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Research article

Estimation of fatigue lifetime of a cervical disc prosthesis using finite element and experimental investigation of the amount of wear

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Abstract

One of the main problems of cervical disc implants is the wear caused by the overlapping of the surfaces, leading to a reduction in the fatigue lifetime of the prosthesis, which in turn results in premature removal of the implant from the patient's body. To obtain the amount of wear and fatigue lifetime of the cervical disc implant, first, a three-dimensional model of a cervical disc implant (prodisc-C), consisting of a core made of ultra-high molecular weight polymer (UHMWPE) material with upper and lower plates made of cobalt-chromium and titanium, was designed in Solidworks software. Then it was transferred to Abaqus software to evaluate the von Mises stress distribution under the application of a concentrated force of 73.6 N. Afterward, the results of this simulation were inputted into the Fe-safe software and the fatigue lifetime of the implant was calculated. Furthermore, the wear rate of the polymer used in the central core was experimentally investigated. The calculation results of the maximum fatigue lifetime cycle of the prosthesis were acquired in three positions in the upper plane, middle plane, and lower plane. The wear volume (i.e., volumetric wear) obtained numerically during 10,000,000 cycles was equal to 17.5 mm^3, and the wear mass acquired by the wear test during the probe movement on the sample in a 1000 m distance was equal to 0.005 gr.

Keywords: Fatigue, Lifetime, Wear, Cervical disc prosthesis, Finite element.

1- Introduction

More than 25% of people suffer from damage and wear of the vertebrae of the spine, causing severe pain and disrupting their life [1]. The natural disc between the cervical vertebrae is an amazing mechanical structure from the engineering point of view. This disc can withstand large pressures and at the same time can perform wide movements between the cervical vertebrae. The underlying biological factors leading to cervical pain usually result in the progressive deterioration of the cervical intervertebral discs. However, disc destruction occurs gradually with the progress of time and increasing age, and intensifies due to injuries to the spine [2-4].

Owing to the emergence of these anatomical problems, cervical disc prostheses have been designed as an alternative to carry out the functions of the degenerated discs and to allow the spine to function normally so that the replaced disc can function in all respects like the natural disc [5,6]. Different types of cervical disc prostheses have been designed and manufactured. Some of these discs have two end plates separated by a plastic separator. These two end plates are made of cobalt-chrome and titanium alloy. A plastic core made of ultra-high molecular weight polymer (UHMWPE) is placed between two end metal plates [7]. In the design and manufacturing of discs used in the body structure, different analyses should be conducted according to human anatomy and movement conditions. These analyses are performed in terms of the properties of the materials employed and the geometry and shape of the prosthesis to provide a more realistic model with a longer fatigue lifetime. Examining the mechanical properties of the materials utilized in the cervical disc has been the subject of the research of a number of researchers. The research results of these scholars have been used to determine the stress-strain contours and the amount of wear to optimize the design. Among them, Moussa et al. focused on the numerical optimization of the cervical disc prosthesis (prodisc-C). Through optimization of the prosthesis geometry, they presented a new design for the prosthesis geometry to reduce the von Mises stress. By optimizing the shape of the cervical spine prosthesis, favorable conditions for improving performance and relieving the patient were provided [8].

One of the most important problems of cervical disc prostheses is the wear of the contact surfaces of the implants, which reduces the fatigue lifetime of the prosthesis. In the past years, much attention has been paid to the problem of wear and improvement of contact surfaces by applying appropriate coatings and optimizing the geometry of cervical prostheses. Based on ideas from wear simulations of hip and knee, several research groups developed mathematical models to evaluate disc joint wear [9,10]. Bhattacharya et al. investigated wear in the cervical disc implant using a finite element model (FEM), and examined the influence of the structures adjacent to the spine on the wear of an artificial cervical disc [11]. Besides, to evaluate the wear, they used the FEM to simulate a part of the spine. Moreover, they investigated wear in a disk prosthesis with a metal-on-metal movement structure and presented a mathematical model. Their objective was to determine the coefficient of wear performance of metal on synthetic disk metal and to compare the wear performance of prosthesis with a metal-on-polymer movement structure in vivo mode and in vitro simulation using finite element modeling [12]. Viv et al. evaluated the wear of the cervical disc prosthesis. They investigated the wear in 10,000,000 cycles and obtained the average wear rate of UHMWPE, 0.53 mg per million cycles [13].

Numerous investigations have shown that there is a strong relationship between disc degeneration and fatigue damage in the disc [14,15]. The main indicator of cervical pain is fatigue damage to the cervical intervertebral discs [16]. Many studies have been carried out to investigate the fatigue failure characteristics of intervertebral discs, such as the number of load cycles to failure for different stress ranges and the change in compressive stiffness of the disc as a result of fatigue. Yu et al. conducted a study on the geometrical and morphological changes of pig intervertebral discs under fatigue loading. Considering the similarity of the ligament structure and joint orientation of pig vertebrae with those of humans, the results of this research can be suitable for the study of human spine injury [15]. Subromani et al. developed a biomechanical computational model for cervical disc fatigue, and predicted the initiation and progression pattern of fatigue damage in the cervical disc [17]. Qasem et al. performed computational fatigue simulations using a FEM of a lumbar spine segment, with compressive cyclic loading under different amplitudes. In all loading conditions, they observed that the fatigue damage began from the inner posterior ring and propagated outward toward its periphery [18,19]. Macwana et al. utilized a FEM of a cervical spine segment to examine the pattern of damage initiation and fatigue progression in the disc annulus. They also briefly reviewed the methods of intervertebral disc degeneration including water loss and disc height change [20].

Fatigue is one of the causes of cervical spine disc damage and is an influencing factor in the reduction of the lifetime of the prosthesis. Due to more activity in young people, there is a greater need to decrease prosthesis damage and fracture in youths. As mentioned, various investigations have been carried out in the area of fatigue lifetime of the cervical spine and cervical disc in the body. However, the knowledge about the fatigue lifetime of cervical disc prosthesis is lacking because no previous study has examined it. Therefore, to fill this research gap, the present study was performed to determine the fatigue lifetime of human cervical disc prosthesis (prodisc-C) under cyclic load in axial loading mode and also to experimentally investigate the wear of polymer material used in the central core of cervical prosthesis (UHMWPE). Prosthesis simulation was carried out using Abaqus software, and the stress contour results of prosthesis components were transferred to Fe-safe software to determine the fatigue lifetime of the prosthesis. Finally, by conducting a wear test on the polymer material used in the core of the prosthesis, the amount of wear of this material was determined via Archard's wear law.

2- Finite element simulation

First, a three-dimensional model of the cervical disc prosthesis (prodisc-C) was drawn and created using Solidworks software according to the geometric parameters optimized by Emajid Mousa [8] (see Fig. 1). The upper plate of the prosthesis was made of cobalt-chrome (CoCrMo) and the lower plate was made of titanium (Ti6Al4 V) and the central core was made of UHMWPE with the mechanical properties of the elastic structural model according to Table 1 [5]. According to Fig. 2, Based on the biomechanical behavior of the spinal discs, we c totally fixed the lower metal plate. Loading in static conditions as a vertical concentrated force of 73.6 N newtons (which is in the range of the weight of the human head) to the superior metal endplate in all three different positions (with 8° of flexion, with 6° of flexion and position normale 0°), vertical direction to the gravity force applied [6,21]. the polymer core was fixed on the bottom plate. The sliding interactions between the polymer core and the upper plate were simulated as "hard contact" with a friction coefficient of 0.2 [11]. The bottom plate was fixed in all directions. The polymer core and upper and lower plates were meshed using reduced tetrahedral elements (C3D4) with four nodes.

In three different positions, the study of the prosthesis was carried out under a load of 73.6 N (Fig. 3). In the first position (a), the prosthesis was in a 0o flexion, where the metal plates were parallel. In the second position (b), the prosthesis was bent 6o, that is, the upper plane was inclined 6o relative to the lower plane. In the third position (c), the prosthesis was bent 8o, meaning that the upper plane had an inclination of 8o relative to the lower plane.

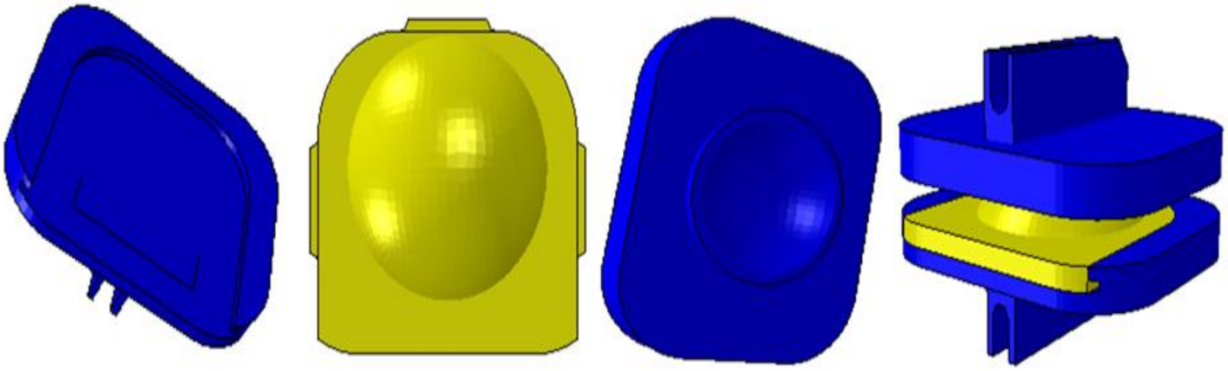


Fig. 1 Geometrical modeling of the prodisc-C cervical prosthesis

Table 1: Properties of the materials used in the three parts of prodisc-C prosthesis [5]

Material	Young’s modulus E (MPa)	Poisson’s ratio υ
CoCrMo	220000	0.32
Ti6Al4 V	114000	0.35
UHMWPE	1000	0.49

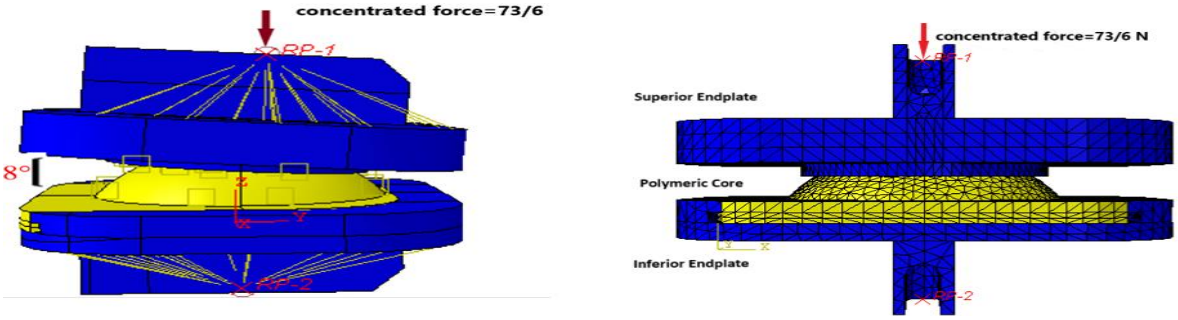
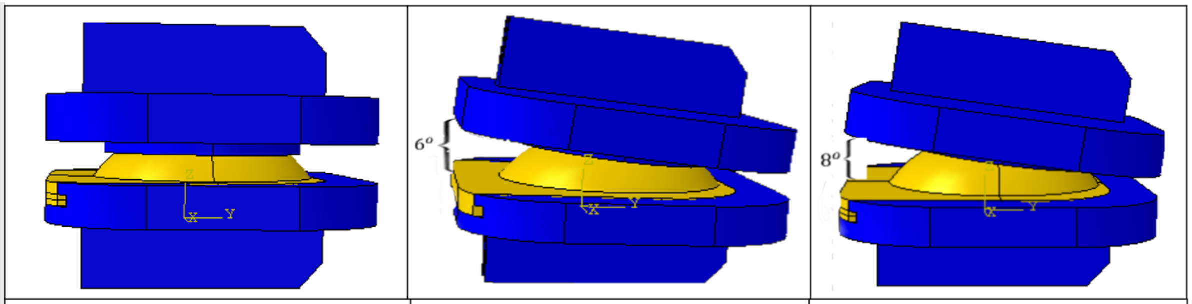


Fig. 2 Meshed model of the cervical implant (prodisc-C) including two metal end plates and a main polymer core component and the load applied on the upper plate.



a) without flexion
b) with flexion of 6°
c) with flexion of 8°

Fig. 3 The three positions of prodisc-C cervical disc arthroplasty

The Von Mises stress contours obtained from this simulation for all three main parts of the implant are shown in Figs. 4-6. We utilized the obtained simulation results to determine the fatigue lifetime of the prosthesis (see the next section). Table 2 presents the results of the largest von Mises stress obtained from the analysis and simulation of the prodisc-C prosthesis in three positions of the implant on each of its three parts.

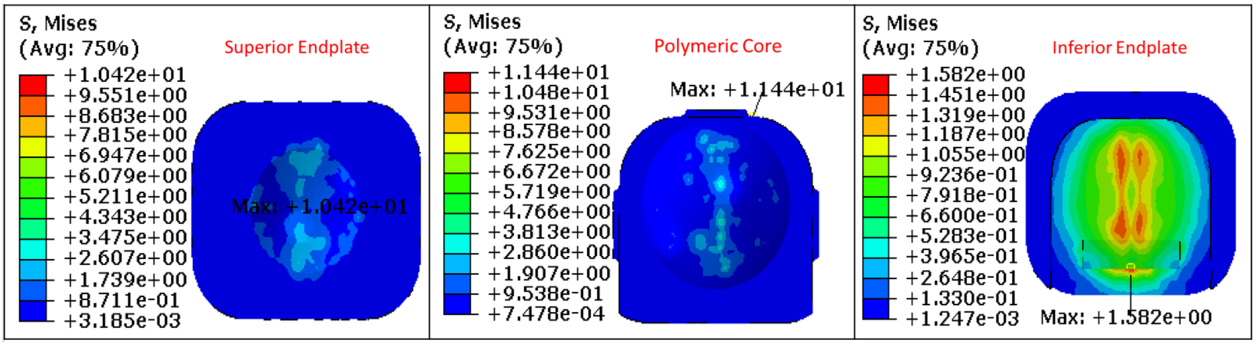


Fig. 4 Stress contour obtained on three parts of the prodisc-C implant using FEM at 0º flexion

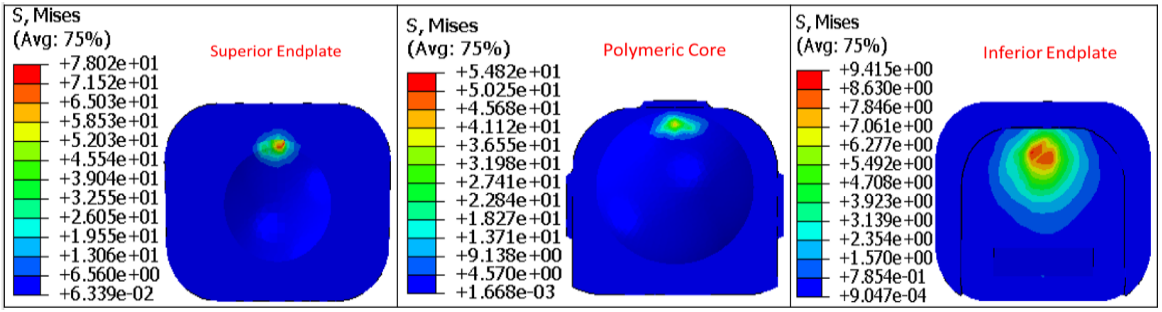


Fig. 5 Stress contour obtained on three parts of the prodisc-C implant using FEM in 6° flexion

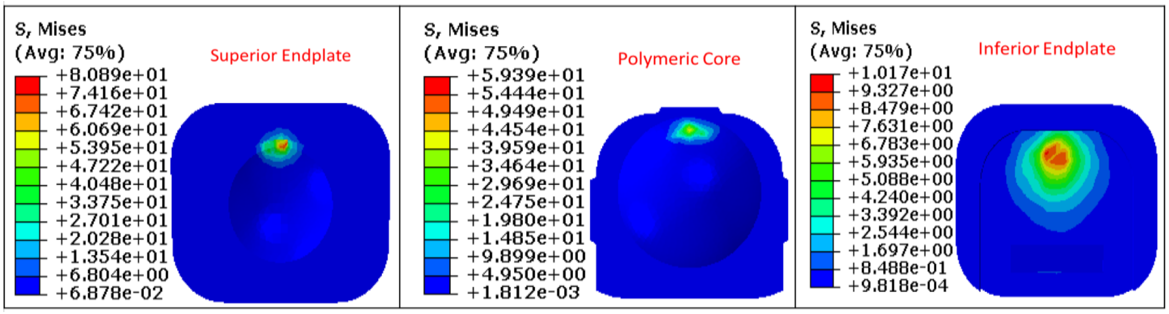


Fig. 6 Stress contour obtained on three parts of the prodisc-C implant using FEM in 8° flexion

Table 2: Von Mises stress contour results of the prodisc-C prosthesis in three different positions

Positions	**Von Mises maximum stress of the prosthesis(MPa)**		
	Normal position (0°)	with 6° of flexion	with 8° of flexion
Superior Endplate(CoCrMo)	10.4	78	80
Polymeric Core(UHMWPE)	11.4	54	59
Inferior Endplate(Ti6Al4 V)	1.6	9.4	10

According to Table 2, in the normal state, the polymer (the central core of the prosthesis) has the largest von Mises stress, which is equivalent to 11.4 MPa. However, in the case of 6° bending, the maximum von Mises stress of the top plate (cobalt-chrome) is equal to 78 MPa. In the state of 8° bending, the top plate (cobalt-chrome) has the greatest stress (equal to 80 MPa), which is the largest von Mises stress among all positions.

3- Fatigue lifetime estimation

Repeated exposure to cyclic loads due to daily activities over several years can lead to fatigue damage in cervical disc prostheses.

The obtained stress distribution in Abaqus software was transferred to Fe-safe software as a file with an odb format. Fe-safe software is a specialized software in the field of fatigue lifetime analysis that uses different algorithms such as Goodman, Gerber, and Walker to determine and estimate the fatigue lifetime. According to past investigations, Goodman's algorithm [6, 21] was utilized at a frequency of 1 Hz [11, 22] to determine the fatigue lifetime for the upper plate (CoCrMo), lower plate (Ti6Al4 V), and central core (UHMWPE). Figs. 7-9 exhibit the fatigue lifetime cycle in the main components of the cervical disc implant at angles of 0^o, 6^o, and 8^o. The results are presented logarithmically with base 10.

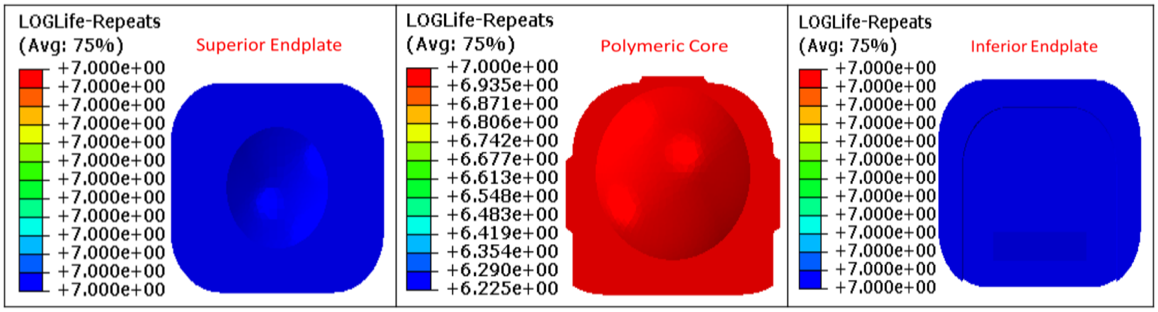


Fig. 7 Fatigue lifetime obtained on three plates of the prodisc-C implant at 0^o flexion

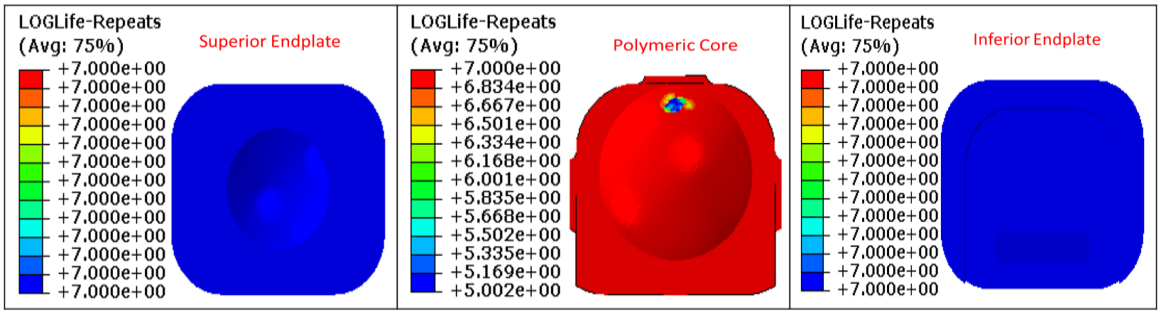


Fig. 8 Fatigue lifetime obtained on three plates of the prodisc-C implant in 6^o flexion

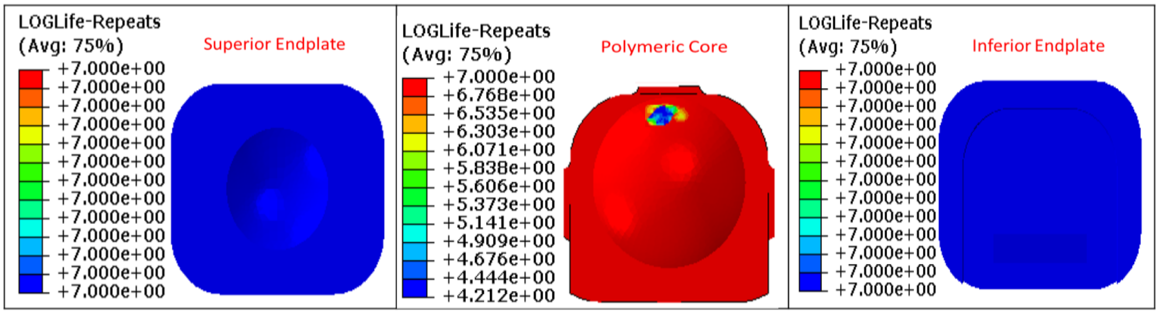


Fig. 9 Fatigue lifetime obtained on three plates of the prodisc-C implant in 8^o flexion

Table 3: Fatigue lifetime results of the prosthesis

Positions	**log life（Number of Cycles）**		
	position normale(0°)	with 6° of flexion	with 8° of flexion
Superior Endplate(CoCrMo)	7 e	7e	7e
Polymeric Core(UHMWPE)	6.225e	5.002e	4.212e
Inferior Endplate(Ti6Al4 V)	7e	7e	7e

As can be observed, the fatigue lifetime created on the upper and lower plates is a constant number equal to 7e. This is attributed to the high lifetime of cobalt-chromium and titanium under this amount of applied stress. According to the research of Desia et al. [23], the lifetime span is almost infinite in stresses smaller than 100 MPa. However, in the middle polymer core, the fatigue lifetime cycle is different in the above-mentioned three positions. Table 3 presents the fatigue lifetime results procured through the analysis and simulation of the prodisc-C prosthesis by Fe-safe software. Table 3 suggests that the fatigue lifetime of the upper and lower plates is infinite in all three cases. The fatigue lifetime cycle of the prodisc-C prosthesis in the central core of the prosthesis (UHMWPE) is different in all three positions, the highest value of which is equal to 1,778,279/4 cycles in the normal position (0°), and it is equal to 100,461/58 cycles in the 6° bending position. Besides, the fatigue lifetime in the bending position of 8o is equivalent to 16,292/97 cycles, which is the smallest fatigue lifetime among the three positions.

4- Determination of the wear amount

Considering the high importance of the problem of wear in the cervical disc implant, which is one of the main indicators reflecting the durability of the desired function and fatigue lifetime, the wear of the central core polymer of the prosthesis is estimated using classic Archard's wear law [10, 24, 25]. Archard's wear formula is expressed using the following equation:

$$V=K_w\,FX \tag{1}$$

where V represents the volumetric wear rate, K_w denotes the wear coefficient between the probe and the polymer tablet, F stands for the contact force, and X signifies the relative sliding distance. The parameter X depends on the radius of the prosthesis and the number of cycles. The value of F is considered as a loading force of 73.6 N. The wear coefficient is considered 19.48×10^{-10} mm^3/Nmm according to the reference [10]. Therefore, the amount of volumetric wear obtained using equation is estimated to be 17.5 mm^3 during 10 millio(1) n cycles. The experimental wear test was also conducted on a tablet made of the same polymer (49 mm in diameter and 5 mm thick based on the wear device standard) in the materials laboratory of Isfahan University of Technology (Fig.

10). A wear speed of 0.2 m/s for the probe, a vertical load of 7 kg, and a probe travel distance of 1000 m were considered based on the ISO 18192 standard [26, 28]. The weight of the polymer piece was measured before wear. During the test, the weight was re-measured every 200 meters During the wear test, the weight difference of this polymer was found to be 0.005 gr. Fig. 11 displays the graph obtained during the wear test of the polymer tablet. In general, "wear is not a material property, but a system response". In other words, wear is a comparative test, so in order to compare the results, the ratio of the results of two coatings should be compared with the same ratio.

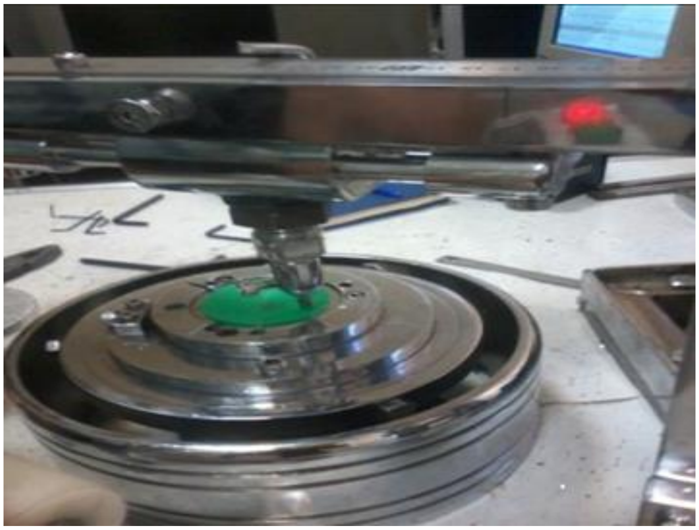


Fig. 10 A view of the wear test conducted on the same polymer tablet with the central core of the prosthesis

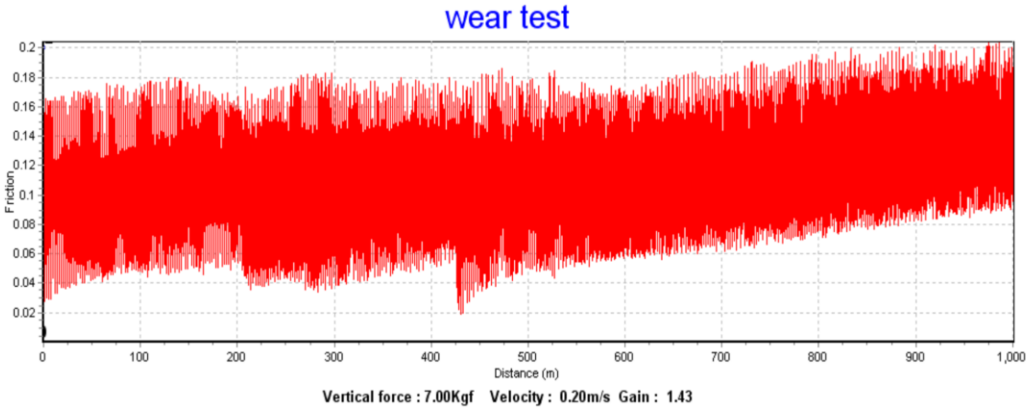


Fig. 11 The graph acquired for polymer (UHMWPE) during the wear test of polymer tablet in the laboratory

5- Conclusion

Cervical disc prosthesis is one of the new achievements of medical engineering knowledge, and one of the most important problems of cervical disc prostheses is the wear between the contact surfaces and the damage caused by fatigue of the prosthesis. In this research, the lifetime span and the period of useful operation of the cervical disc implant (prodisc-C) were determined from the two perspectives of fatigue lifetime and wear rate, by applying an axial force and considering the presence of frictional contact between the prosthesis components. For this purpose, first, the geometric model of the entire prosthesis, including the upper and lower plates and the central core, was drawn using the Solidworks software. Afterward, the force analysis was carried out by using Abaqus software to determine the stress distribution on the prosthesis components under normal operating conditions. By transferring stress distribution information to Fe-safe software, the fatigue lifetime of the prosthesis was determined under three positions. in the normal state, the polymer (the central core of the prosthesis) has the largest von Mises stress, which was equivalent to 11.4 MPa. However, in the case of 6^{o} bending, the maximum von Mises stress of the top plate (cobalt-chrome) was equal to 78 MPa. In the state of 8o bending, the top plate (cobalt-chrome) has the greatest stress (equal to 80 MPa), which was the largest von Mises stress among all positions.

Also, the fatigue lifetime of the upper and lower plates was infinite in all three cases. the fatigue lifetime cycle of the prodisc-C prosthesis in the central core of the prosthesis (UHMWPE) was different in all three positions, the highest value of which was equal to 1,778,279/4 cycles in the normal position (0°), and it was equal to 100,461/58 cycles in the 6° bending position. Besides, the fatigue lifetime in the bending position of 8o is equivalent to 16,292/97 cycles, which was the smallest fatigue lifetime among the three positions. Furthermore, the volumetric wear of the prosthesis was estimated during 10 million cycles via Archard's wear law formula. The amount of volumetric wear was estimated to be 17.5 mm3. The wear rate of the polymer used in the central core was experimentally investigated. The amount of wear was determined based on the results of the experimental test performed on a homogeneous polymer tablet with the central core of the implant. Finally, the wear rate of the polymer was found to be 0.005 gr during the wear test.

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