Smart Lower Limb Prostheses with a Fiber Optic Sensing Sole: A Multicomponent Design Approach

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A review on a multicomponent design is presented for the development of a lower limb smart prosthetic system based on fiber optic sensing. The key component of this system is the smart sole consisting of a group of fiber optic sensors called the fiber Bragg grating (FBG). Such a group of sensors allow the human sense of touch to be mimicked through strategic sensor placement while identifying minute changes in contact conditions. Gait control through plantar pressure measurements is an important feature of lower limb prosthetics and allows for the identification of terrain through ground reaction forces (GRFs). Current smart lower limb prosthetics consist of a powered ankle equipped with torque sensors and a motorized assembly to enable proper gait control. Adding a smart sensing sole, which incorporates the sense of touch in addition to GRF identification, will enable patients with neurological disorders or amputation to relive the experience of a normal human being. Prosthetic technologies that will assist in developing a smart lower limb prosthetic system with a multicomponent design are presented on the basis of review, and a complete integrated system that will include sensing, processing, and control is suggested. The control can come through two approaches: (a) a trained system based on artificial intelligence or (b) a direct intervention of the subject. The intervention in the latter approach is based on sensing the signals from the smart foot and receiving them in the brain through a brain–machine interface (BMI).

1. Introduction

Prostheses have been used for a long time as they can be found in ancient artifacts,[1] where the prostheses tried to not only replicate the human functionality but also regain the aesthetic appearance of the lost body part. Prosthetic replacement for the loss of an eye, an ear, a nose or a limb causes an emotional/psychological imbalance in patients and requires emotional recovery and corrective procedures through immense training. Human locomotion is affected when any portion of the lower limb is affected either by spinal cord injury (SCI) or a loss of a limb. The human gait is affected the most and produces discomfort in performing different tasks such as walking and running. SCI patients with their limbs intact lose sensory features, which limit

their response to external stimuli. A large number of patients who undergo amputation in the lower extremities are those with vascular diseases such as diabetes.[2] The lower extremity loss could mean the loss of a foot or the entire leg. The annual number of amputees in the lower extremities in the US alone is around 185000 as determined by the Amputee Coalition of the USA. In the Middle East and North Africa (MENA) region, Saudi Arabia has the highest rate of lower limb amputation owing to diabetes.[3] To improve the quality of life of the amputees and alleviate the psychological trauma that the patients suffer, lifelike prosthetic attachment to the body plays an important role.

The development of lower limb prosthetics includes developing a functional prosthesis with limited capabilities[4] or with advanced features such as gait control and allowing patients to walk on various terrains with minimum difficulty.[5] Current research includes a vast range of foot prostheses[6,7] where different sensors and electromechanical devices are installed to replicate a more biological aspect of the human foot. Handicap International reports that the cost of a high-end prosthesis can be up to USD 5000. Extensive research with off-the-shelf technologies and interest in affordable manufacturing can pave ways for the development of an economical smart prosthesis. This could enhance the patient's experience of using the prosthetic part as a normal part of their body. For this purpose, researchers adopt different routes. First, to increase the locomotive functionality, different structural components combined with electrical circuitries are developed.[8] Batteries that produce charge to drive motors, sensors, and controllers have restricted working durations to power most of these devices. The sensing is provided by different sensors such as strain gages, encoders, and accelerometers, which guide the controller to drive the motors to take actions based on a programmed gait performance of a healthy human.

Today's high-end prosthetics are equipped with sophisticated electromechanical devices that are controlled by an on-board chip.[9] The powering mechanism consists of a rechargeable battery supplying necessary operating currents and voltages to the electromechanical circuitry and a control box. The physical contact with the ground is made with a foot pedal,[10] which is a hard surface, sometimes enhanced in structural features to carry the patient's load and provide a variety of locomotive functions. An electromechanical and powered foot ankle prosthesis is shown in Fig. 1. In such a prosthetic device, the gait stability is provided by sensors attached to different moveable portions of the prosthetic foot/leg (for instance, ankle and knee joints). They give feedback to a controller to make corrective actions against a preprogrammed healthy human gait style. The controller design is based on valuable parameters collected from sensors and can be implemented with different control system approaches such as that shown in Fig. 2. The controller then needs to adjust the prosthesis function according to the patient's weight and physical stature. To enhance the comfort of the patient, machine learning algorithms train the prosthetic controller according to the comfort of the patient while maintaining an optimum human gait cycle.

A demand by patients is not only to regain functionality but also the associated sensory response from that part. In this regard, substantial research would enable us to deal with such problems using modern medicinal and technological practices. Robotic devices that mimic human locomotion can also benefit from lower limb prosthetic research.
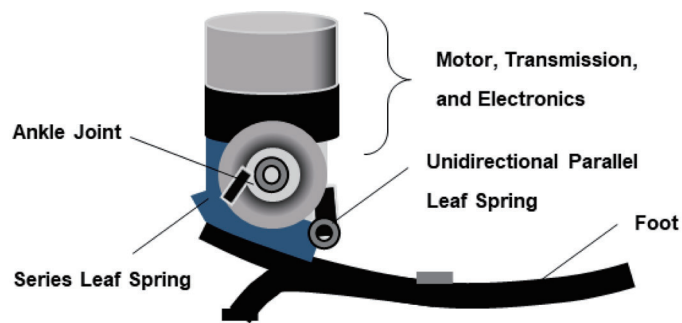
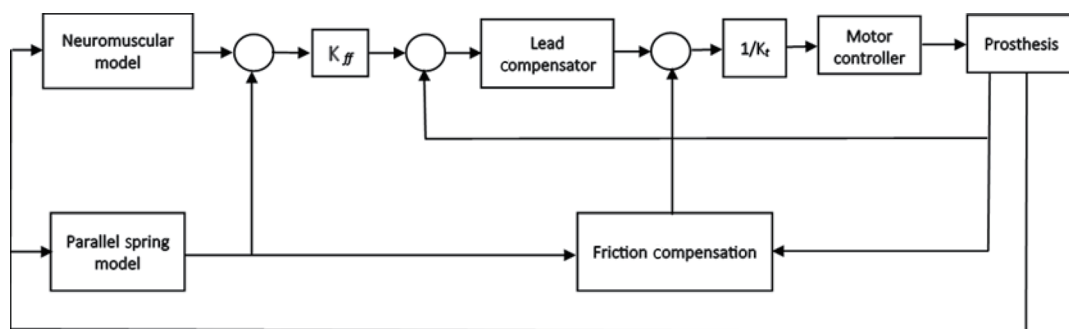Fig. 1.   (Color online) Powered ankle foot prosthesis.

Fig. 2.   Control system block diagram for foot prosthesis.

A foot prosthesis can be made smart through sensors installed in critical positions in the sole and an adaptive algorithm, which trains the system to support the efficient locomotion of the patient. A smart sole can also be used with non-amputee patients, such as those with neuromuscular disorders. Identifying these disorders with a dynamic contact information platform means freedom to investigate in a nonconfined setup. A desirable feature would be to have the signals from the smart sole be transmitted wirelessly through a Wi-Fi connection and a mobile application that could monitor the patient's activity in real time. We would like to see such benefits when the smart sole technology has matured to the extent that more user-friendly features are incorporated such as caution from stepping onto a hazardous surface. High-data-rate channels would enhance the real-time information collection, but the issues with power supply to such hardware would also mean increasing the battery capacity and thus increasing the prosthetic weight. This type of work would also demand miniature batteries with more storage or alternative means of generating power, for instance, kinetic energy stored through locomotive actions.

With the successful development of this technology, we could address issues in the fields of human rehabilitation, biomedical engineering, health, smart system development, and robotics.

We suggest a smart sole equipped with fiber optic sensors that give maximum coverage on the foot sole for response to different stimuli such as force, pressure, and temperature, and also to map the complete contact information of the sole with the ground. The smart sole will not only give feedback for gait control but also enhance the sensing feature for the patient

to differentiate between soft and hard or hot and cold. The existing smart prosthesis can be equipped with this additional feature giving them an advantage of "sense of touch". The smart sole will also be useful for patients with neuromuscular disorders. Physical therapy patients undergo monitoring through motion trackers or contact measurement platforms. Using a standalone wearable smart sole could give freedom from static investigative hardware and can be tested on different terrains (uphill or downhill) without modifying the investigating scenario.

This review article is divided into the following sections. In Sect. 2, we provide the biomechanics perspective on human gait that highlights the essential requirements of the lower limb prosthetic design. In Sect. 3, we discuss the individual components that build up the smart lower limb prosthetics and the technologies involved in their development. In Sect. 4, we present a conclusion on the review and provide readers with suggestions to venture into the development aspect of the prosthetic technology. The next section provides a biomechanics perspective on human gait.

2.   Human Gait, a Biomechanics Perspective

A typical human gait cycle is shown in Fig. 3. A proper gait cycle ensures the possibility of executing different forms of human locomotion, such as running, jumping, and climbing in an effective and efficient manner. The human gait cycle initiates with the heel strike and ends when the same foot returns for the second contact.[11] A gait cycle is normally divided into two periods: (a) stance and (b) swing. The stance contributes to 60% of the gait cycle where the striking foot remains in contact with the ground. To propose a multicomponent design for smart lower limb prosthetics, we first need to study the human gait and the biomechanics involved. It would also be interesting to study the working of different elements in human physiology, which contribute towards a normal gait pattern and how to replicate them through synthetic resources.
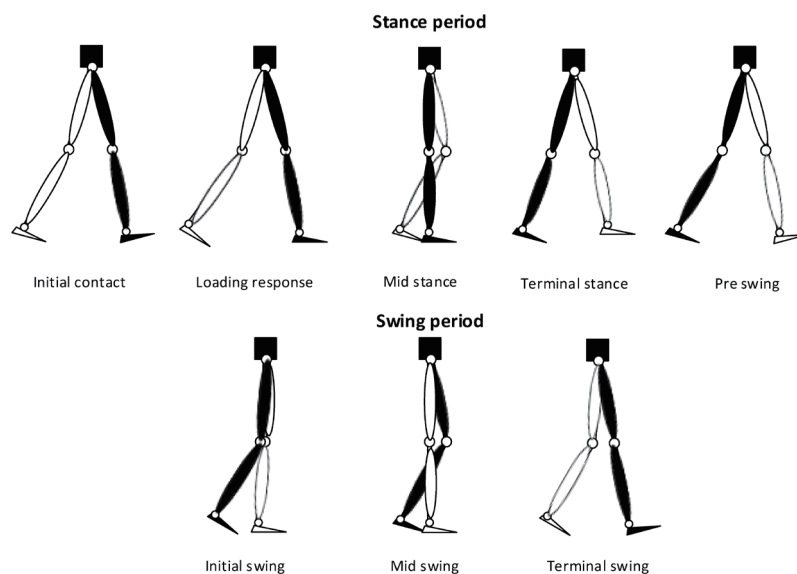

Fig. 3.   Typical human gait cycle.

Currently, technologies are limited to develop a fully functional substitute of a natural human limb, but efforts are underway to bring the functional and aesthetical aspects as close to the natural one.

The primary information on the foot contact comes through the plantar nerves in the human foot sole. These nerves send a signal to the brain for the adjustment of the human gait. An early detection of an abnormal gait helps clinicians and medical professionals take corrective procedures for the well-being of the patients. These procedures can be introduced in physiotherapy, medical treatment, or surgical adjustments. The foot sole is divided into different regions as shown in Fig. 4. This type of division helps clinicians investigate the cause of an improper gait through the study of different test subjects with various anomalies. Therefore, it is imperative that a reliable plantar pressure measurement system be utilized. In the case of a smart foot prosthesis, we would like to have a smart sole that would be installed on the prosthetic foot in such a way that it accurately captures the real-time contact information through plantar pressure measurements.

Normally, to capture the gait and different musculoskeletal movements, different setups such as force plates and imaging systems to capture the three-dimensional movement of the targeted regions are incorporated.[12,13] A more in-depth investigation for different wearable and nonwearable sensors for gait analysis is presented in Ref. 14. The use of force plate measurement systems has been the traditional approach to investigating the foot plantar pressure distribution where a static platform is used to map all active foot sole pressure points. For a mobile pressure measurement through in-sole sensors (wearable sensors), we would like to have certain attributes of the sensors such as miniaturization, lightweightness, and minimum connection requirements where the sensor density is large.

Since the importance of human muscle mechanics and the role of plantar pressure measurements in human gait analysis have been established, we will now introduce a component-component design strategy for our smart foot prosthesis. The essential element of this system is the smart sole that is envisaged to demonstrate close to human sensing capabilities.
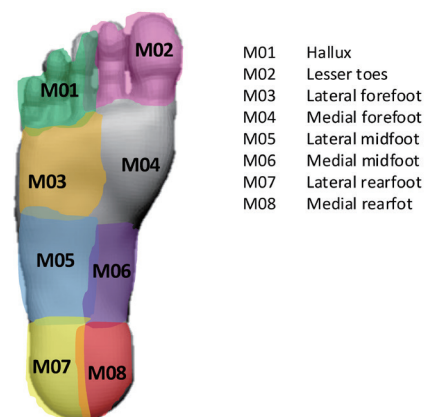

M01	Hallux
M02	Lesser toes
M03	Lateral forefoot
M04	Medial forefoot
M05	Lateral midfoot
M06	Medial midfoot
M07	Lateral rearfoot
M08	Medial rearfot

Fig. 4. (Color online) Eight-region foot mask used to analyze plantar pressure measurement through a force plate measurement device.[15]

3.   Smart Lower Limb Prosthesis

The main components of the smart lower limb prosthesis are (1) smart foot sole, (2) smart powered ankle, (3) processing, control, telemetry, and power, and (4) brain–machine interface (BMI). In the following section, we will describe in detail the components of a smart lower limb prosthesis that will help us understand its working principle.

3.1   Smart foot sole

The proposed smart foot sole will have a physical sole with embedded sensors to measure the plantar pressure. The use of fiber optic sensors for biomedical applications is increasing, as can be seen in Refs. 16–18. Contemporary foot prosthetic designs[6] include a composite foot pedal, which only gives structural support but has no sensing capability similar to a normal human foot. The sensing part is taken care of by the smart powered ankle, which only establishes the identification of rotational and load attributes. We intend to apply the concept of a sensing sole that is smart to differentiate between temperature variations, such as hot and cold, and is based on tactile sensing to differentiate between soft and hard surfaces. This concept is also similar to a smart skin[19,20] in which fiber optics are suggested to build tactile sensing capabilities. This type of technology is feasible for robotic tactile sensing where sensors are required in a non-electromagnetic interference (EMI) field.

The sensing smart sole can be attached to an existing prosthetic device that could act upon the information of the sole making ground contact. A proper distribution of the sensors on the foot sole is critical to map an accurate contact scenario and thus guide the controller for the prosthesis to maintain a stable gait. Typically, in clinical trials, the gait in different forms of locomotion, such as walking, striding, and running, on different terrains (uphill/downhill) is investigated through motion capturing setups.[13,21] These motions correlate with the data acquired from a healthy person performing similar tasks. The prosthetic device adjustments are then made accordingly to incorporate any biomechanical motion flaws. Sophisticated biomechanics analysis tools are used for this purpose.[22] Adding a smart sole could mean that motion capturing relies less on the static hardware (force plate setup and motion tracking cameras) than a dynamic platform, which moves with the patient during the clinical trials.

The current trend in producing prosthetic devices is to improve functioning through lightweight designs with better control capabilities and longer operational and functional life. What we propose is to add another feature to establish a sense of touch and use the same sensory information to produce a better control environment for the electromechanical prosthetic foot. Haptic devices are trained through various algorithms for the identification of the object in contact by referencing them to known information. The smart foot sole with its high sensor spatial density can distinguish between different contact surfaces using the same principle.

Terrain-based information from the contacting smart sole is considered to provide more data to the controller to fine tune the gait stability. We now present our candidate sensor for the smart sole, the fiber Bragg grating (FBG), which is an optical sensor. In the following section,

the use of FBGs in biomedical applications and its working principle will be explained, followed by a discussion on its usage in various studies related to plantar pressure measurements.

3.1.1 FBG sensors

Fiber optic sensors have shown tremendous potential for biomedical applications as can be seen in Refs. 23–25, where they have been used for *in vitro* and *in vivo* biomedical investigations. Fiber optic sensors when compared with their counterparts, such as strain gages and piezoelectric and magnetostrictive sensors in strain sensing applications, have numerous advantages. These advantages are small size, higher sensitivity, resistance to high temperature and chemically corrosive environment, nonreactive to EMI and ease of multiplexing. Advantages and disadvantages of different sensors used for plantar pressure measurements are listed in Table 1. Wearable fiber optic sensors for biomedical applications can be seen in Ref. 26, where they are used for monitoring tensile loadings in joints and bone structures, as well as for muscle movement and respiration monitoring of patients. The fiber optic sensors used are mostly FBGs. When compared with other fiber optic sensors, FBGs are more suitable for biomedical applications owing to their intrinsic nature and investigation based on wavelength modulation. Intensity-based and extrinsic sensors have difficulty in acquiring data and have a complex setup for investigations. Contemporary fiber optic sensors and their usage in medical applications are presented in Table 1. FBGs work on the principle of wavelength modulation where a change in wavelength due to a strain activity allows us to monitor an environmental change. This change is caused by force, pressure, or temperature. The FBG principle is depicted in Fig. 5.

A major advantage of using FBGs for biomedical applications is their immunity to EMI, small size, and ease of multiplexing. A single fiber strand can host numerous sensors that can be located at strategic locations based on the investigation type and scenario. Thus, a smart sole equipped with FBG sensors can give us an advantage of full field coverage giving maximum information on sole contact.

Table 1
Advantages and disadvantages of different contemporary sensors for plantar pressure measurements.[27]

| Sensor technology	Advantages	Disadvantages
Magnetoresistor	• Not sensitive to moisture	• Hysteresis • Temperature compensation required
Strain gauge	• Simple design • Easy to measure	• Requirement of an additional structure to extract shear forces • Temperature compensation required
Optical	• Good resolution due to small size • Nonelectric • Immune to EMI	• Fragile and prone to damage • Optical measurement is challenging and expensive
Piezoelectric	• Thin, slightly flexible to integrate in laminated structure • No need for auxiliary energy • Easy to measure	• Affected by temperature changes • Does not measure static load
Capacitive	• Simple design • Can measure both static and dynamic loads	• Prone to EMI and moisture • Material fatigue can be an issue for the dielectric material
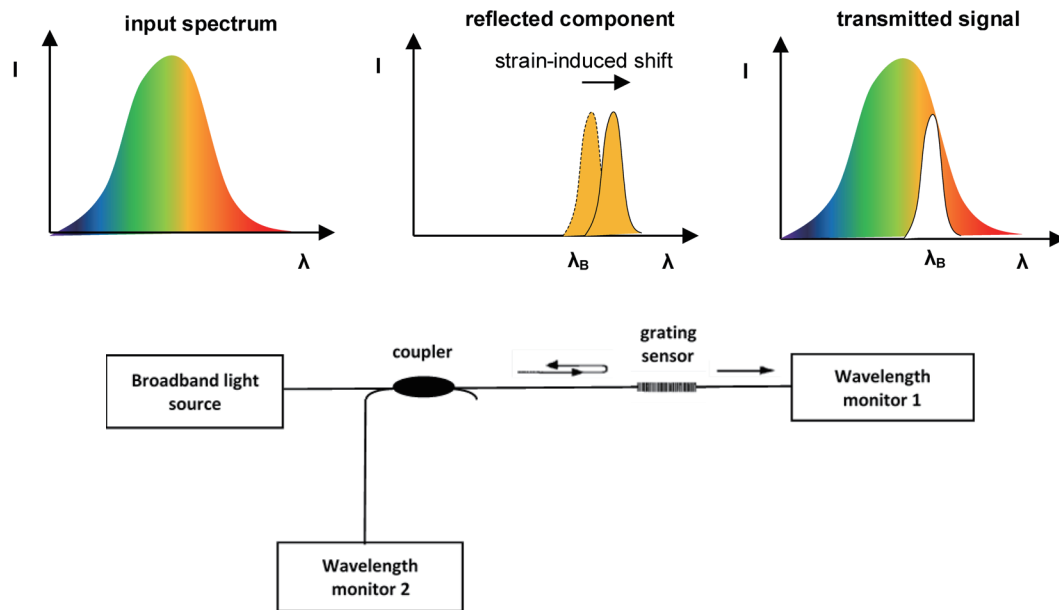
Fig. 5.   (Color online) Basic Bragg-grating-based sensor system with transmittive or reflective detection option.

3.1.2   Issues with conventional optical fibers

The sensor integrity is critical in applications such as plantar pressure measurements. Conventional silica fibers are fragile and would require coating such as polyamide to provide strength. Since we would require a stretchable sensor undergoing large strains, other options such as polymer optical fibers (POFs) have been shown to perform well (in terms of linearity, hysteresis, and integrity) with large strains (0.4–40% stretch) and cyclic loadings of more than 90000 N in biomedical applications.[17,25,26] In Ref. 17, the authors discussed the different performance aspects of such sensors such as linearity, hysteresis, and sensitivities, in reference to various biomedical scenarios. The applications are mainly for respiratory and cardiac activity monitoring. A smart textile based on FBG sensors was designed and its performance was compared with that of optoelectronic plesthymography.[25] The results showed good agreement between the FBG reading and the optoelectronic system. The sensors were attached to a flexible textile with silicon rubber adhesive. Another type of POF commercially named 'CYTOP' was tested for foot plantar pressure measurements.[28] CYTOP is a POF where the C–H bonds are replaced by C–F bonds, reducing the fiber attenuation at a larger stretch. The measurements were taken using a five-array FBG on a single fiber and attaching it to a cork sole machined to the size of the subject foot sole. FBGs were encapsulated in epoxy resin with a cylindrical structure (1.0 cm diameter and 0.5 cm height). The sensors were calibrated to a subjected load between 10 and 150 N. The cork sole provides thermal isolation and has a low Poisson's ratio, allowing plantar pressure measurement for normal ground reaction force (GRF) without shear loads. This design is based on an in-sole measurement system where we can

freely embed such sensors into the smart sole. The sole should be capable of measuring normal and shear loads along with temperature measurements.

The smart sole is intended to have optical fibers embedded in a silicon sole produced from a 3D-printed mold similar to the technologies explained in Refs. 28 and 29. We suggest a smart sole equipped with fiber optic sensors giving maximum coverage on the foot sole for response to different stimuli, such as force, pressure, and temperature, and also to map the complete contact information of the sole with the ground. The smart sole will not only give feedback for gait control but also enhance the sensing feature for the patient to differentiate between soft and hard or hot and cold. The existing smart prostheses can be equipped with this additional feature giving them an advantage of sense of touch. The smart sole will also be useful for patients with neuromuscular disorders. Physical therapy patients undergo monitoring through motion trackers or contact measurement platforms. A standalone wearable smart sole can give freedom from static investigative hardware and can be tested on different terrains (up hill or down hill). The smart sole concept is shown in Fig. 6.

3.1.3   Plantar pressure measurement

Foot plantar pressure is the pressure field developed on the foot sole by its interaction with a contact surface during locomotion. This pressure field has two components: (a) normal and (b) shear. The normal component is acquired owing to perpendicular GRFs, and the shear component is generated owing to the sliding of the contact. Plantar pressure information is useful in gait analysis, which helps diagnose neurological disorders, improve footwear design, rehabilitate amputees, and provide solutions for robotic applications. In the recent past, different types of sensors have been used for plantar pressure measurements.[27,31] The main requirements are miniature size, high spatial resolution, linearity, hysteresis, sampling frequency, low power consumption, and communication. Fiber optic sensors, particularly FBGs, meet all such requirements as can be seen from the comparison presented in Ref. 27. The sensing area is 10×10 mm^2 with sensitivity ± 8 pm/kPa and can measure pressure up to 800 kPa.[28]
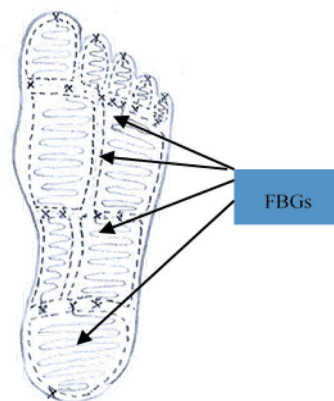

Fig. 6.   (Color online) Smart sole foot concept.

The smart sole that we are interested in developing should be able to differentiate between normal and shear pressures as well as simultaneous effects of various temperatures. A combined normal and shear pressure detection was demonstrated in Ref. 12, where the optical fibers perpendicular to one another were placed in a mesh pattern inside an elastomeric substrate. The sensing principle is based on the measurement of attenuation in light intensity through a macrobend as shown in Fig. 7. Upon compression, the junction where the adjacent fibers cross over would tend to attenuate the light intensity and hence be calibrated for normal pressure. On the other hand, the shearing would cause the attenuation in the fibers due to a pull along the fiber axis direction, as shown in Fig. 8. The attenuation in fiber signal was calibrated for normal and shear loads, from which a 2D map was constructed to identify pressure points and their relative movements. Another novel technique was developed and described in Ref. 32, where FBG sensors were used in a cell arrangement with two cavities. One cavity was isolated from the other by a cork wall in order to isolate the effect of shear loading. The cell design is presented in Fig. 9. The cell material is mostly polylactic acid (PLA) and is installed at five critical locations (toe, metatarsal heads, midfoot, and heel) of an insole.
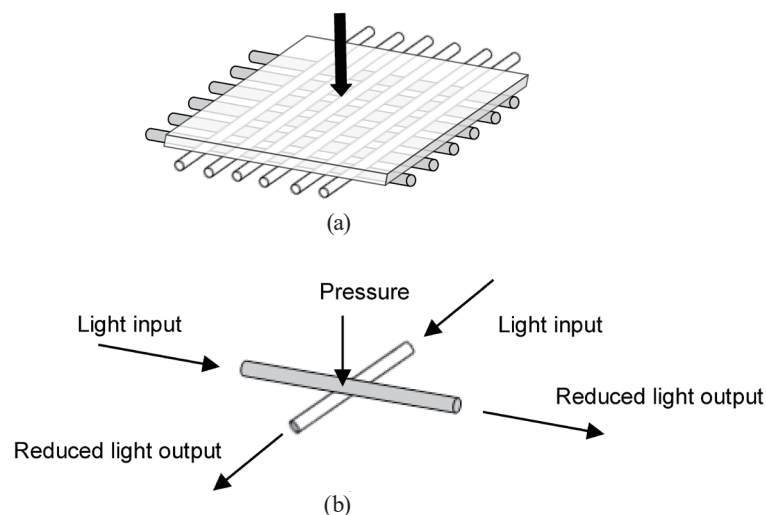

(a)

(b)

Fig. 7.   (a) Basic configuration of fiber-optic sensor system and (b) light loss from an applied pressure.
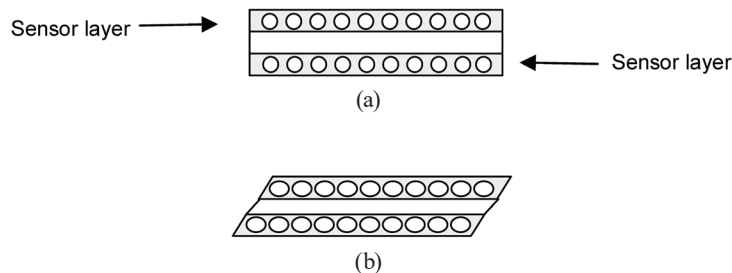

(a)

(b)

Fig. 8.   Basic design of shear-sensor configuration, (a) original and (b) sheared positions.
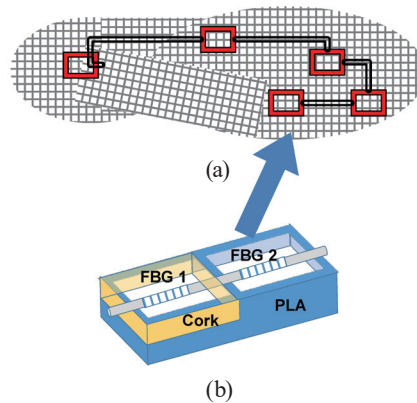
Fig. 9.   (Color online) (a) Insole used for shear and plantar pressure monitor incorporating five FBG cells. (b) Schematic illustration of the designed sensing cell for simultaneous vertical and shear force measurements.

3.2   Smart powered ankle

The leading brands of a smart prosthetic foot, such as Triton Smart Ankle (Ottobock), Elan (Endolite), and Kinnex (Freedom Innovations), consist of design features presented in Fig. 1. In most smart lower limb prosthetics, the foot is a polymer composite spring, which is designed to be inserted into a cosmetic foot shell. The sensory features of the foot sole are missing, which the smart foot sole design can compliment.

3.3   Processing, control, telemetry, and power

A microprocessor-controlled smart prosthesis allows for handling complex sensor data through different algorithms. For gait control, a prefed database exists on the system memory for a healthy human gait pattern. The microprocessor speed should match a prompt response from the actuating powered ankle, once the sensor input has been acquired. The time delay of this system should be less than 100 ms. Prior research has demonstrated that with a time separation of more than 100 ms, subjects have a difficult time discriminating between inputs.[33] The microprocessor not only handles the control inputs of the smart foot but also trains the system over multiple trials to adapt to an unrealized scenario. Artificial intelligent (AI) algorithms meet such demands. A recent work on gait estimation using a deep neural network was demonstrated in Ref. 34, where the algorithm could estimate and quantify the gait temporo-spatial parameters from foot characteristics.

Different modern smart prosthetics, such as those mentioned in Sect. 3.2, are equipped with Wi-Fi that allows for the transfer of real-time data to the user's mobile device. Mobile-application-controlled features of the smart foot give more freedom to the user and hence require seamless connectivity between the smart prosthesis and the mobile device. This requirement could be met by installing low-power miniature antennas that are housed inside the smart foot.

A portable power supply is an essential driving force for the mobility of a smart lower limb prosthesis. Lightweight (16 g), low-power (2.96 W·h), and long-endurance (22.4 h) batteries such as that reported in Ref. 35 can give us a future direction towards compact systems. Lightweight designs and long-endurance batteries are one of the key choices users make while purchasing smart prostheses. This has to be accompanied by the miniature-level design of every subcomponent in the prosthesis with low power consumption. To consume less power, a design can be perceived to incorporate energy harvesting through energy generated by locomotion.[10] Unfortunately, the optoelectronic device that powers and sends light signals to the FBG sensors has not yet been miniaturized to the level of housing it in the smart foot. However, the active engagement of researchers in the field of biomedical engineering with a special interest in fiber optics will pave the way for developing miniaturized setups.

3.4   BMI

A BMI is a device that communicates the signals to and from the brain. This device carries the electromyography (EMG) signals to and from the brain to the electrodes connected at the nerve endings. Functional electrical stimulation (FES) has been used in brain-controlled muscle stimulation for the restoration of motor function.[36] The FES system shown in Fig. 10 is a significant advancement for the development of noninvasive investigations in contrast to the invasive procedures depicted in Fig. 11.

Another advantage of the smart sole will be the mapping of contact information to the brain. This will enhance the sensory feelings of the patient. For this purpose, we need to attach a BMI by noninvasive procedures similar to the concepts explained in Ref. 36. The BMI could also

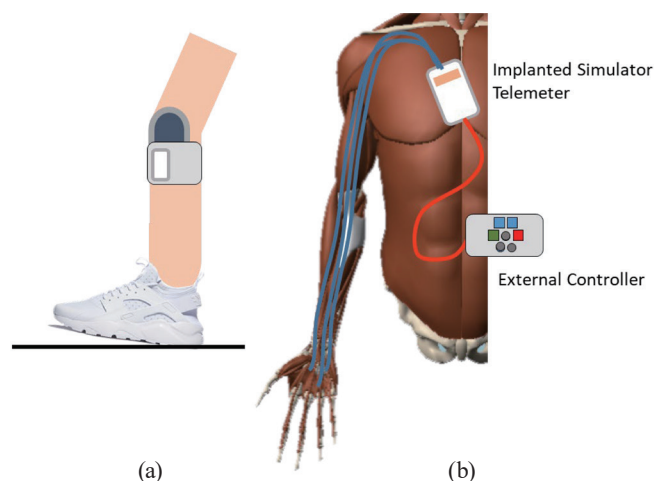(a)   (b)

Fig. 10.   (Color online) Example of FES system developed for human clinical use. (a) The Bioness L300 uses a pressure sensor located in the insole of the shoe to sense heel strike and lift-off. (b) The networked neural prosthesis system (NNPS) is based on a network of implants distributed throughout the body, each dedicated to a specific sensing or stimulus function.
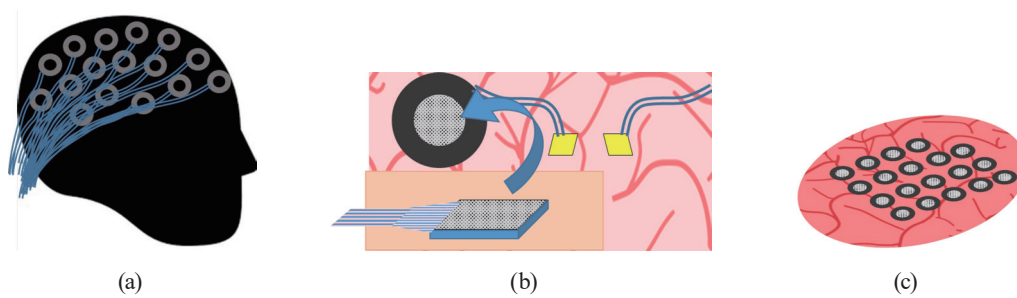
Fig. 11.   (Color online) Setup for recording neural signals from the cerebral cortex. (a) 128-channel active EEG electrode system with electrodes held in predefined positions. (b) Inset: 100-electrode array allows intracortical single cell recording. Two arrays are implanted in two brain segments in a monkey. (c) Electrodes used for monitoring and localizing epileptic foci during operative procedure.
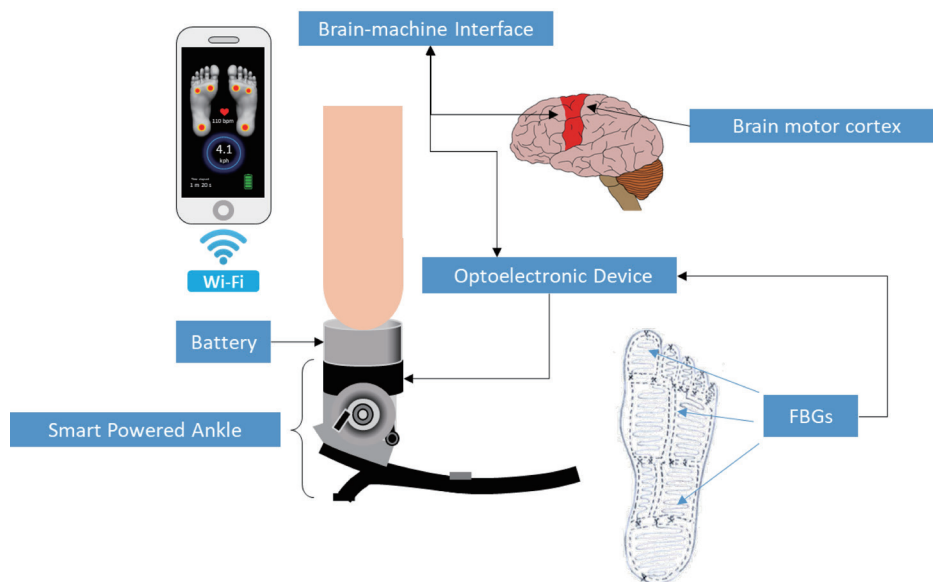

Fig. 12.   (Color online) Multicomponent design for smart lower limb prosthetics.

bridge the feedback from the brain through EMG signals to the electromechanical prosthetic foot to perform intentional motion.[37] The development of such a system is a challenging task as it is a multidisciplinary problem. A complete integrated system proposed for a smart lower limb prosthetic design is shown in Fig. 12. The fiber optic sensors in the foot sole communicate the contact information to an optoelectronic device. The optoelectronic device along with the smart powered ankle and the communication devices are powered by a battery. The contact information is passed onto the brain motor cortex to be processed and to relay feedback from the brain to make corrective actions. All the activities can be monitored through a mobile device, allowing constant monitoring of the smart lower limb and brain–machine connectivity.

4.   Conclusion

We presented a novel approach to producing a prosthetic foot sole that enhances the sensing capability of an amputee. A few recent developments identified key technologies that would enhance the research in the field of prosthetic development and robotics. Developing a biomimetic prosthesis would also be beneficial for robots that are more lifelike. Concerning patients who suffer limb loss, especially those with sensory loss, relieving the patient from the misery of enduring such a loss is considered to produce a positive impact and enhance the patient's quality of life. Every person deserves a better life, and to enable such individuals to re-engage in the mainstream society would be a great success.

Acknowledgments

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