NJESR/ June-2023/Volume-5/Issue-6 E-ISSN-2582-5836
DOI-10.53571/NJESR.2023.5.6.17-31

Applications In Biomechanics And Rehabilitation That Make Use Of Fiber Bragg Grating Sensors: A Review Study

Sushama.K.K
Lecturer
Department Civil Engineering
Government Polytechnic College
Maharajas Technological Institute
Thrissur

(Received:5May2023/Revised:25May2023/Accepted:3June2023/Published:11June2023)

Abstract

Due to their advantageous properties of small size, light weight, biocompatibility, chemical inertness, multiplexing capability, and immunity to electromagnetic interference (EMI), fiber Bragg gratings (FBGs) have become increasingly appealing for sensing applications in biomechanics and rehabilitation engineering in recent years. Additionally, they provide a high-performance alternative to conventional technologies for high-sensitivity biochemical analysis or the measurement of a variety of physical parameters. Aeronautical, automotive, civil engineering structure monitoring, and undersea oil exploration are just a few of the specific sensing applications for which FBG-based sensors have demonstrated their viability; However, their application in biomechanics and rehabilitation applications is relatively new, and its viability for widespread implementation is still unclear. They could be utilized for identifying strain in bones, pressure planning in muscular joints, stresses in intervertebral circles, chest wall disfigurement, pressure appropriation in Human Machine Connection points (HMIs), powers prompted by ligaments and tendons, points between body sections during stride, and numerous others in dental biomechanics. The purpose of this article is to provide a comprehensive overview of all of the potential applications of FBG sensing technology in biomechanics and rehabilitation, as well as the state of current global research, highlighting the FBG's advantages over other technologies.

Keywords: fiber Bragg grating, Bragg sensors, Biomechanics, Rehabilitation

Introduction

Due to their prominent advantages, such as their small size, biocompatibility, chemical inertness, immunity to electromagnetic interference (EMI), and multiplexing capability, fiber

Bragg gratings (FBGs) have demonstrated a great potential for applications in the fields of biomechanics and rehabilitation engineering over the past ten years [1,2]. Because of their adaptability to the sensor material, FBGs are suitable for human body applications and can be used for in vivo and long-term monitoring [3]. They additionally offer elite execution elective, in contrast with standard advances like electrical strain check (ESG), piezoelectric, resistive or other strong state detecting, either for estimating actual boundaries or for performing high-responsiveness biochemical examination [4].

FBGs are currently used extensively for a variety of specific applications, including undersea oil exploration, the automotive industry, structure monitoring in civil engineering, and aeronautics [5–7]; in order to measure a number of parameters, including strain [8, force], force [9], pressure [1], displacement [1], temperature [2], humidity [3], and radiation dose [4]. On the other hand, the majority of studies aimed at combining optical FBG sensing technology with biomechanics and rehabilitation applications are relatively new [3] and have not yet been made available for commercial use. They have been shown to be useful for measuring a wide range of parameters; including forces induced by tendons and ligaments, angles between body segments during gait, strain inside and on the surface of intact and plated bones, shrinkage stresses in bone cement during polymerization, pressure mapping in orthopaedic joints, stresses in intervertebral discs, deformation in the chest wall for the purpose of studying lung biomechanics, pressure distribution in Human Machine Interfaces (HMIs), and many other aspects of dental biomechanics.

The general applications of FBG sensing technology in biomechanics have only been partially discussed in two articles to our knowledge [3,5]. However, these two articles did not fully cover all of the previously reported as well as the very recent and emerging applications of FBGs in the fields of biomechanics and rehabilitation engineering. This article expects to give a far reaching outline of the uses of FBG innovation in biomechanics and recovery as far as the exceptionally late advancement and the situation with progressing explores cutting-edge all around the globe. In addition, a comparison of FBGs and other conventional technologies is made to demonstrate that FBG technology is more adaptable to the majority of applications in this field.

FBG Working Principles

A short section of a single mode optical fiber with a cladding diameter of 125 m is used for the FBG, which involves a spatially periodic modulation of the refractive index along a specific region of the core [8]. In the event that light from a broadband source is coupled into an optical fiber containing the FBG, a limited range is back-reflected and based on the purported Bragg frequency λB (Figure 1(a)) which relies upon the occasional variety Λ of the FBG and the compelling refractive file neff :

$\lambda_B = 2n_{\text{eff}}\Lambda$

The back-reflected peak wavelength of the FBG sensor will shift in accordance with the degree to which the external mechanical or thermal perturbations influence the FBG sensor, which is spectrally very sensitive when subjected to axial strain [7]. Through compression and expansion changes in the spacing of the periodic variation and the strain-optic effect, which causes an alteration in the optical fiber's effective index, neff [2], the axial strain directly affects the FBG response. B changes as a result of the refractive index and grating period being affected by the temperature increase T [2]. The impact of strain and encompassing temperature on the grinding period and the refractive file can be communicated as follows:

$$\Delta\lambda_B = 2\left[\Lambda\frac{\partial n}{\partial l} + n\frac{\partial \Lambda}{\partial l}\right]\Delta l + 2\left[\Lambda\frac{\partial n}{\partial T} + n\frac{\partial \Lambda}{\partial T}\right]\Delta T$$

where ΔT is the change in temperature andΔ l is the strain-induced change in FBG length. When conducting experiments inside of laboratories, optical spectrum analyzers (OSAs) are frequently used to determine the Bragg wavelength λB. When conducting experiments outside of laboratories, other specialized interrogators are utilized. The FBG sensors would be more suitable for monitoring strains in locations subjected to dynamic loads with high-speed interrogation systems [5].

Applications

Bone

Understanding bone diseases and designing medical devices require an understanding of the biomechanical behavior of the musculoskeletal system [6]. The skeleton regularly adjusts to mechanical stacking, hence comprehension of how bone distortion under load happens is of interest. The measurement of bone deformation under load has been attempted using a variety of approaches. The strain measure (SG) was the highest quality level whose electrical opposition fluctuates relatively to how much strain. Using bone staples made of electrical SGs, an Israeli research team measured strain in human bone during running, stationary bicycle riding, leg presses, and stepping in six subjects in vivo [6]. As of late, a few scientists have concentrated on the capability of FBG sensors for in vivo applications as an estimation device for bone strain, reasoning that FBGs enjoy shown cutthroat upper hands over the traditionally utilized SGs. While the SG itself is a foreign body implant, FBGs are entirely made of biocompatible SiO2 glass ceramics [5], which pose a lower risk of infection. They can likewise be utilized where the utilization of regular SGs is actually irrelevant [4]. For instance, the electrical resistance of an SG changes in proportion to the applied strain when it is loaded; Consequently, it cannot be utilized in an electromagnetic setting. In addition, there are additional distinct advantages of FBGs over SGs: they can undoubtedly stick to bone and other unpredictable surfaces [6].

Talaia et al. [8] have used FBGs and SGs to measure bone strains in plated and intact synthetic femurs to investigate the effects of fracture fixation plates. For the unblemished femur, 20 pivotal SGs were put on the front, back, average and horizontal sides at various degrees of cortex femur. A 10-hole stainless steel bone plate was used to fix a simulated 45° fracture on the other femur sample (Figure 2(a)). Seven FBGs were stuck at various areas along the bone plate (Figure 2(b)) and 13 SGs were fixed to the cortex femur (Figure 2(c)). Both the plated and unplated synthetic femurs were subjected to a static load of 600 N, and bone strains were recorded at the same locations on the bone plate and the femur cortex. For the various loads, the sensors have demonstrated excellent linearity. FBGs, on the other hand, made it much simpler to measure strain on bone plates than conventional SGs did, and they made it easier to track how strain changed in bone. FBGs are able to assess the stiffness of fractured bone callus formation from a biological perspective.

Fresvig and others 6] have assessed the utilization of FBG sensors to recognize deformity in human corpse femur bone under in vitro stacking conditions, with expected in vivo application. In this study, a human femoral bone sample of the same length and an acryl tube were used. Four polyamide-coated FBG sensors and four SGs were positioned around the circumference at the center of each sample and were interspersed at every 45°. The two examples were stacked utilizing a Mechanical Testing Machine and the initiated strains were recorded in like manner. The FBG approach showed its reasonableness for dynamic in vitro estimations. In general, there were no significant differences between the FBG and SG sensors, indicating that the FBG sensors could be used effectively for in vivo measurements.

FBG sensors can likewise be utilized to comprehend how much the bone calcium misfortune influences strain reaction of bone [3]. Two goat tibia samples were used: One gradually decalcified, while the other did not undergo any treatment for the purpose of a comparison study. At the midpoint of both samples, there was a direct connection between two FBG sensors. The two samples were then put through a three-point bending test with loads ranging from 0.1 kg to 4 kg, as shown in Figure 3(a). In order to comprehend the effect of decalcification and degeneration over time, the strain values were derived from the simultaneous FBG wavelength shifts recorded for both samples. During the experiment, the strain that was produced for the untreated sample remained largely unchanged, whereas for the decalcified sample; strain values for same burdens expanded and turned out to be a lot higher with more calcium misfortune (Figure 3(b)). By utilizing FBG method, the strain reaction gives an immediate sign of the level of calcium present in bone.

FBG sensors could be a novel method for assessing bone biomechanics in vivo, according to the aforementioned studies. Recent studies by Carvalho et al. 3] explored the detecting ability of FBGs when put in direct contact with human osteoblast cells refined around the FBG fiber and evaluated the response of these cells to optical filaments. Osteoblasts were found to have excellent adhesion and growth capabilities over both the protective polymer coating and the fiber. In addition, the FBG's capacity for sensing did not change during the culture period. Consequently, these fantastic cytocompatibility and detecting capacity of optical FBG strands propose the chance of its osseointegration expecting various in vivo applications in bone mechanical elements.

Even though bone tissues are very good at adapting to optical fibers, which makes it possible to use FBG sensors in vivo, there are still some problems that prevent them from being used in this field on a large scale. The need of fiber connect between the FBG detecting region nearby tolerant and the estimating unit is the most widely recognized issue [5]. In emergency clinics or versatile consideration units where this disadvantage is limited, convenient cross examiners could be utilized, yet for nonstop observing of patients everyday exercises, which is a significant prerequisite for muscular medicines and biomechanical studies, these gadgets can be unwieldy for patients [6]. The evolutionary path toward effective in vivo applications of FBG sensors in the human body is now open thanks to today's technology, which makes it possible to produce very small wearable interrogators in the not-too-distant future without any external fiber links.

A recent study by Reikeras et al. [] examined the impact of total joint replacements on bone strains. 3] used SGs and FBGs to compare the internal and external cortical strains in the proximal femur following the implantation of a cemented and uncemented hip stem prosthesis. One cadaveric femur was extracted from a 64-year-old male patient who had died of a heart attack within 24 hours. As depicted in Figure 4, four optical fibers were sealed at the internal femoral cortex proximally and four SGs were attached to the external femoral cortex both proximally and distally. At the point when hub load was applied onto the prosthesis, the resist the proximal level were all the while recorded at the inside cortex (by FBGs) and at the outer cortex (by SGs) and were then contrasted all together with assess the distinction in strain designs at the inward and outside cortices. It had been hypothesized in the past that strain on the internal cortex reflects strain on the external cortex. Notwithstanding, this study showed that the strain design on outside cortex was fundamentally not the same as that got at the interior cortex. To put it another way, the situation on the external cortex is not the same as the situation on the internal cortex, so it is impossible to subtract the strain measured on the internal cortex from the strain measured on the external cortex. The ingrowth of bone and soundness of the prosthesis rely upon the inside cortical surface, thusly, future examinations ought to focus on this reality.

The strain conduct at the foremost femoral indenting district during all out knee substitution and its ramifications on the cortex of the distal femur was concentrated by Completo et al. [4]. In addition, they questioned whether the use of femoral stem in an anterior femoral notching to reduce the risk of fracture was effective. It had been conjectured that femoral scoring debilitates the cortex of femur which can make it helpless to crack in the early postoperative period [5]. Twelve synthetic femurs were chosen for this study and subjected to two load scenarios during the experiments. In order to experimentally predict the strain levels at the notch edge using FBGs and at the notch region using SGs, femoral components with and without femoral stems were implanted in femurs with varying notch sizes (Figure 5). The main finding of this study is that the strain conduct was unique for the different indent profundities. For indent profundities lower than 5 mm, the utilization of stem decreases the strain level at the score edge to values beneath the unblemished femur condition, while for profundities more noteworthy or equivalent to 5 mm, the strain levels at the indent edge were higher than the flawless femur condition (going from +10 to +189%). This recommends the utilization of a prophylactic stem for indent profundities more noteworthy than 5 mm, adding to decreasing the crack gamble.

Bone Cement

One of the primary causes of total hip replacement failure is damage to the bone cement caused by long-term dynamic loading, which results in the prosthesis loosening [6]. To confirm the cement's action, both during the curing process and after consolidation, in vitro studies employing human and animal bone models could be useful. Stolk et al. used embedded rosette gauges to measure the strain of bone cement in femoral prostheses [37]. Nonetheless, the FBGs enjoy shown their benefits in examinations relating to these issues. Ramos and others 8] evaluated the precise pressure and strains extents inside concrete mantles utilizing FBG sensors which could be valuable to foresee the mechanical disappointment. A femoral prosthesis that had already been designed was joined by 12 FBG sensors; four at the proximal, distal, and a big part of the stem, and were decisively joined in the foremost, back, average and parallel viewpoints. The FBG-instrumented prosthesis was inserted into the femur canal at a distance of one millimeter from the cement-implant interface, just like the FBGs. Compared to measuring cement strains using SGs, this method requires less time and is simpler to implement.

PMMA's functional durability can be predicted with the aid of FBGs. Frias and co. 8] tried the capacity of FBGs to quantify strains inside bone concrete during various mechanical tests at ongoing. Bone concrete was tried at various temperatures and burden conditions concurring with those normal inside the human body. Short-term quasi-static tests were used to examine the mechanical behavior of various PMMA bone cement samples in order to predict the material's durability. FBG sensors were utilized in a variety of test procedures to measure the tensile and compression strains on PMMA bone cement. In separate tests, the embedded FBG was subjected to some of the same physical parameters as bone cement in an artificial joint. Using an OSA, the optical reflected spectrum was recorded at the conclusion of each test. All the strain estimations inside bone concrete detailed a straight reaction that shows a decent transformation and streamlining of the heap move between the PMMA concrete and the implanted FBG sensor.

Tendons and Ligaments

Measurements of ligament and tendon biomechanics in living humans are crucial for gaining a deeper comprehension of function and injury as well as for maximizing treatment [2]. The biomechanical properties of tendons and ligaments have been studied with FBG sensors, and the results have been encouraging. Vilimek proposed using a tensile machine (MTS Minibionix) in a vertical orientation to examine the in vitro biomechanical properties of porcine tendons using FBG sensors [3]. By grouting a point into the tendon whose ends were attached to the actuator using the freeze clamping method, the FBG sensor was included crosswise. Using the MTS, the sensor was loaded and unloaded multiple times in steps, and the measurement continued until the tendon was destroyed. It is possible to estimate the loading force because the measured forces by MTS and the measured signals from the FBG sensor produced the same proportional changes in all of the trials. The FBG sensors were more delicate and precise than other fiber-optic techniques in view of decrement of light properties during squeezing change of cross area size. Due to the minor injury that results from its application, this method is suitable for measuring musculotendon forces in humans in vivo for the purpose of validating muscle force computational models.

Ren and co. proposed a displacement sensor based on FBG to monitor strains in tendons and ligaments as they develop in different postures and while moving [4] and compared the results to those obtained with conventional camera displacement sensors. The FBG was encased in a micro-shape memory alloy tube before being attached to a human cadaver's Achilles tendon surface and mounted to a material testing apparatus for a loading test. The performance of the FBG sensors and conventional camera displacement sensors was compared following sensor calibration in the laboratory. Extra examinations were acted in cadaveric knees to evaluate the plausibility of the FBG sensors to quantify tendon disfigurement in various recreated stances. When compared to the more conventional methods of measuring tendon and ligament displacement, the findings indicate that the proposed FBG sensor is a highly accurate, simple to implant, and minimally invasive option.

Human Body kinematics

The checking of various human body kinematics and the examination of stance and motion are essential in bioengineering and restoration. It aims to improve athletic performance in competitions and to regularly evaluate patients receiving therapeutic treatments to determine the effectiveness of the treatment. For the purpose of monitoring the kinematics of the human body, a number of different systems have been proposed [5], but all of them are unable to withstand particular environments, including high temperature, electromagnetic noise, chemical solutions, and others [8].

A Portuguese research team has recently proposed a smart skin polymeric foil that can be used to measure body kinematics and is based on FBG sensors []. Rocha et al. [7] have approved this wearable framework by observing greatest knee flexion and expansion and every one of the in the middle between during a full time of human walk. A single FBG was embedded in a rectangular structure made up of three layers of flexible and stretchable PVC materials at the center of the knee joint. Small metallic pressure buttons make it simple to attach or remove this sensing structure from an elastic knee band. This ensures that the FBG can only detect flexion and extension as the subject moves around. The subject went through various kinds of running and strolling on a monetarily accessible treadmill to evaluate the dependability and consistency of this framework and the developments of knee joints were being estimated as an element of the FBG frequency, and, simultaneously, with video recording for examination purposes. As depicted in Figures (a,b), the findings demonstrate that the stage at which the maximum flexion/extension in the knee joint, as well as on the FBG, corresponds to the maximum and minimum wavelength values. This detecting structure shows a decent aversion to precisely quantify the knee flexion/expansion during the strolling and running tests and can be utilized for any joint in human body. Numerous biomechanics and other fields can now benefit from this FBG-based PVC foil.

Rehabilitation engineering is interested in monitoring stroke patients' hand gestures and posture in order to evaluate their hand's capacity for correct action during therapy sessions. Several wearable glove systems have been proposed using various approaches [148–152], but there are some concerns [3]. Silva et al. have planned a wearable detecting glove in light of FBGs to empower the estimation of points between the finger phalanxes and to defeat the restrictions introduced by other recently revealed strategies [5]. Fourteen FBGs obliged in a solitary optical fiber were decisively positioned in a curvilinear design and implanted in the center layer of an adaptable PVC foil cut into the hand shape so each FBG would be situated over every one of the 14 phalanx joints present in a solitary hand. After that, this individualized sensing foil in the shape of a hand was sewn to the upper face of a standard fabric glove (Figure(a)) to make sure that each FBG was placed where it was supposed to be during the experiments. The FBG's performance and functionality were evaluated using hand flexion and extension tests. Figure (b), left), shows a sinusoidal response from the sensor, with positive and negative limits representing the opening and closing of the hand, respectively. The strength of the applied load of 7.8 N that caused the 1 nm wavelength shift that led to the retrieval of information about joint angles can be estimated. The system accuracy was represented by a linear fit with an R-square of 0.99929 and a slope of 0.99869 when the real and measured angles were compared (Figure (b), right). A hand motion capture system based on a 3-D virtual model of the hand was built in the second part of this study (Figure(a)). This system allows for the real-time visualization of hand movement on a PC and can be used to provide information about hand angles, strength, and movement range. This wearable framework could have an extraordinary potential in exercise based recuperation applications, specifically for hand-debilitated individuals, and while concentrating on human kinematics, among others.

Conclusions

The literature clearly demonstrates that FBGs can be successfully used in a wide range of biomechanics and rehabilitation engineering applications. This is because, in comparison to other conventional systems, FBGs have a number of distinct advantages, including their small size, chemical inertness, light weight, biocompatibility, and multiplexing capability. In the field of biomechanics and rehabilitation, FBGs have demonstrated their viability and superiority to existing technologies, but they have not yet been commercialized. Due to the rapid advancements in this field and the necessity of successfully implementing FBG sensors, a collaborative effort involving medical professionals, fiber-optics specialists, and programming engineers is required to establish the practicality of this technology. Additionally, FBG sensors must be user-friendly, cost-effective, and simple to use products to meet the needs of both medical professionals and end users. As of late, versatile cross examination frameworks with high velocity information procurement (up to 5,000 Hz) were made accessible, prompting expanded research regions and tracking down new specialty applications. This article provides an in-depth analysis of all of the potential applications of FBG sensors as well as current worldwide biomechanics and rehabilitation engineering research. It also demonstrates the FBGs' superior advantages over the other technologies currently in use. In biomechanics and rehabilitation engineering, it is anticipated that FBG sensors will play a significant role in the future and provide efficient solutions for a wide range of applications.

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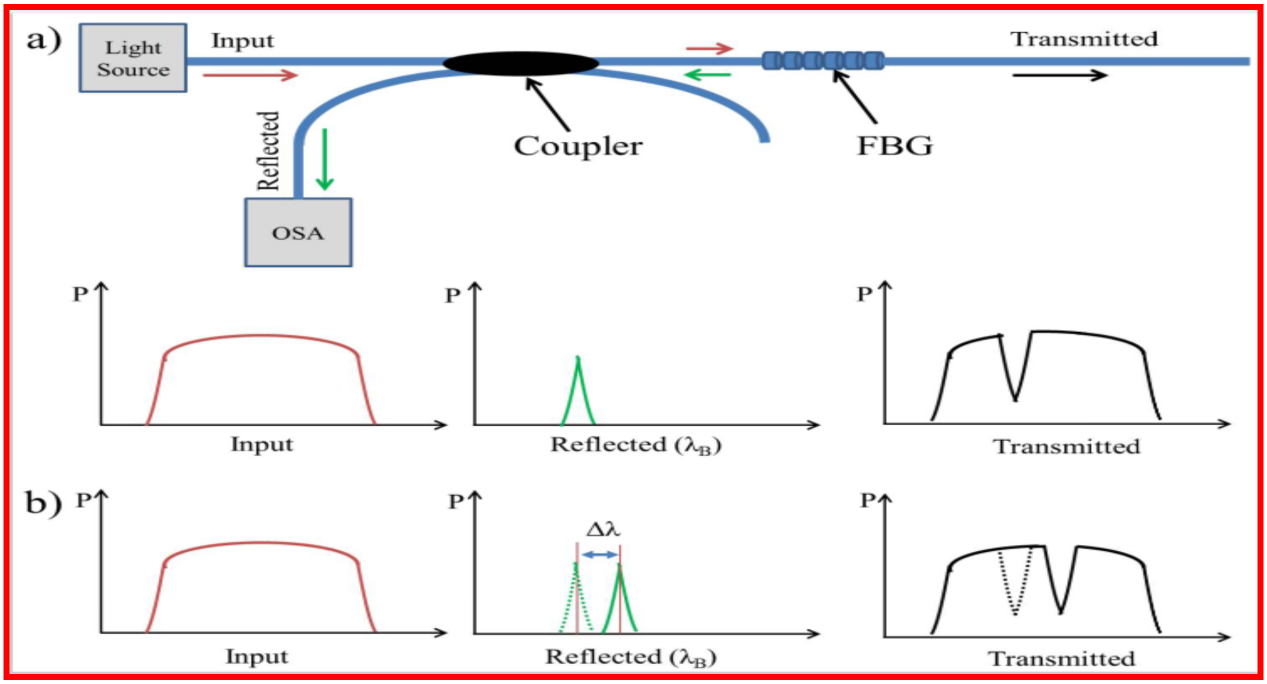

Figure 1: (a) The light source (Brown color) is transmitted through the FBG and a narrow band (Green color) is back-reflected, centred around λB, and monitored by OSA. (b) The back-reflected band is shifted (Δλ) shortly after applying external perturbations.

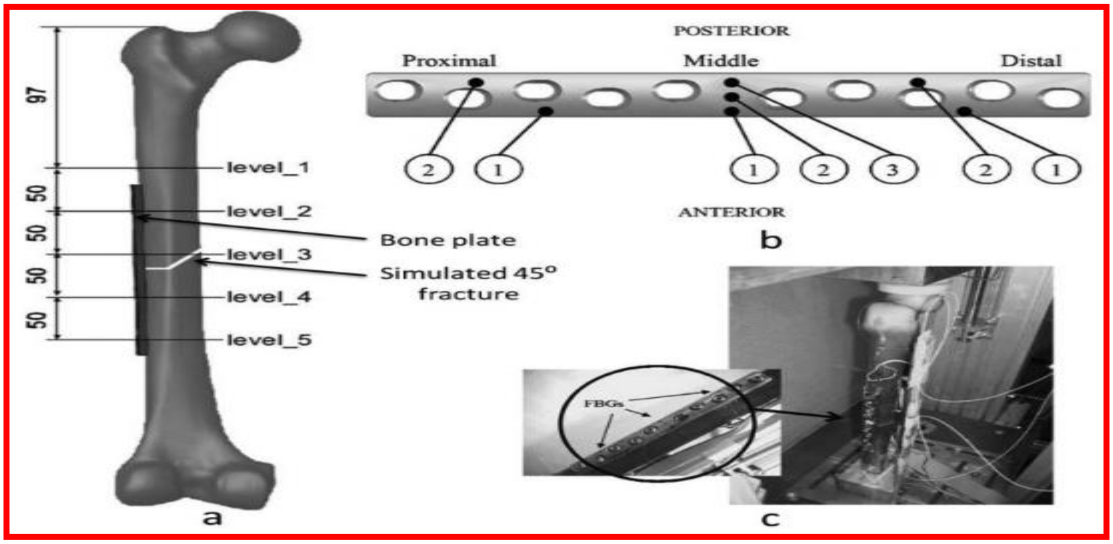

Figure 2: (a) The simulated 45° fracture and the locations of the SGs on the intact and plated synthetic Femurs. (b) The locations of the FBGs on the bone plate. (c) Representation of the experimental apparatus used and detail of bone plate with FBGs [3].

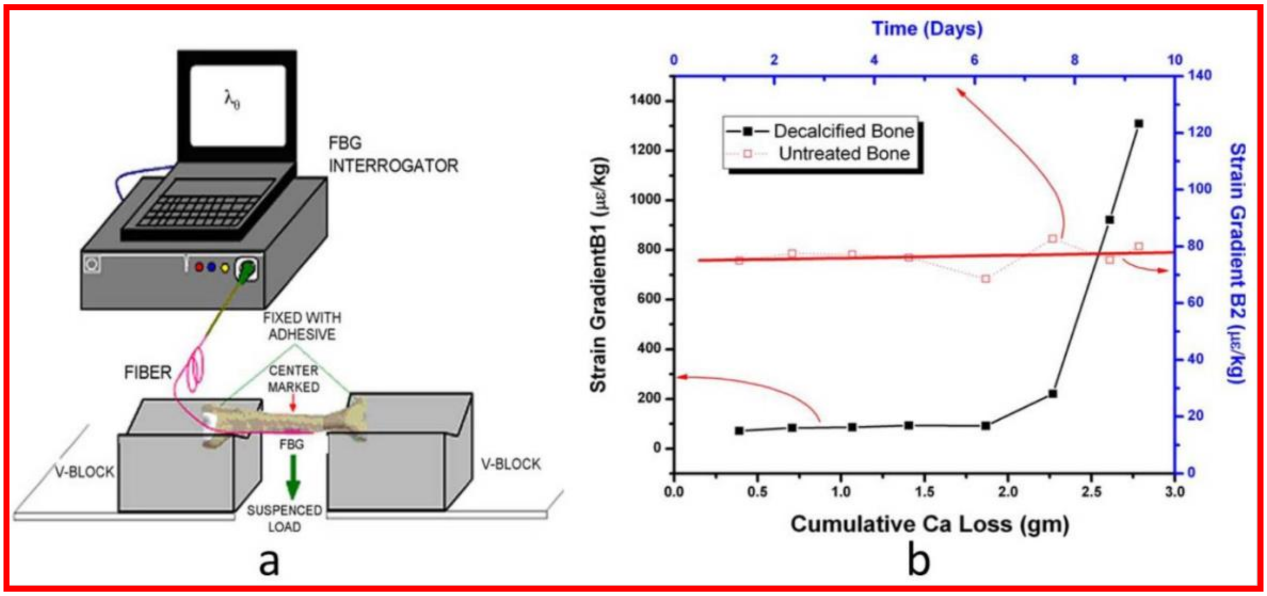

Figure 3: (a) The schematic of experimental set-up. (b) The comparison between strain response of decalcified and untreated bones [3].

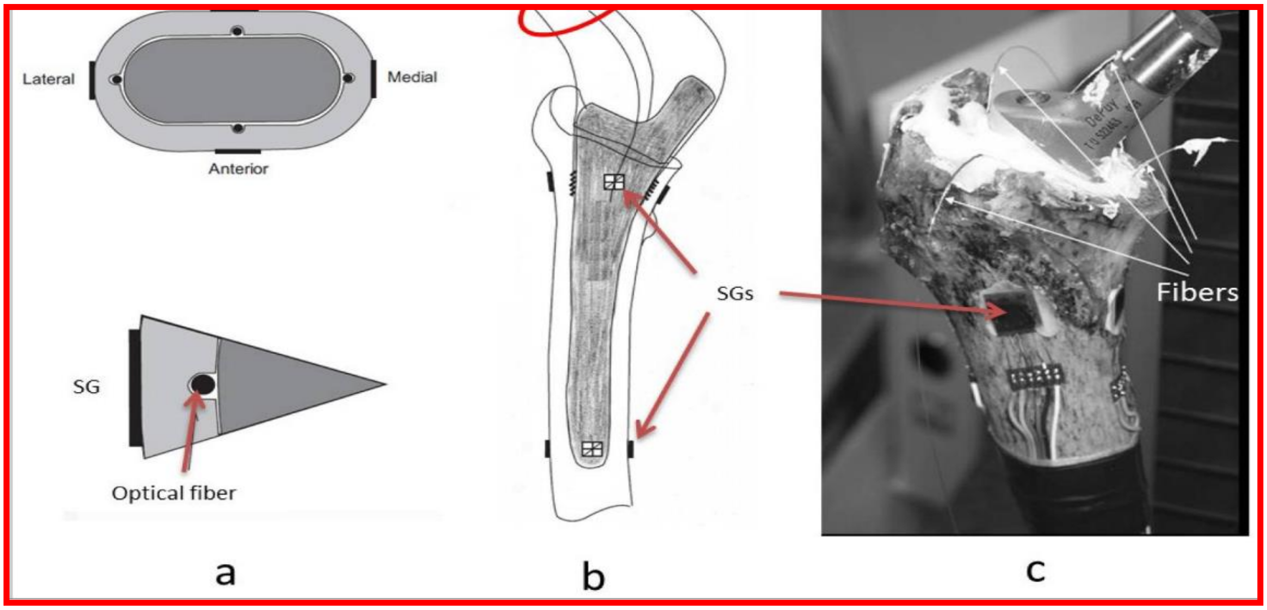

Figure 4: Schematic of the experimental set-up. (a) A cross-section of the implanted femur, showing the locations of FBGs and SGs. (b) Schematic drawing of the femur with cemented prosthesis, showing the internal (optical fibers) and external (SGs) positions of sensors at the proximal and distal levels. (c) Image of the experimental set-up of an implanted cadaveric femur [3].

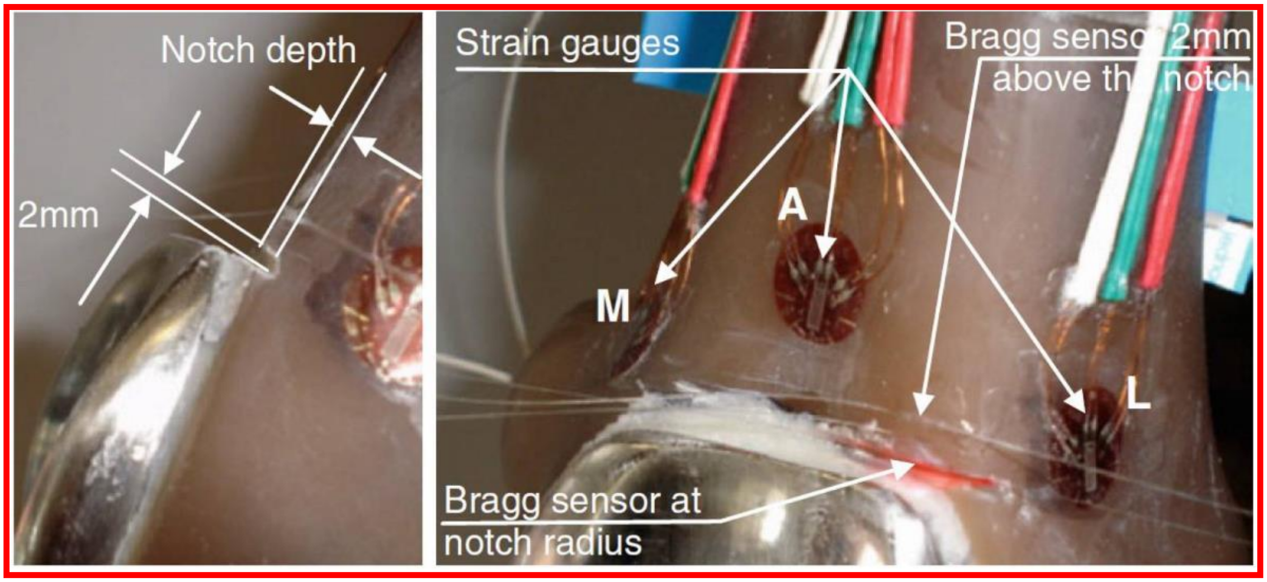

Figure 5: Images depicting the composite femur models with notch. (left) The notch dimensions, and (right) the positions of SGs (A anterior, M medial, L lateral) and FBGs [4].

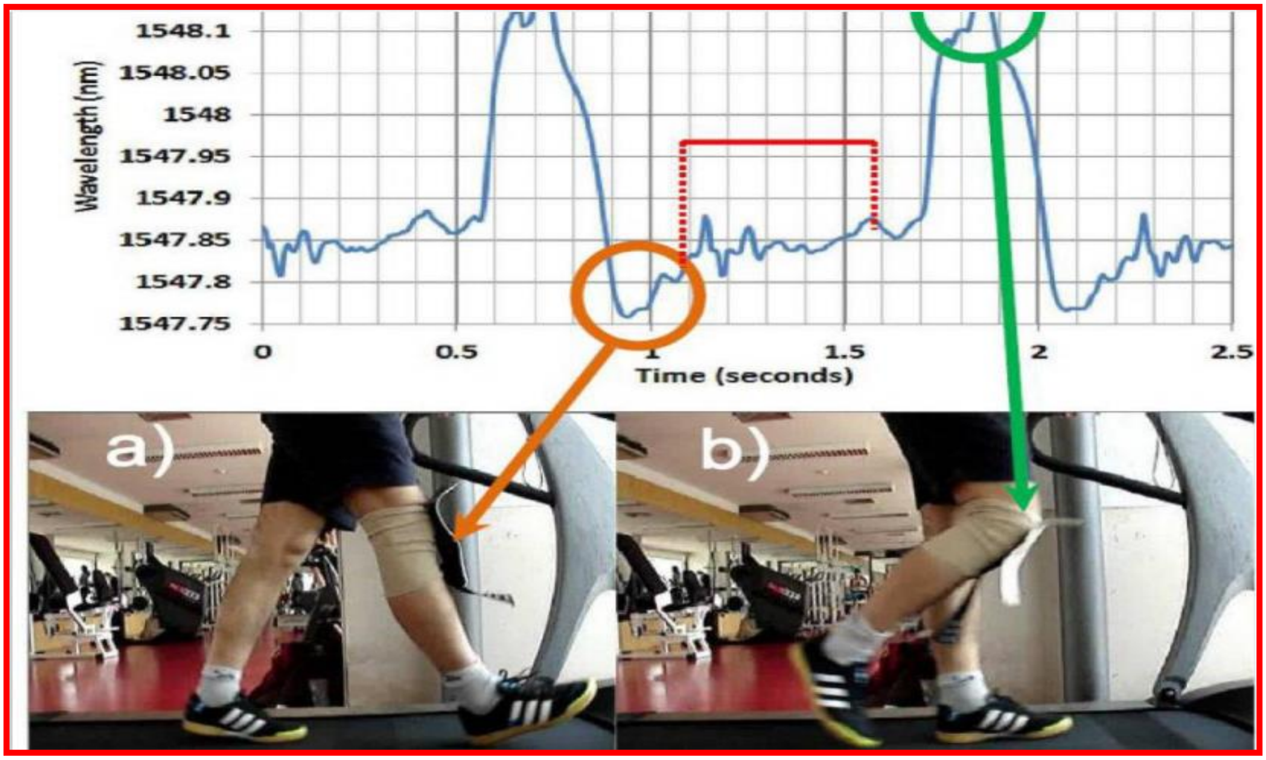

Figure 6 :The wavelength values for a walking at 4 km/h. (a) and (b) show the minimum and maximum deflections of the FBG, respectively [7].