitis which makes him unable to control the stability of knee extension, as shown in the figure (1). While, the same producer of collecting the data was done on normal young man, his age was about (39 years) with height (178 cm) and weight (85 Kg).

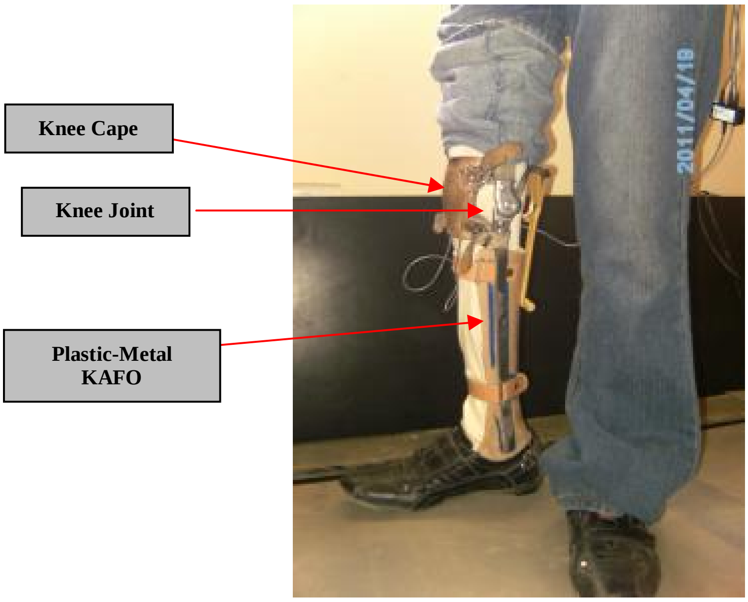


Figure (1) the subject wearing KAFO with knee cap.

NUMERICAL ANALYSIS

The finite element method (FEM) is now widely used in a variety of fields in engineering and science. Taking the advantage of the rapid development of digital computers with large memory capacity, as well as fast computation. In this work, FEM with the aid of ANSYS Workbench 12.1 software were used as a numerical tool to illustrate the effect of the fatigue performance in a structure element to determine the variation maximum stress, total deformation, fatigue life and safety factor [10]. The meshing process has been done by choosing the volume, then the shape of element was selected as tetrahedron (Automatic meshing), as shown in Figure (2). The total number of elements was (95298 elements) with total number of nodes of (182108 nodes).

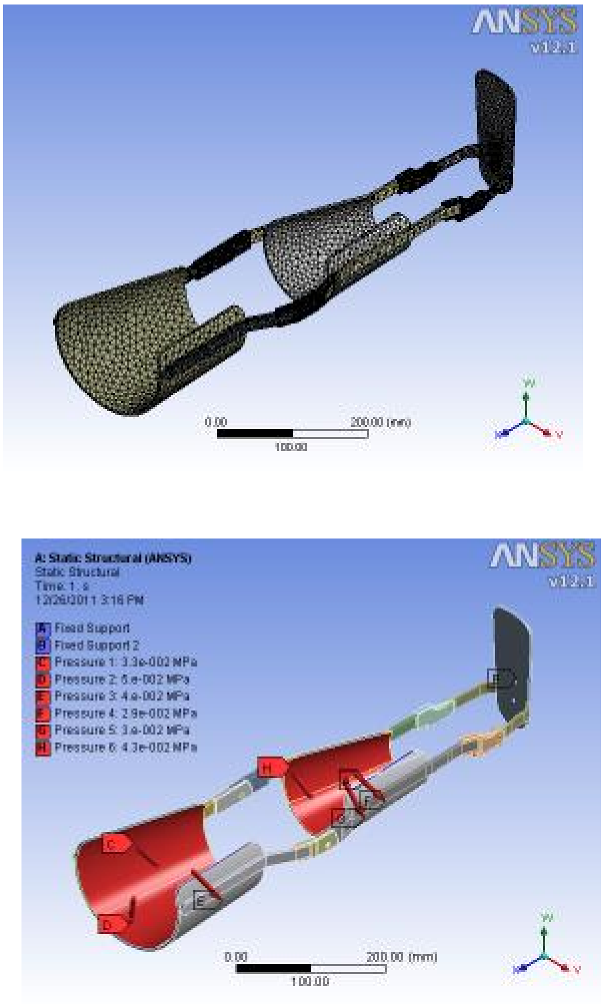


Figure (2) The model of KAFO with meshing and subjecting to pressure load.

EXPERIMENTAL WORK

Many experimental tests are recommended for designing and manufacturing the knee ankle foot orthosis for the three types of KAFO (plastic-metal, metal-metal and composite materials).

The experimental work is including:

Manufacturing the three types of KAFO are exhibited in Figure (3), and testing the mechanical properties for all materials, tensile test, fatigue test and chemical composition.

Also ground reaction forces and gait analysis parameters were measured by force plate device.

The specifications of the tensile test have been restricted according to the American Society for Testing and Materials specifications (ASTM); the tensile specimen's geometry and dimensions for standard (A370) which specified for metals (Stainless steel & Aluminum), while (D638) was specified for plastic (Polypropylene & Composites material), To measure the mechanical properties for composites material, the method of preparation of composite specimen is called vacuum method, it prevents cavities or defects.

The type of fatigue testing machine is Alternating bending fatigue (HSM20) with constant amplitude. The specimens were subjected to deflection perpendicular to the axis of specimens at one side of the specimens, and the other side was fixed, developing bending stresses (cantilever beam). To improve the composite material KAFO as suggested design, the thigh and shank calf can be divided into two segments, the circumferential segment which is, as expected, will subject to the main part of the alternating load; therefore, the 13 and 9 layers can be selected. While, the second segment was the remaining of the central area of the thigh and shank calf. Hence, the 9 and 6 layers can be used.

The measurement of pressure was carried out at specific positions on the thigh and shank segment by piezoelectric sensor as shown in Figure (4). Six positions were taken, three on the thigh and the remainder on the shank. The thigh segment was divided in to three parts longitudinal, in the middle and two parts on the terminal of the segment as shown in Figure (2). The same division was considered on the shank segment.

COMPOSITE MATERIAL SPECIMENS WITH VACUUM METHOD

There are different types of composite materials; which can be used in rehabilitation centers. The following specimens were manufactured by vacuum method:

1- Specimen was manufactured from 13 layers (6 Perlon fiber, 1 Carbon fiber, 6 Perlon fiber and acrylic matrix)

2- Specimen was manufactured from 9 layers (6 Perlon fiber, 1 Carbon fiber , 2 Perlon and acrylic matrix).

3- Specimen was manufactured from 6 layers from Perlon only and acrylic matrix.

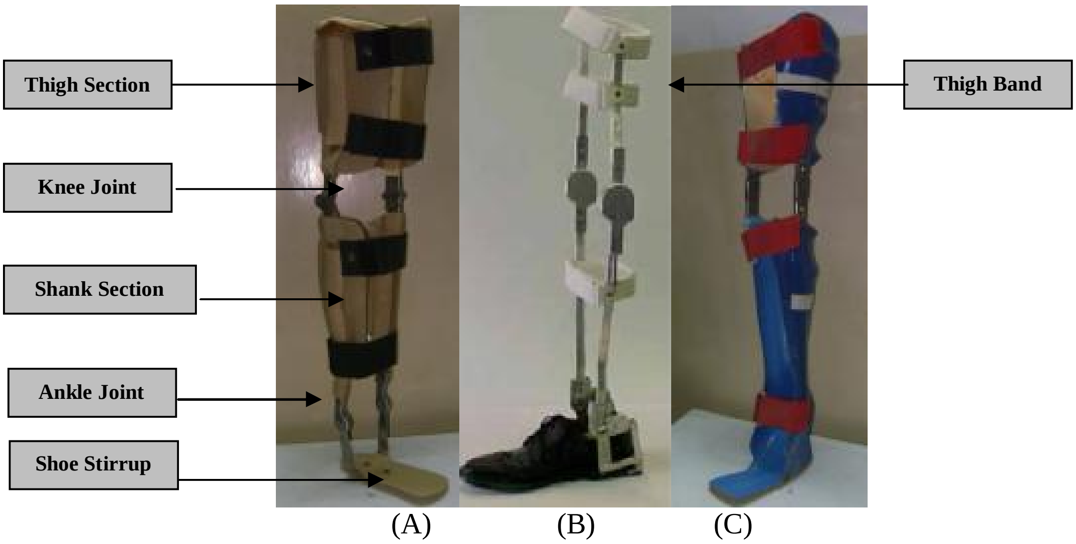


Figure (3) Types of KAFO: A: Plastic—metal KAFO. B: Metal—metal KAFOC: Composites material KAFO.

Figure (4) The piezoelectric sensor (Diameter = 15mm).

EXPERIMENTAL RESULTS AND DISCUSSION

The mechanical properties and chemical composition of the KAFO's materials:

The results of the mechanical properties (tensile test) for the KAFO's materials will be exhibited separately, as exhibited in the Table (1), and the behavior of (S-N) curve for fatigue testing shown in Figure (5).

Table (1) the mechanical properties of the KAFO's materials.

Materials		Young's Modulus (GPa)	Yield Stress (MPa)	Ultimate Stress (MPa)
Aluminum		54.650	119.75	130.4
Stainless Steel		192	792	820
Polypropylene		1.24	27.2	37.3
Composite materials	Layers (13)	12.4	78.3	
	Layers (9)	10.3	62.7	
	Layers (6)	3.6	23.6	

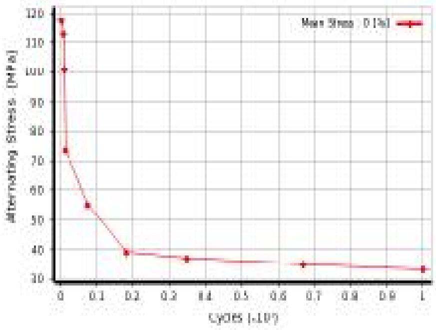
The chemical composition test is shown in table (2).

Table (2) Chemical Composition of Aluminum alloy 1200.

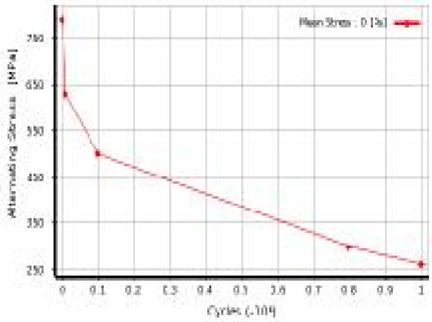
	%Si	%Fe	%Cu	%Mn	%Mg	%Cr	%Zn	%other	%Al
Standard[11]	1.00		0.1	0.3	0.3	0.1	0.1	0.15	Reminder
Actual	0.066	0.203	0.0027	0.0083	0.0809	0	0.0137	0.0038	Reminder

The (S-N) curves for Aluminum Alloy, Stainless Steel, Polypropylene and composite layers (13, 9, and 6) are shown in the Figure (5).

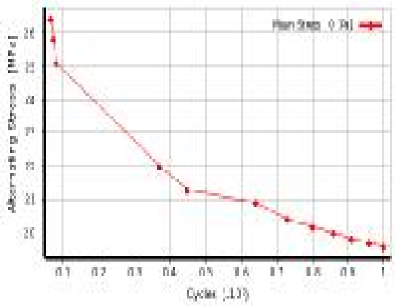
These curves are draw by adjusting the load (stress) on the specimen less than yield stress value for each material separately, and the number of cycle (life) calculated via counter device. The number of cycle fatigue recorded depending on the failure of specimen. The fatigue stress limit is selected at (1,000,000) cycle to be safety alternating stress in design. Most of the (S-N) curves are decreasing with increasing of the number of cycle for fatigue test.



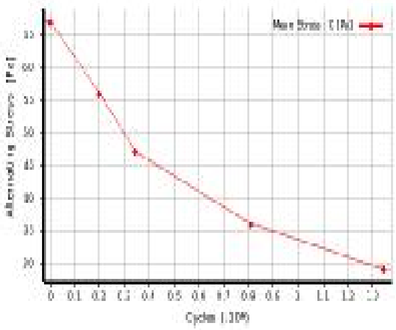
A: (S-N) curve for Aluminum Alloy 1200 adopted from [12].



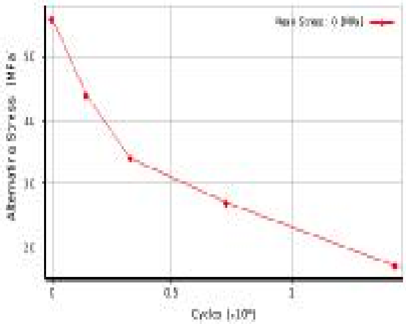
B: (S-N) curve for Stainless Steel,



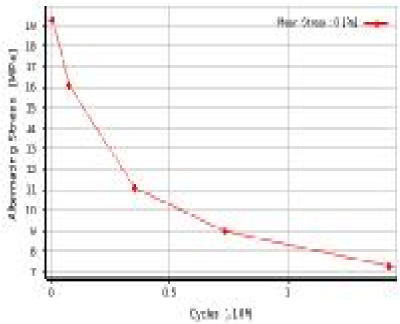
C: (S-N) curve for (PP)



D: (S-N) curve for (13 Layers)



E: (S-N) curve for (9 Layers)



F: (S-N) curve for (6 Layers)

Figure (5) (S-N) curves for; A: Aluminum Alloy 1200, B: Stainless Steel, C: PolypropyleneD: (13) layers. E: (9) layers. F: (6) layers.

THE RESULTS AND DISCUSSION FOR KAFO'S MODELS

The analysis of KAFO's models established by FEM software, to compute the safety factor of fatigue. The safety factor for Aluminum KAFO model passed in design while, the failure was clear in the polypropylene KAFO model as shown in the Figures (6-B), (6-A) respectively.

The safety factor counters for fatigue were shown in the figures (6-C), (6-D) and (6-E) for composites material KAFO's model (13, 9 and 6) layers respectively.

The model of (13) layers show that, for fatigue safety factor was about (1.48), which is safe in design. While, the model of (9) layers give a critical result for safety factor (1.05), which is not recommended in design. But, the model of (6) layers exhibited the failed result about (0.41) which is out of safe design. These differences in the results were due to the change of properties of materials for KAFOs, where the area still constant.

The safety factor fatigue for (13-9) layers and (13-6) layers was more than (1.3) as shown in Figures (7-F) and (7-G) respectively, while the (9) layers and (6) layers failed in the above recommended stages. But, when the (9) layers and (6) layers are used in unique KAFO model as (9-6) layers give a critical result (1.18) as presented in the Figure (7-H).

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, (σ_e) is the equivalent stress, and (σ_y) is the yield stress.

The safety factor for fatigue will be safe in design if the safety factor about or more than (1.25) [13].

The comparison of the Safety Factor for equivalent (Von-Mises) stress for all models of KAFO is shown in the Figure (8). Where, the comparison of the Safety Factor for Fatigue is shown in the Figure (9).

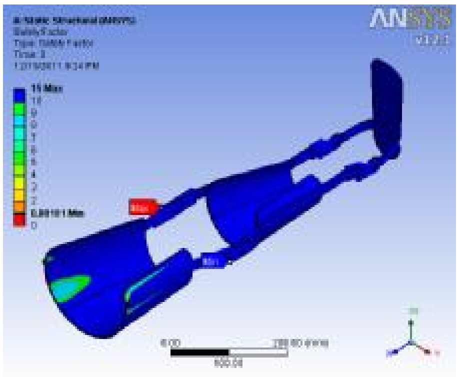
THE RESULTS AND DISCUSSION OF THE GAIT CYCLE PARAMETERS

The obtained data from the gait cycle test compared between the two cases, pathological and normal, to recognize the major differences for the parameters of the right and the left leg.

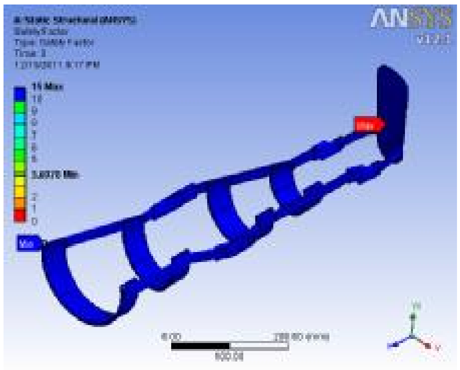
The ground reaction force (GRF) from treadmill device, for the pathological and normal subject for the right leg are shown in the Figure (10-right) and (11-right) respectively. Regardless of the magnitude of the GRF, which it depending on the subject's weight, in general, the discussion will be supported by the behavior of the GRF curve. This curve can be divided into three segments. The first segment is from the starting until the first peak which represents the heel strike, the second segment of the curve is the stage of mid- stance and distributes the load of the body for the whole area of the foot, and the third segment is considered from the initial of the second peak which is equivalent to the toe off stage. All these segments (GRF) occurred through the stance phase.

For the first segment, both Figures (10-right) & (11-right) are similar in the general form, but there is a difference between them from peak to peak of the other curve about (4%) of the gait cycle, while the second and the third segment give a difference about (8%) of the gait cycle.

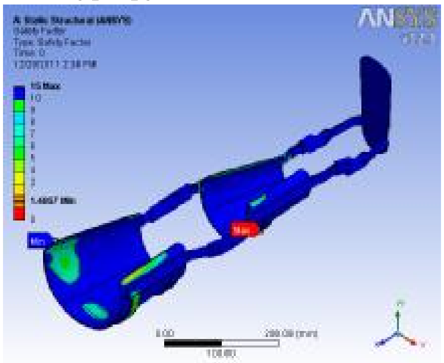
Figures (10-left) & (11-left) depict the GRF curves for the left leg of the pathological and normal subject, respectively. The first and third segments are similar on the gait cycle scale, but the second segment (mid stance) in the figure (10-left) for the pathological case approaches to be a straight line without any valley that backs to, the patient tries to keep the balance of his body through the walking, therefore, the subject's depending was on the left leg, while the right is the defected, and the stages of the dorsiflexion of the ankle are not found in the left foot.



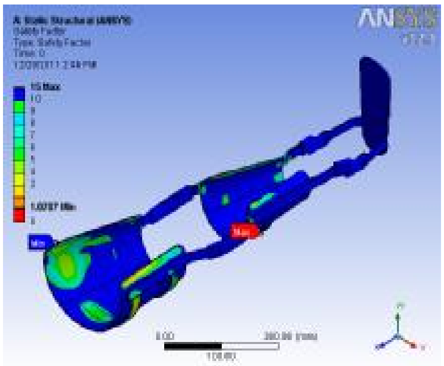
A: Polypropylene KAFO



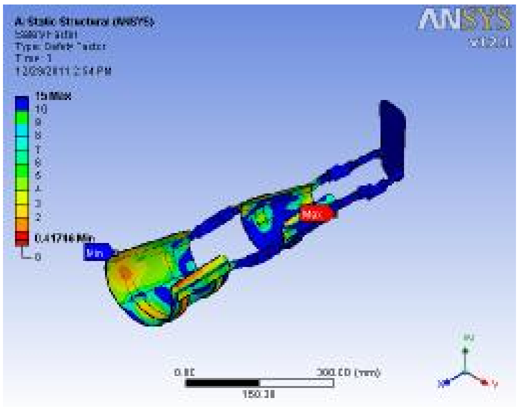
B: Aluminum KAFO



C: Composite (13) layers KAFO

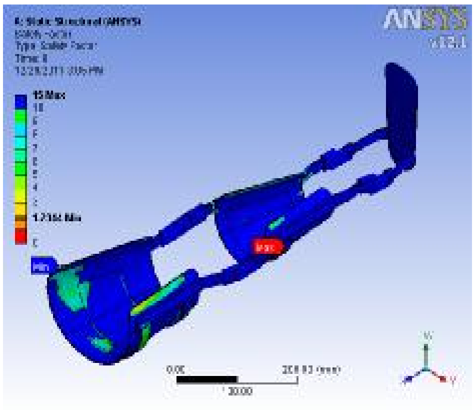


D: Composite (9) layers KAFO

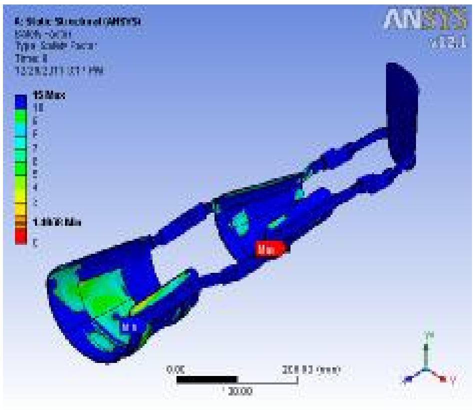


E: Composite (6) layers KAFO

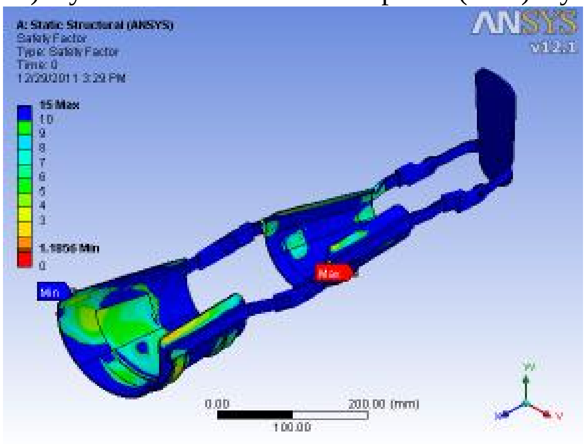
Figure (6) The Safety Factor for Fatigue:- A: (Polypropylene), B- Aluminum, C: composite 13 layers, D: composite 9 layers, E: composite 6 layers.



F: Composite (13-9) layers KAFO



G: Composite (13-6) layers KAFO



H: Composite (9-6) layers KAFO

Figure (7) The fatigue Safety Factor for suggested composite KAFO Models: F: Composite (13-9) layers, G: Composite (13-6) layers, H: Composite (9-6) layers.

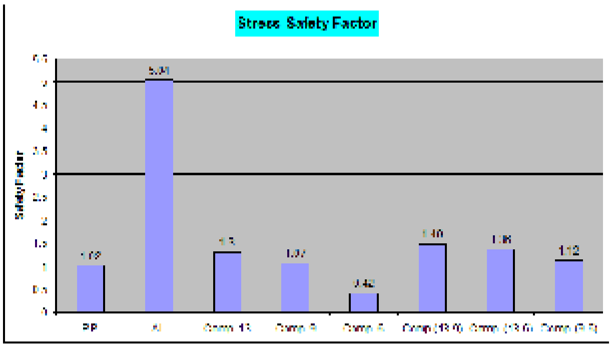


Figure (8) Comparison of the S. F. for Stress .

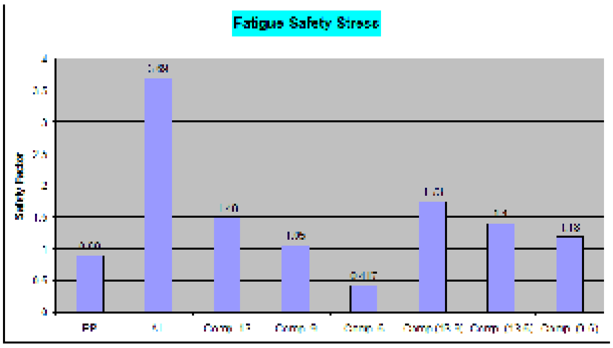


Figure (9) Comparison of the S. F. for Fatigue.

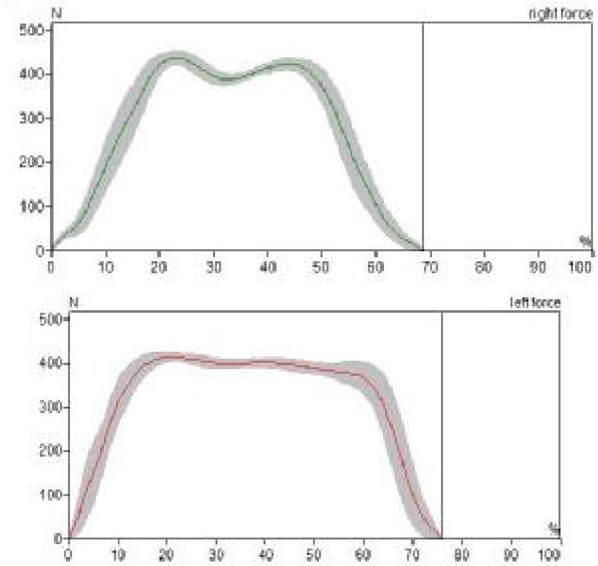


Figure (10) The GRF (right & left) for pathological subject wearing KAFO.

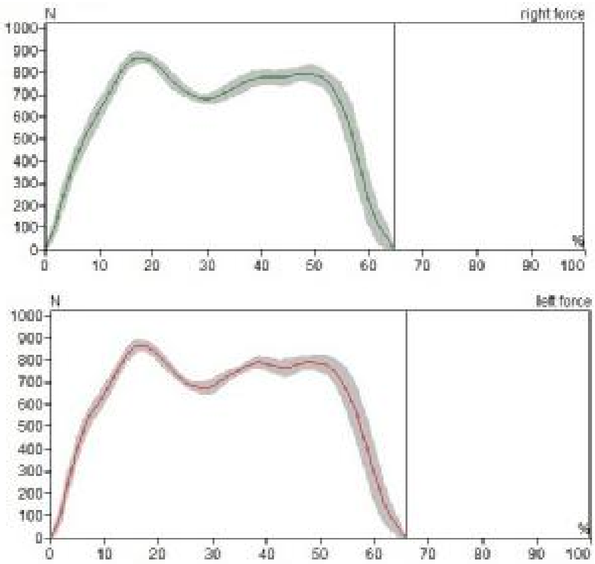


Figure (11) The GRF (right & left) for normal subject.

CONCLUSIONS

The following conclusions may be drawn from the results obtained in this work:

1. The knee ankle foot orthosis type polypropylene exhibited failure in fatigue life design when the value of the safety factor was about (0.88).
2. The aluminum knee ankle foot orthosis gave good results in equivalent Von-Mises stress and the safety factor for fatigue, and this led to the longer life design. This type of the KAFO is commended to a limited kind of the patients, depending on the weight, because of the concentration of the forces between the regions of the aluminum bands and the patient's leg, and that causes discomfort for the patient.
3. The composite material type (13) layers used in the model of the KAFO were better than (9 and 6) layers according to the design conditions.
4. The suggested design in the composite models of KAFO gave an improvement in the results (safety factor & Von-Mises stress) more than the KAFO models of composite material (13, 9 & 6) layers.
5. The comparison process between the pathological subject and the normal subject in the gait cycle test showed major differences between the two subjects and that back to the circumduction.
6. The piezoelectric sensor, which is used to measure the interface pressure, was suitable for the alternating load between the calf and the patient's leg.

REFERENCES

[1].Rodrigo Licio Ortolan, Fransergio Leite Da Cunha, Daniela Cristina, Juracy Emanual, Adriana Simone Santa & Alberto Cliquet Jr., “Trends in Orthopedic Biomechanics Applied to Rehabilitation”, ACTA ORTOP BRAS, 2001, Vol. 9, No. 3, pp. (44-58).

[2].T. Suga, O. Kameyama, R. Ogawa, M. Matsuura, & H. Oka, “Newly designed computer controlled knee-ankle-foot orthosis (Intelligent Orthosis)”, Prosthetics and Orthotics International, 1998, Vol. 22, pp: 230-239.

[3].Steven E. Irby, Kenton R. Kaufman, Roy W. Wirta, and David H. Sutherland, “Optimization and Application of a Wrap-Spring Clutch to a Dynamic Knee-Ankle-Foot Orthosis”, *IEEE* 1999, Vol. 7, No. 2, pp: 130-134.

[4].Steven E. Irby, Kenton R. Kaufman, James W. Mathewson, & David H. Sutherland, “Automatic Control Design for a Dynamic Knee-Brace System”, *IEEE* 1999, Vol. 7 , No. 2, pp: 135-139.

[5].Terris Yakimovich, Jonathan Kofman, & Edward Lemaire, “Design, Construction and Evaluation of an Electromechanical Stance-Control Knee-Ankle-Foot Orthosis”, IEEE 2005, pp: 2333-2340.

[6].Stefania Fatone, & Andrew H. Hansen, “Effect of ankle-foot orthosis on roll-over shape in adults with hemiplegia”, JRRD 2007, Vol. 44, No. 1, pp: 11-20.

[7].Gregory S Sawicki and Daniel P Ferris, “A pneumatically powered knee-ankle-foot orthosis (KAFO) with myoelectric activation and inhibition”, Journal of NeuroEngineering and Rehabilitation 2009.

[8].Priya Chantal Davis, Timothy Michael Bach, & Darren Mark Pereira, “The effect of stance control orthoses on gait characteristics and energy expenditure in knee-ankle-foot orthosis users”, Prosthetics and Orthotics International June 2010, Vol 34, No. 2, pp: 206–215.

[9].Nadire Berker & Selim Yalcin, “The Help Guide to Cerebral Palsy”, Second Edition. Merrill Corporation, Washington, 2010, pp: 49.

[10].M. Muhsin Ali, “Design and Analysis of a Non-articulated Prosthetic Foot for People of Special Needs”, M.Sc. Thesis in Mechanical Engineering, AL- Nahrain University, 2010.

[11].British Standard, “Aluminium and aluminium alloys – Chemical composition and form of wrought products- part 3 “, EN 573-3: 2009.

[12].S. Lampman, “Fatigue and Fracture, Fatigue and Fracture Properties of Stainless Steels”, ASM International Handbook. Vol. 19, 1996, pp: 1811.

[13].Brett A. Miller, “Failure Analysis and Prevention, Fatigue Failures”, ASM International Handbook. Vol. 11, 2002, P 1470.