# Biomedical engineering: A brief survey into current challenges and a proposed research roadmap

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# Biomedical engineering: a brief survey into current challenges and a proposed research roadmap

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**Abstract:** The goal of this paper is to direct the readers' attention to the main challenges facing some of the most active research areas in biomedical engineering. These include brain machine interface (BMI), telemedicine, biomedical microrobotics, virtual experimentation and comfortable vehicles' design. Moreover, the paper discusses some research directions that can be pursued to overcome these challenges in the near future.

**Keywords:** biomedical; BMI; brain machine interface; microrobots; ANN; artificial neural network.

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## 1 Introduction

Biomedical engineering is a charming, exciting, challenging and extremely important branch of engineering. It is clear that any advance that God helps us achieve in this field is a true blessing, as it directly affects the lives of human beings in many ways large and small. Any engineering design discipline that requires understanding of biological effects related to human health can be considered a biomedical engineering branch. Over the years, advances in biomedical engineering helped relieve and save the lives of many people. Examples of these advances include robotics that aid in minimal invasive surgery, telemedicine that helped deliver high-quality medical care to people in locations unreachable by the required qualified medical staff, development of safe effective therapies and helping students of medicine to obtain a realistic training to improve their skills without risking the lives of patients. Yet, despite all these advances, there still remain many unsolved challenges. An unsolved challenge in this field of engineering means people suffering, others losing their lives and entails a less effective community owing to the disability of some of its members or inability to serve their societies as they should. Thus, new research directions that help solve these challenges are extremely valuable and need to be pursued as soon as possible. This paper aims to highlight some of the main challenges facing biomedical engineering research directions, discuss the solutions currently pursued by researchers to overcome them as well as propose other research-worthy candidate solutions.

## 2 Current challenges in prominent biomedical engineering branches

### *2.1 Brain Machine Interface (BMI)*

As its name implies, BMI is concerned with designing an interface between the human 'brain' and a rehabilitation device 'machine' so as to help a disabled person either recover a lost sense (like vision or hearing) or mobility or at least cope with them (Lebedev and Nicolelis, 2006) (see http://computer.howstuffworks.com/brain-computer-interface.htm/printable, http://en.wikipedia.org/wiki/Brain%E2%80%93computer_interface, Normann et al., 1996).

If the rehabilitation device is to help recover a lost mobility, the BMI task is to interpret the neuronal activity of the motor cortex into a corresponding desired motion. Measuring the neuronal activity is possible using either invasive (intra-cranial) or non-invasive (Electroencephalograms (EEGs)) methods. Invasive BMI approaches are based on recordings from ensembles of single brain cells (also known as single units) or on the activity of multiple neurons (also known as multi-units). These readings are obtained using implanted electrodes in the patient's brain. Non-invasive systems primarily exploit EEGs. On the basis of this interpretation of neuronal activity readings, the BMI should afterwards determine the appropriate muscles excitation in case of a paralysed person, actuator input in case of an amputee or a cursor position in case of a Brain Computer Interface (BCI) (see Figures 1 and 2).

On the other hand, if the rehabilitation device is to help recover a lost sense, the BMI task is to decide an excitation plan for the brain neurons based on collected sensory information from the rehabilitation device, which will be a camera and digital signal processor in case of vision prostheses, so that the patient 'feels' that he or she 'sees' the image captured by the camera. This is an even more difficult problem. After determining which neurons should be excited to create a certain image 'sensation', BMI must also specify how these neurons will be excited. Again, there are two possible methods namely invasive and non-invasive. As seen in Figure 3, invasive methods may, for example, implant an array of electrodes in the visual cortex (Normann et al., 1996). The neurons, which the signal processor decided that they should be excited, receive the excitation trigger through a transcranial interconnect. In non-invasive methods, transcranial magnetic stimulation can be used to stimulate the neurons that should be excited (Rossi et al., 2009). With vision, an additional challenge is determining which part of the visual pathway should be excited (Pezaris and Eskandar, 2009). However, a detailed discussion of this point is out of the scope of this paper.

**Figure 1** Basic Brain Computer Interface Steps. First, the signal corresponding to the patient intention is collected. Second, it is interpreted to a required cursor position. Third, the interpreted position is displayed on screen (see http://computer.howstuffworks.com/brain-computer-interface.htm/printable) (see online version for colours)

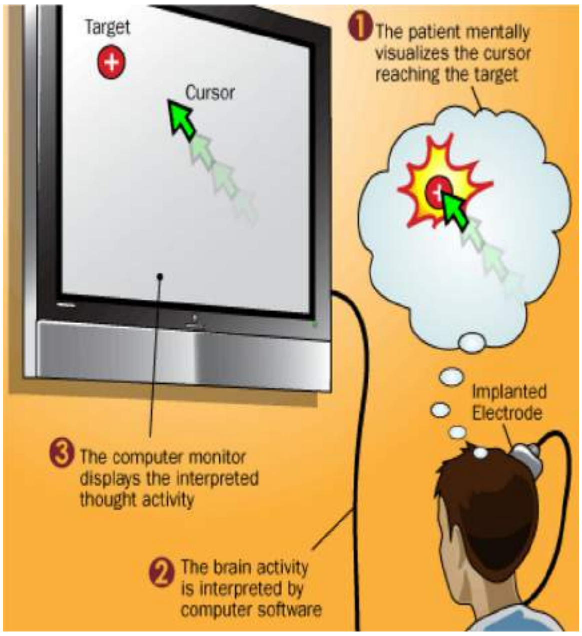
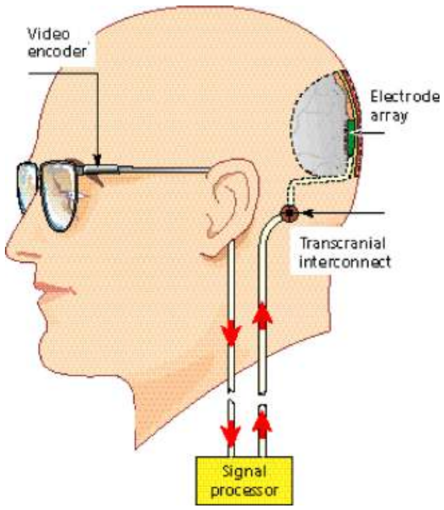



**Figure 2** In this successful experiment, collected signals from monkey's cortex were used by it to control a robotic arm and feed itself using it (see http://en.wikipedia.org/wiki/Brain%E2%80%93computer_interface) (see online version for colours)

Several successful BMI case studies have been reported. Most of them have been related to BCIs. Figure 1 shows how a BCI works. The patient visualises where he or she wants the cursor to go. His brain activity is interpreted and the result is sent to the computer to actually move the cursor to the desired position. The success of such a BCI largely depends on its exploitation of neuronal plasticity. The patients need training. In this training, the patient tries on and on to concentrate until the cursor moves to the desired position. By this, he or she is actually exploiting his or her own natural neuronal plasticity as God created it. He or she learns to adapt his or her neuronal activity so that the BCI 'understands' his/her intentions (desired cursor position) correctly.

**Figure 3** Basic components of an artificial eye (eyeglasses with a video encoder connected to a signal processor connected to implanted electrodes (see online version for colours)




*Source*: Courtesy to Normann et al. (1996)

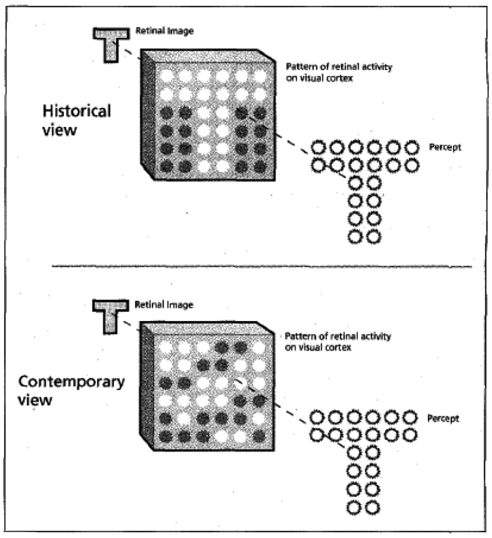
To the author's knowledge, to date, mobility restoration using BMI has been limited to experimental animals. Figure 2 shows one successful attempt. Here, the monkey's own arm was restrained from movement and all it can move is a robotic arm. The robotic arm actuators were 'wired' (connected) to the monkey's brain so that the cortical neuronal activity excites the actuators and thus moves the robot arm. Once more, the success strongly relied on God's created natural neuronal plasticity. The monkey simply keeps attempting a move until it successfully reaches its target. By this, it is actually learning how the neuronal activity should look like for the correct move to be achieved.

However, despite these successes, BMI faces fundamental challenges. The main challenges are related to measuring and understanding neuronal activity. Accurate high fidelity neuronal activity measurement is an essential pre-requisite to its understanding. We need to measure neuronal activity from healthy subjects in case of lost senses to be able to study the relation between this activity and the corresponding input sensory information (seen image in case of vision or heard signal in case of hearing). We need sufficient measurements from many neurons and recorded over long periods of time. In addition, measuring neuronal activity in patients may be needed in case we employ closed-loop control to excite the neurons that should be excited to create a certain sensation. With mobility prosthesis, accurate measurements are needed both in healthy subjects and patients as well. Once again, in healthy subjects, these measurements are necessary to study the relation between subject's intention (desired move) and the corresponding neuronal activity. This understanding is important because based on it, we can decide how the prosthesis can interpret patient neuronal activity into a desired move and, thus, the actuators/muscles can be excited accordingly. In patients, measurements will be needed to decode a neuronal activity into an intended move. As we have pointed earlier, measurements are possible either using invasive or non-invasive methods. For obvious reasons, invasive methods are not acceptable for most patients. On the other hand, despite having the great advantage of not exposing the patient to the risks of brain surgery, EEG-based non-invasive techniques provide communication channels of limited capacity. Their typical transfer rate is currently 5–25 bits/s. Such a transfer rate is not sufficient to control the movements of an arm or leg prosthesis that has multiple Degrees of Freedom (DOF).

Similar to neuronal activity measurement, neuronal activity excitation is important both with vision prostheses and mobility prostheses, especially if closed-loop control is used such that the deviation from the desired move needs to be fed back to the brain so that the cortical neuronal activity is modified to minimise this error. Invasive excitation techniques are more reliable but more risky to patient's health. On the other hand, non-invasive techniques, such as transcranial magnetic stimulation, are less reliable and are not free from risks themselves (Rossi et al., 2009).

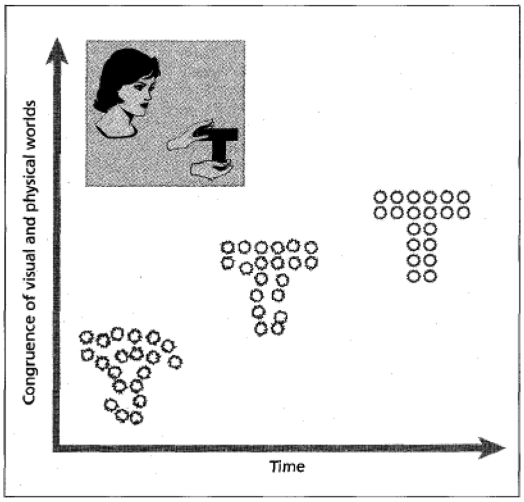
Neuronal activity understanding is perhaps the major BMI challenge. First, as we just explained, the challenges associated with neuronal activity measurements make the available information insufficient to learn the complex mappings between the sensory information and neuronal activity (see Figure 4) and that between the neuronal activity and the subject's intention (desired move). In addition, although insufficient, the available data is still quite huge, rendering this understanding as a challenging data-mining problem. Indeed, up till now, no one can claim that any success in BMI was based on a true understanding of this activity. All we know about this activity remains to be speculations (Musallam et al., 2004; Guigon et al., 2007; Taylor et al., 2003; Ciocarlie et al., 2008; Light et al., 2002; Sergio et al., 2005; Kemere et al., 2008). Instead as we explained, most successes rely on exploiting the neuronal plasticity that God created in us. This makes the prostheses design and operation to date an ad-hoc stochastic process, with no real success guarantees. Furthermore, exploiting neuronal plasticity with mobility is possible because the subject simply monitors how his or her prosthesis move and thus can detect the error compared with his or her intention and update the neuronal activity accordingly. However, a similar behaviour with vision is very difficult. Figure 5 illustrates this difficulty. With vision, a person has no way of detecting whether what he or she sees is correct or not. The only way he or she can guess this is perhaps through 'touch' (by feeling an object and comparing what he or she feels with what he or she sees) and through error feedback in the form of missing a target or hitting an obstacle. This makes the improvement of the vision prosthesis with time quite limited. The complexity of the retinotopic mapping (see Figure 4) together with the difficulty of exploiting neuronal plasticity with vision led to a very slow progress in vision prostheses development. To date, most vision prostheses have had very limited success with true vision functionality restoration to the blind (Pezaris and Eskandar, 2009; Dobelle, 2000) (not quite much improvement in the quality of life compared with conventional aids such as a cane, a dog and Braille writing).

**Figure 4** This figure compares the historical view and current view of the relation between a seen image and the corresponding visual cortex activity. Historically, it was assumed that a 'T' image would excite a 'T' neuronal activity. However, it turned out that the actual mapping is quite non-linear and complex




*Source*: Courtesy to Normann et al. (1996)

**Figure 5** The neural plasticity (adaptation capability) of the visual cortex should allow for continuous improving correlation between the physical world and the evoked phosphenes. Immediately after an electrode array is implanted, the evoked phosphenes are likely to result in a poor performance of 'T'. With time this should improve. (Courtesy to Normann et al., 1996). However, such an improvement based on adaptation requires some form of error feedback to the patient. Unfortunately, with vision, there is no direct reliable way for such a feedback. This makes the adaptation slow as it can benefit only from the knowledge a patient gains by comparing 'touch' information with visual information as well as the experience gained through missing a target that she reached for or hitting an object due to incorrect visual information



In short, for BMI to be useful in restoration of a lost mobility or sense from a sophisticated clinical point of view as required to improve patients' lives and bring them back to the workforce, a prosthesis design must be turned into a direct design process totally under control of the designer. Moreover, the prosthesis should operate in a closed loop. Closed loop means that there must be a direct way to assess the performance of the prosthesis and to adapt it based on this assessment.

Additional important challenges also exist. First, the invasive prosthesis needs to be made from biocompatible material in order not to trigger adverse attacks from the human body immunity system. Second, in case of amputees, mobility prostheses need to have similar functionality to that of human limbs and muscles. This is important for the patients to accept the prosthesis and is more likely to make his or her exploitation of their neural plasticity easier. In addition, we need reliable feedback sensors to deliver the necessary force feedback to the subject's brain. Moreover, designing suitable signal processors small enough to be wearable and yet can perform the complex computations required by BMI-prostheses in real time, remains to be a challenge.

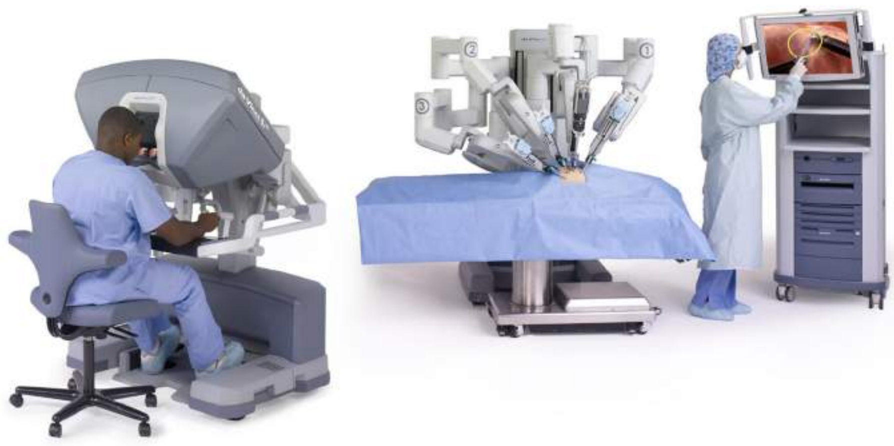
We would like to conclude this section with a final remark. In May 1996, an IEEE Spectrum special issue was launched with the title 'Towards an artificial eye'. The paper anticipated that by 2010, vision prostheses would become a common sophisticated clinical practice. Clearly, however, this did not happen. The challenging nature of this field and its value to millions of suffering people, to whom we may belong one day, makes BMI research more than just an interesting engineering research but more like an engineering duty to whoever can help with it.

## *2.2 Telemedicine/telesurgery*

By 'Tele', we mean delivering medical care at a distance (remotely) (Adler, 2000; Ackerman et al., 2002). There are three main motivations for this. First, in emergencies the assistants in an ambulance may need consulting staff from the hospital regarding a critical case. Second, it may be impossible or at least very difficult for the required qualified physician to reach the site of the patient (this may be due to security regions as in wars or owing to the patient being in a different developing country). Third, minimal invasive surgeries, such as laparoscopic surgery, are becoming increasingly popular owing to their advantages, which include shorter postoperative hospitalisation, less pain, and a faster return to normal activity (Lobontiu and Loisance, 2007). However, these surgical procedures rely on making several tiny incisions in the patient body through which the surgeon must operate. This decreases the surgeon's manual dexterity and often requires a surgeon to assume uncomfortable poses for large periods of times. This in turns increases the probability of a human error and thus risks to patients lives. Moreover, it makes non-invasive surgery limited to a class of simple operations. Using telesurgery overcomes these limitations. The surgeon simply sits in a comfortable position at a remote console showing a clear magnified view of the site of the operation at the patient's body. Figures 6 and 7 show an example of a telesurgery system set-up and its tools.

Several successful examples of telemedicine systems exist. They may be classified as belonging to either systems used for remote (and may be quite long distance) diagnosis or telesurgery systems with both the surgeon and the patient at the same site. Examples of such systems include the following systems. Most examples exist in developed countries. The National Aeronautics and Space Administration (NASA) has been doing remote medical monitoring since the early manned missions and is currently developing advanced life-support systems for the International Space Station. Because of the obvious shortage of medical specialists in space, NASA's Earth-based doctors rely heavily on the use of telemedicine to monitor astronaut's vital signs. The astronaut's telemetry can provide critical information to doctors on Earth in the event of a medical emergency in space.

**Figure 6** A typical telesurgery set up. Male surgeon using *da Vinci Si* console with nurse at vision cart (see online version for colours)



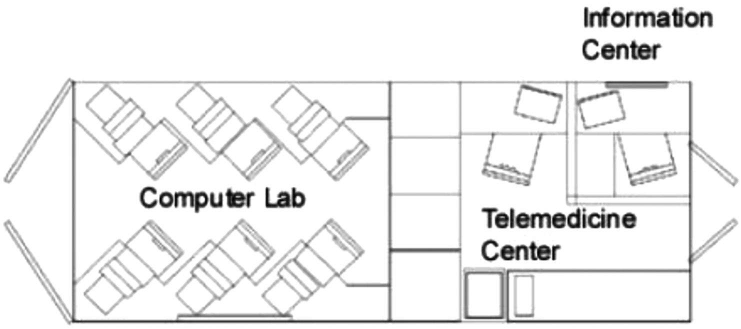
Courtesy to http://www.intuitivesurgical.com/corporate/newsroom/mediakit/gallery_davincisi.aspx)

**Figure 7** DaVinci system tools: (a) Endowrist$^{TM}$ technology at instrument tips; (b) motion scaling and (c) hands position corresponds to instrument tip orientation (Lobontiu and Loisance, 2007). Refer to the text for details (see online version for colours)

(a) (b) (c)

An interesting example in developing countries is the LINCOS system (Adler, 2000) (Figure 8). Shipping containers were chosen for the construction of the LINCOS units because they offer many benefits: standardisation, security, structural integrity and low cost (because there is a large recycled after-market for them). Also, there already exists a widespread infrastructure for their transportation. They can be carried from their construction site to their final destination by boat, train, truck or helicopter. The telemedicine centre is at LINCOS. The telemedicine centre provides the space and tools for a health practitioner to perform telemedical consultations. In addition, it houses a small environmental testing and monitoring lab. The telemedicine room consists of a small private space within the container that contains an examination table, a mobile sink, a desk and cabinet space for storing medical instruments and supplies. A portable telemedicine kit was designed to be used primarily at the telemedicine centre to take advantage of the connectivity at the LINCOS container. The kit consists of a laptop computer and several medical peripherals that allow the health practitioner to capture a patient's medical data in the form of text, graphics, video, audio and data files. This information is subsequently forwarded over the internet to a doctor for diagnosis.

**Figure 8** Courtesy to Adler (2000). LIINCOS container plan view



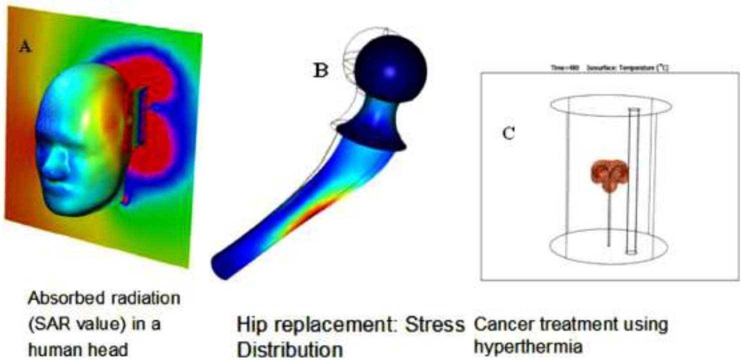

A particularly interesting robot-assisted telesurgery system is the daVinci System (Lobontiu, see Figure 6). The da Vinci™ system (see http://www.intuitivesurgical.com/corporate/newsroom/) consists of a master console that connects to a surgical 'manipulator' with two instrument arms and a central arm to guide the endoscope. Two 'master' handles at the surgeon's console are manipulated by the user. The position and orientation of the hands on the handles trigger highly sensitive motion sensors and translate to the end of the instrument at a remote location. The surgeon sits comfortably at a master console located at a distance from the patient with eyes focused down towards the operative site mirroring an open surgical technique and the slave unit provides 'tele-presence' within the abdomen or chest for microinstruments manipulation. A 10 mm high-resolution 3D 0° or 30° endoscope (with two three-chip charge coupled device – CCD cameras) is used for better perception of depth and optical resolution. The endoscope is held by the central four DOF manipulator of a remote centre design, similar to the slave tool manipulator. The camera manipulator is capable of positioning the tip of the endoscope in 3D by working through the fulcrum made by the port incision at the body wall. This Navigator™ Camera Control system gives the surgeon a third arm to hold and move the camera without the need for an assistant. The basis of the dexterity experienced in open surgery relies on the almost unlimited wrist, elbow and shoulder's DOF. The DOF in laparoscopic surgery is limited because instruments need to be long and are manipulated through fixed ports. The surgeon has to move around these fixed ports. To solve these limitations, tools have been developed that have an articulation at the tip, which increases the DOF. Addition of the wrist at the tip of the instrument gives tool manipulation much more complex. Computer assistance is warranted, as the human brain cannot efficiently manipulate articulated instruments by mechanical means. A robotic wrist provides articulated motions with a full 7 DOF inside the abdominal or thoracic cavities (EndoWrist™ technology, see Figure 7). The surgical instrument with this EndoWrist robotic wrist at its tip is attached to the surgical arm. Handles motions are sensed by high-resolution motion sensors, processed and transferred to the two surgical manipulators. These slave manipulators (surgical arms) provide 3 DOF (pitch, yaw and insertion).

Despite these successful attempts, still full medical care delivery at a distance suffers from various obvious challenges. The challenges that face telemedicine may be summarised as follows. First, fast real-time video feedback from the patient site must be possible. Second, surgeons' manual dexterity and their safe operation on patients strongly rely on force feedback. This is lost in telesurgery and must be compensated for by a suitable haptic interface. Third, for long distance telemedicine critical information to patients privacy and safety are transmitted over unsecure links. Thus, they need to be encrypted with a suitable procedure that does not hamper real-time operation. Fourth, for telemedicine to be successful there must be a safe way to handle possible network black outs without risking patients lives. Fifth, it is quite challenging to design and control a robot having the necessary manual dexterity required by complex surgical procedures.

## *2.3 Virtual biomedical experimentation*

It is quite dangerous to try therapies and related tools on humans without prior safety checks. Trying these procedures even on animals without any mild safety guarantees is also rejected by many owing to obvious ethical reasons. The same holds for training young medicine students on living beings. In addition to that, several phenomena that are suspected to affect humans' health need thorough experimentation in a controlled environment. For example, electromagnetic radiations have a proven effect on tissues. This effect is important from two points of view. First, it means that electromagnetic radiations can be used as a tool in non-invasive therapy (such as hyperthermia). Second, it means that mobile phones, their base stations and other similar devices are more likely to have adverse effects on subjects' health (Bernardi et al., 2000). Thus, an accurate assessment of the biological effect of electromagnetic radiations can help subjects choose suitable places for their houses, children schools, hospitals, etc. It can also help the relevant agencies set regulations on base stations and mobiles transmitting power as well as base stations locations to avoid endangering subjects health. The needs of all these applications can be satisfied by using a multiphysics simulator (Ge and Ratcliffe, 2009; Mohammed and Verhey, 2005) (augmented with virtual reality tools in case of surgical training). Figure 9 shows some typical applications where virtual biomedical experimentation using a suitable simulator is needed. Figure 9(a) shows the absorption of microwave radiations from a mobile handset in a Human head model. On the basis of this absorption distribution, the impact of a mobile handset on its user's health can be assessed. Figure 9(b) depicts the stress distribution in a hip-replacement study. The most common reason that people have hip-replacement surgery is the wearing down of the hip joint that results from osteoarthritis. Other conditions, such as rheumatoid arthritis (a chronic inflammatory disease that causes joint pain, stiffness and swelling), a vascular necrosis (loss of bone caused by insufficient blood supply), injury and bone tumours, can also lead to the breakdown of the hip joint and the need for a hip replacement (see http://www.comsol.com/, COMSOL biomedical engineering minicourse). The estimation of the stress distribution is very important to make sure that a hip replacement will be successful. Figure 9(c) shows the heat distribution in a cancer treatment using hyperthermia application. Hyperthermia is a method for removing cancerous tumours from healthy tissue by heating the malignant tissue to a critical temperature that kills the cancer cells. It is important to study the heat distribution to make sure that all cancerous cells are killed and yet that the surrounding healthy tissues are not damaged.

**Figure 9** Shows some typical applications where virtual biomedical experimentation using a suitable simulator is needed: (A) shows the absorption of microwave radiations from a mobile handset in a human head model; (B) depicts the stress distribution in a hip-replacement study and (C) shows the heat distribution in a cancer treatment using hyperthermia application (see online version for colours)




A multiphysics simulator uses computational methods to solve the Partial Differential Equations (PDEs) that represent the physical laws that govern the system under consideration. By solving these equations, the system performance can be predicted without the need for practical experimentation. Such simulations often use numerical methods such as the Finite Element Method (FEM) (Bonet and Wood, 1997) or finite volume method (Leveque, 2002). These methods discretise the continuous problem geometry into a mesh of discrete locations (see Figure 10). The governing PDEs are converted into a system of algebraic equations with the unknowns being the PDE variables values at these locations. COMSOL (www.comsol.com) and CAElinux-based OpenFOAM (www.caelinux.com) are examples of such simulators. However, the development of a multiphysics simulation that replicates the actual physical reality with high fidelity faces several challenges. First, constructing accurate models of the human body (and the surrounding environment in case of electromagnetic radiation effect assessment) is far from easy. In addition, developing a mathematical model of all relevant phenomena and the different multiphysics effects is not easy. There are too many details that need to be taken into account and that vary from case to case. Second, the problem is essentially multiscale. The high-frequency range requires a very small step size to be used by numerical simulators. However, the humans and their environments dimensions are in the order of metres. The multi-scale nature of these problems results in very large problems. Figure 10 shows a typical tumour ablation example. The model approximates the body tissue with a large cylinder. The tumour is located near the centre of the cylinder and has the same thermal properties as the surrounding tissue. The model locates the probe along the cylinder's centre line such that its electrodes span the region where the tumour is located. The geometry also includes a large blood vessel. The model requires a mesh with over 51,000 elements leading to over 76,733 variables to accurately predict the therapy's effect even for an over-simplified model of the instruments and body environment. The problem is even further exaggerated with microwave cancer therapy, where the multiscale nature is even more clear. Microwave frequencies require very small mesh elements in mm range, while the human body scale is much larger than that. Figure 11 shows the mesh required for accurate study of a cancer microwave therapy. Even for an over-simplified 2D model, 5869 mesh elements are required leading to a problem with over 43,439 variables. Thus, to be able to simulate such systems, we need new fast numerical methods to be developed.

**Figure 10** A typical tumour ablation examples requires a mesh with over 51,000 elements to accurately predict the therapy's effect even for an over-simplified model of the instruments and body environment (see online version for colours)

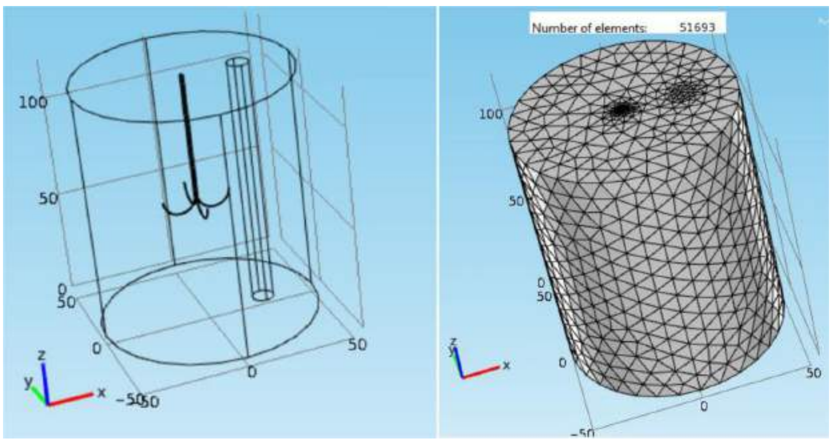
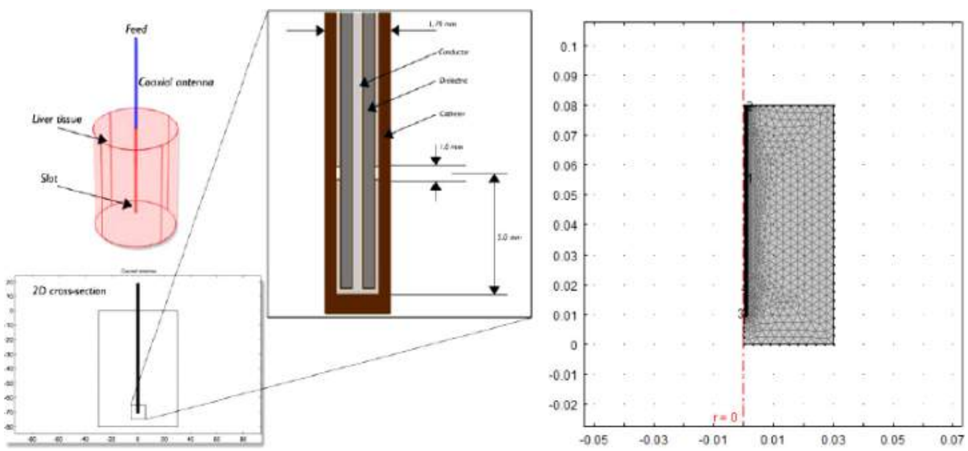



**Figure 11** Shows the mesh required for accurate study of a cancer microwave therapy. Even for an over-simplified 2D model 5869 mesh elements are required leading to a problem with over 43,439 variables (see online version for colours)



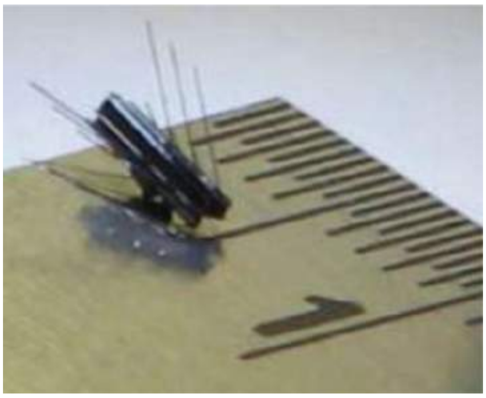
## *2.4 Microrobotics*

Microrobots are very small robots that can be injected within the human body to either perform diagnostic actions (Lee et al., 2004), deliver a therapy (Shoham et al., 2008) or even perform a surgery (Tawfik et al., 2009). Clearly, microrobots offer a non-invasive solution to medical problems. Currently, several successful microrobots have been deployed in real clinical applications.

According to Kim et al. (2004), the first capsule-type microrobot endoscope called the M2A was developed and commercialised in 2001 by Given Imaging Inc. of Israel. It is 10 mm in diameter and 27 mm long with a CCD camera, an RF module, illuminating LEDs, and a battery integrated. It can be swallowed and can transmit wireless still and moving images from the gastrointestinal tract. Because of the development of wireless capsule endoscopes, it is now possible to diagnose small intestines, which cannot be achieved by conventional endoscopes, and to reduce pain and discomfort of the patient. Another wireless-type endoscope called Norika V3 is being developed by RF System Co. in Japan. It moves passively from the mouth to anus by the peristaltic waves.

A particularly interesting microrobot is (Shoham et al., 2008) ViROB (see Figure 12). ViRob is an autonomous revolutionary crawling microrobot controlled by electromagnetic fields. Miniaturisation is made possible since actuation and control are not onboard. Actuation power is given owing to an external magnetic field subjected onto the robot, while crawling velocities are determined using different external magnetic field frequencies. The robot consists of a central torso from which tiny arms stretch out, allowing the robot to strongly grip the vessel walls. The operator can manipulate the robot to move in increments, and its unique structure allows it to crawl within a variety of vessels with differing diameters. The robot has been fabricated using Microelectromechanical Switches (MEMS) technology and has a diameter of 1 mm. Potential medical applications for ViRob include targeted drug delivery procedure, diagnostic procedures, neurosurgery and imaging.

**Figure 12** ViROB microrobot developed by Shoham et al. (2008). Potential medical applications for ViRob include targeted drug delivery procedure, diagnostic procedures, neurosurgery and imaging (see online version for colours)



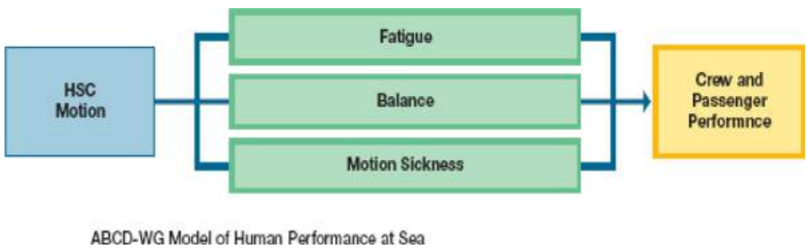
Despite these successful attempts, the extremely small size of the microrobots leads to three challenges, which become obvious, especially if we are seeking the true widespread of microrobots in complex biomedical applications, such as complex surgical procedures.

The first is choosing a suitable powering method that can fit with the size constraint and power requirements. The second is developing a suitable actuation strategy. Clearly, conventional motors torque/size ratio is not suitable for use of microrobots. Using those limits the applications of microrobotics in biomedical engineering. The third is developing a suitable on-board processing units and sensors to give the microrobot a certain degree of autonomy. Usually, microrobots perform a set of pre-programmed task. However, diagnosis and surgery are active processes. You cannot really fully pre-program the microrobot to perform a certain task. The microrobot should ‘understand’ the goal of the surgery or the diagnosis and based on that it is expected that it might need to alter its plan. Some actions may not be possible owing to unforeseen conditions or patient’s health concerns that are detected on-site by the robot. Other additional actions may be needed to resolve an ambiguity in case of diagnosis. Thus, the robot needs a sophisticated degree of autonomy. The miniaturised processors and sensors capable of providing such sophisticated autonomy remain to be a challenge.

## *2.5 Human factors impact on vehicles design*

Certainly, passengers comfort is an important factor for vehicles (train, bus, car, aircraft or ship) design from an ethical as well as an economic point of view. Simply, people would not ride in a ‘thing’ that makes them feel sick. Moreover, there is currently a tendency to decrease the number of crewmembers on board of ships, for example. This makes it quite important to assure that each member of the crew is quite fit. Even if they do not lead to obvious motion-sickness symptoms, motion of vehicles may still lead to fatigue accumulation as well as a disinclination to work. This is quite undesirable especially with a limited number of crew. Crew’s disorders endanger the vehicle safety as a whole (Stevens and Parsons, 2002). Figure 13 summarises the effects that vehicle motions can have on passengers and crew. These effects are fatigue, balance and motion sickness (see ABCD Working Group on Human Performance at Sea (www.abcd-wg.org), ABCD-TR-08-01 V1.0, High Speed Craft Human Factors Engineering Design Guide, 2010). The pharmacological solutions to motion sickness are unacceptable owing to their adverse side effects. Thus, the acceptable solution is to design vehicles, which exhibit minimal motions that may induce sickness. Ships, in particular, especially with the development of High-Speed Crafts (HSC), represent a challenging design problem, from the point of view of human factors.

**Figure 13** The effect of a High-Speed Craft motion on crews and passengers (www.highspeedcraft.org) (see online version for colours)

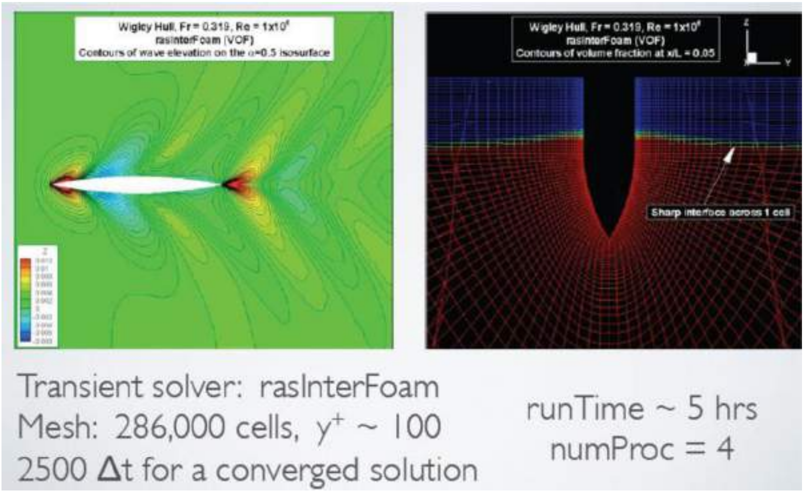



The challenges facing comfortable vehicles design can be summarised as follows. The first and most fundamental challenge is designing suitable controllers that actively minimise vehicles motion. The vehicle's models, especially, for ships are highly non-linear and the derivation of accurate models of them is quite difficult. It is difficult to develop suitable control schemes that are guaranteed to work successfully with such non-linearity, model uncertainty and rough environmental disturbance challenges.

The second challenge is developing accurate models to deduce motion-sickness occurrence (index) based on vehicles motion. In general, the issue is a matter of frequency bands (Giron-Sierra et al., 2003). There are three different filters. The vehicle vertical accelerations filter representing the environment state (sea-state, for example, in case of ships) transfer function, the motion-sickness filter representing the passengers response and the vehicle response filter. The effect of motion-sickness on passengers depends on the overlap between all three filters. The more they overlap the worse it is for passengers. Thus, the passenger can be viewed as a band-pass filter only oscillating with vertical accelerations with frequency inside motion-sickness band. Finding the mathematical model of these filters is an optimisation problem. The frequency response of the filters can be obtained from available data. The filter model parameters are computed so that they minimise the error between the filter actual response and the true response estimated from practical data. However, gathering sufficient data to ensure accurate filters models derivation, especially, with the motion sickness filter, is quite challenging. In addition to the type, frequency, duration and intensity of the motion encountered, several other factors influence human susceptibility to motion thickness and thus should be taken into consideration into a motion-sickness filter, yet they are very difficult to model. There is wide variation in susceptibility to motion sickness, both between different persons (inter-subject variability) and within an individual on different occasions (intra-subject variability) (Griffin, 1990). These differences are attributed to psychological variables including the experience, personality and adaptability of the person, and to different individual dependencies on vestibular, visual, or somato-sensory information. Significant research has been conducted to determine the characteristics of motion that are most nauseogenic and that create the greatest malaise among passengers and crew. Although there are specific motions that cause people to become motion-sick, the exact nature of the relation of the vehicle's motion to the sickness it causes is not well defined.

The third challenge is developing methods suitable for accurate simulation of large vehicles motions in a reasonable time. For ships in particular, developing an accurate model of a ship in its environment under the different possible sea states and simulating it is very challenging. The simplest models involve meshes with over a million elements (Paterson et al., 2009). A typical mesh is shown in Figure 14 .The accurate estimation of expected ship motions is very important. Since the vehicles motions (the frequencies corresponding to them) are the inputs to the filter representing humans response to vehicle motion, an inaccurate estimation of these motions will lead to an inaccurate estimation of human response, even if the filter representing it have been derived accurately. Thus, an accurate estimation of human response relies heavily on solving the first and second challenges that we discussed. Note that an accurate estimate of human response is necessary if we want to develop a formal optimisation procedure for vehicles design based on passengers comfort because the human response will be the objective function that we want to minimise.

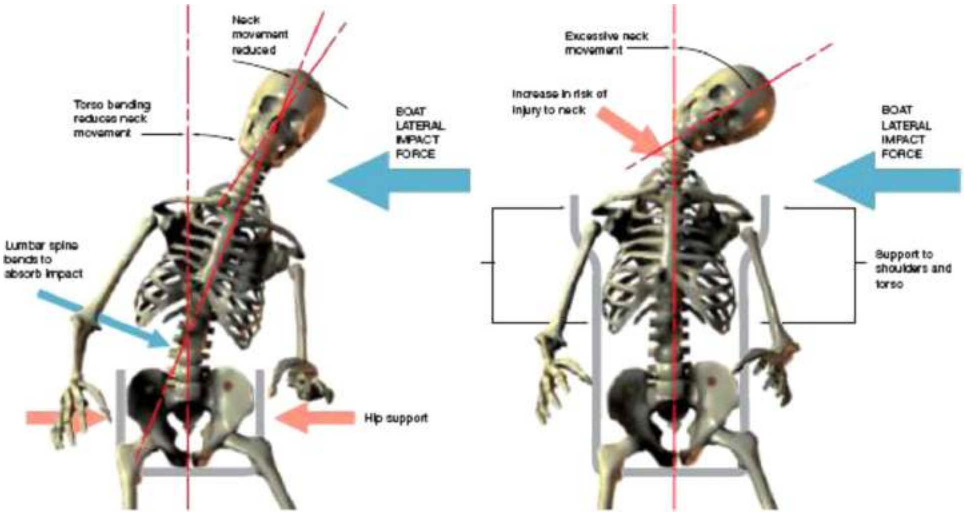
**Figure 14** Shows how numerical simulation of ship performance can be quite challenging. Even the simplest models require over a million mesh elements leading to long simulation times of over 5 hours even on multiprocessor computers (see online version for colours)




*Source*: Courtesy to Paterson et al. (2009)

The fourth challenge involves designing suitable seats. The careful design of these seats to maintain human's safety is quite challenging. The effect of a poor seat design is clear in Figure 15. To overcome the dangers that may result from a poor seat design, the following seat support issues should be carefully considered (see ABCD Working Group on Human Performance at Sea (www.abcd-wg.org), ABCD-TR-08-01 V1.0, High Speed Craft Human Factors Engineering Design Guide, 2010): The first factor is lateral stability. Crews often describe having lateral support as giving them a feeling of security. This support has the potential, if inappropriately designed, to enhance the risk of injury, particularly to the neck. Figure 15 demonstrates how the spine bends in response to a lateral acceleration when supported around the upper torso or shoulders, and at the hips. The second factor is seat cushion shock amplification effect. High-speed vehicles designers should be aware that soft comfortable seat cushions have the potential to amplify the magnitude of an impact. A soft cushion can rapidly compress and 'bottom out' in response to a severe shock as the air inside it is pushed aside and the foam matrix collapses. This can result in an effectively rigid surface providing minimal protection to the seat occupant. For lower magnitudes of vibration, foam cushions will act as mechanical filters, reducing vibrations at higher frequencies, perhaps over 20 Hz, but amplifying some lower frequencies. The foam material, thickness, contouring and covering material will all affect the response of a cushion. The third factor is restraint systems. Restraint systems can be required to restrict the movement of the occupants. In all weather lifeboats, restraints may be used to keep the occupants in their seats as the boat capsizes and self-rights, stopping them from being injured by falling out of the seats. Restraints also help to keep the occupant in contact with the seat, thus reducing the risk or magnitude of seat cushion shock amplification. Whilst the use of lap belts is now more widely accepted by the high-speed vehicles community, the use of shoulder harnesses is less accepted. This is due to the concern that if the upper torso is restrained, lateral forces will primarily act upon the upper cervical spine, resulting in a considerably worse injury.

**Figure 15** A graphical example of the effect of HSC seat lateral support on spine deflection (www.highspeedcraft.org) (see online version for colours)




## 3 Research-worthy solutions to biomedical engineering challenges

The research directions that we will discuss in this paper as directions that can offer candidate solutions to the main current biomedical engineering challenges can be summarised into five main directions.

### *3.1 Developing new fast efficient scalable multiphysics simulators*

A systematic solution to most biomedical engineering challenges can be found if we are able to formulate the challenge as a formal 'numerical' optimisation problem with the challenge of adverse effects or 'desired overcoming it' being the objective function we seek to minimise. By numerical optimisation, we mean that we do not need to have the optimisation objective function to be defined as an explicit closed formula of the optimisation-free variables. All that we need is to have some way of evaluating the objective function value corresponding to a set of optimisation variables values, i.e., all we need is some fitness function that computes the error in desired performance if these free variables are used in the design. The fitness (objective) function value corresponding to a certain set of variables values can be calculated using either a numerical simulator or a practical experiment. On the basis of the "variables values/corresponding fitness function value" information, any optimisation method can be used to iteratively update the design variables values until the desired performance is achieved. A simple numerical gradient procedure is as follows: For a given objective function *Objg*, a free variable *Par* should be updated using the following formula:

$$Par^{n+1} = Par^{n} - lr\frac{\partial Objg}{\partial Par}. \tag{1}$$

The gradient in (1) can be computed numerically as follows:

$$\frac{\partial Objg}{\partial Par_i} = \frac{Objg(Par_i + \varepsilon) - Objg(Par_i - \varepsilon)}{2\varepsilon} \tag{2}$$

where $\varepsilon$ is a small number. Typically, $\varepsilon = 10^{-6}$. $lr$ is an arbitrary constant.

This eliminates the need of having the objective function *Objg* defined as an explicit function of the variable *Par*.

However, especially with high-dimensional optimisation problems with a large number of free variables, a more sophisticated optimisation procedure such as BFGS or Particle Swarm Optimisation (PSO) should be used (Rao, 1984).

It is clear that a key aspect of the success of a formal numerical optimisation procedure is the existence of a reliable method of objective function value estimation corresponding to a set of design variables. Whether the application is a prosthesis design, new biomedical therapy experimentation, microrobot design or comfortable high-speed vehicle, the accurate evaluation of the objective function requires either a practical experiment (which is not always possible either for being expensive or not safe) or a multiphysics simulator. A multiphysics simulator is often needed to simulate the effect of a certain therapy or certain environmental conditions on the human body. As we pointed out earlier, the multi-scale nature of most biomedical engineering problems results in very large problems, which may at some cases approach millions of variables. Moreover, the complex geometry of the human body needs to be represented accurately. Thus, for a multiphysics simulator to be able to solve such problems without resorting to oversimplified models with approximations that may lead to inaccurate results, three methods can be used simultaneously. First, model order reduction (Rozza and Manzon, 2010) techniques can be employed to reduce the number of variables to only those that have the largest impact on the required postprocessing results. Typically, software tools like mor4ANSYS (Bechtold, 2005) use Arnoldi reduction algorithm, which can be viewed as a projection, from the full space to the reduced Krylov-subspace.

Second, Maxwell's equations are known to be form invariant (Ward and Pendry, 1996). This means that a coordinate transformation can be interpreted simply as a change in material properties tensors, while the equations remain unchanged. Formally, speaking:

If the following coordinate transformation used is:

$$u = q_1(x,y,z), \quad v = q_2(x,y,z), \quad w = q_3(x,y,z). \tag{3}$$

Maxwell's equations under this coordinate transformation become:

$$\overline{\nabla} \times \overline{\tilde{E}} = -\tilde{\mu}\mu_0 \frac{\partial \overline{\tilde{H}}}{\partial t}, \quad \overline{\nabla} \times \overline{\tilde{H}} = \tilde{\varepsilon}\varepsilon_0 \frac{\partial \overline{\tilde{E}}}{\partial t} \tag{4}$$

where

$$\overline{\tilde{H}} = (Jac^T)^{-1}\overline{H}, \quad \overline{\tilde{E}} = (Jac^T)^{-1}\overline{E} \tag{5}$$

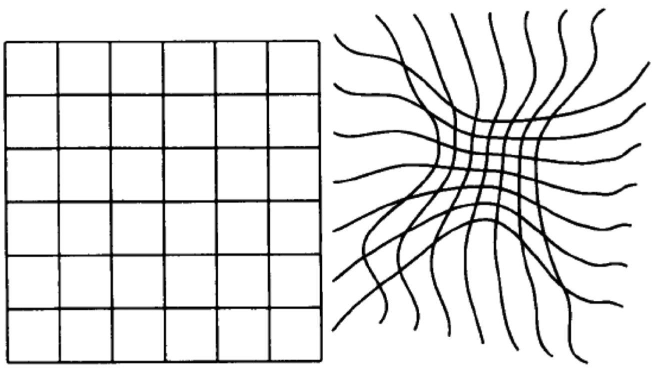
and

$$\tilde{\varepsilon} = \frac{Jac\varepsilon Jac^T}{(\det(Jac))}, \quad \tilde{\mu} = \frac{Jac\mu Jac^T}{(\det(Jac))} \tag{6}$$

where the Jacobian matrix is defined by: $Jac_{ij} = \partial q_i / \partial car_j$, $(car_1 = x, car_2 = y, car_3 = z)$, $\overline{E}, \overline{H}$ are the electric and magnetic field, respectively. $\tilde{\mu}$, $\tilde{\varepsilon}$ are the effective magnetic permeability and electric permittivity that 'appear' to have 'absorbed' completely the effect of the coordinate transformation, respectively.

It is clear from the above-mentioned equations that two different things can lead to exactly the same field solutions $\tilde{E}$, $\tilde{H}$ 'shape'. The first is making a coordinate transformation and so the new axes against which $\tilde{E}$, $\tilde{H}$ are plotted are the $q_1$, $q_2$, $q_3$ axes. The second is that we remain in the same $x, y, z$ space but we replace material properties with $\tilde{\varepsilon}, \tilde{\mu}$. Most physical laws can be transformed into an invariant form (Navier Stoke equations, for example, which govern fluid flow). In a multiphysics simulator using these invariant forms, there is no need to define a complicated curvilinear grid that well represents a complex geometry. Figure 16 shows how equations form invariance can be used to solve a numerical simulation problem on a distorted mesh. Simple cubic lattice points in one-coordinate system (left) maps into a distorted mesh in the other coordinate system (right). Choosing the coordinate transformation correctly we can control a mesh tailored to a particular problem requirement (Ward and Pendry, 1996). Because of equations form invariance, this corresponds to only changing the effective material tensors, while exactly the same Maxwell's equations are solved. Thus, a single software code can be used for all types of meshes.

**Figure 16** Shows how Maxwell's equations form invariance can be used to solve a numerical electromagnetic problem on a distorted mesh. Simple cubic lattice points in one-coordinate system (left) maps into a distorted mesh in the other coordinate system (right). Choosing the coordinate transformation correctly we can control a mesh tailored to a particular problem requirement. Due to Maxwell's equations form invariance, this corresponds to only changing the effective permeability and permittivity tensors, while exactly the same Maxwell's equations are solved. Thus, a single software code can be used for all types of meshes



*Source:* Courtesy to Ward and Pendry (1996)

Although the above-mentioned methods have been known for years, they are still underutilised in commercial solvers. Their use has been limited to custom codes generated by users for special applications. With biomedical applications, however, developing a custom code for a finite element or finite volume method is not easy. Therefore, the author and her colleagues (Elkamchouchi and Abouelseoud, 2011, Using Dynamic Systems Modelling Techniques and Spatial Space Methods for Simulating and Controlling Partial Differential Equations Solutions, submitted to IEEE Antennas and Propagation Magazine Education Column) are currently investigating an alternative method that appears to be promising from the point of accuracy and ease of programming. The method is a continuous state space design-oriented simulation technique. Formulating the spatial–temporal problems associated with biomedical engineering within a state space framework (where the variables at each spatial location represent state variables) paves the road to develop easy-to-program simulators that are capable of not only simulating the system but also optimising it. This is because they can borrow methods from control systems design techniques to control the desired solution. The method discretises the spatial derivative using finite difference approximation, while the time derivatives are left intact without discretisation. This leads to a system of ordinary differential equations in the form:

$$\dot{X} = AX + Bu. \tag{7}$$

$X$ is the state space vector. $A$ is the state space transition matrix, which contains the finite difference coefficients. $B$ is the input excitations coefficients matrix and $u$ is the input excitation.

This system can be readily solved using Runge-Kutta method, which is both accurate and very easy to program. The solution to this system will be the value of the state vector $x$, which contains all the state space variables, with time. These variables are actually the PDE system variables values at each point in space, i.e., the problem solution.

### *3.2 Developing new suitable actuation strategies*

We will discuss actuation solutions related to four biomedical engineering disciplines. It will be noted that smart material technology offers a suitable common solution to most biomedical engineering applications.

Smart materials are often called limited induced strain materials. The smart materials that are of special interest to biomedical applications include Shape Memory Alloys (SMA), piezoelectric ceramics, piezoelectric polymers and the Ionic Polymers Metal Composites (IPMC). Generally, SMAs return to their original shape after they are heated even if they undergo shape change (Lee et al., 2004). This is called shape memory effect (see Figure 17). Shape memory effect occurs as the result of a change in the atomic crystal structure of the alloys by a temperature change: austenite phase at a high temperature and the martensite phase at a low temperature. This kind of simple actuation principle is easy to be realised. The voltage applied to an SMA wire leads to current flow, which leads to the desired heating effect. Thus, an SMA actuator can be controlled simply by varying the applied voltage just like with muscles. Thus, SMAs can be thought of as some sort of artificial muscles. Similarly, piezoelectric ceramics, piezoelectric polymers and the IPMC materials respond with an induced mechanical strain under the application of an electric field and respond with an induced charge variation when mechanical pressure is applied (Penella, 2005). In principle, any of these materials can be used as artificial muscles. Penella (2005) offers a comprehensive study of the differences between these materials. We will focus on SMA-based actuators in particular. SMA has the advantage of low driving voltage. However, straight SMA wire has some problems with small displacement and difficulty to provide bias force, the so-called deformation force. Therefore, an SMA spring is often used to compensate these disadvantages. To design a two-way linear actuator, which moves back and forth, the deformation force is needed because the SMA memorises only the shape at the high temperature. A bias spring (steel spring) can be used to provide the deformation force as depicted in Figure 18. The bias spring is stretched when the left SMA spring is heated. At the same time, deformation energy is stored in the steel spring. Then, the energy deforms the SMA spring to its initial length when it cools. Instead of the bias spring, one more SMA spring can be used to provide the deformation force. However, it requires additional power to operate. Therefore, the actuator with a bias steel spring has advantages of low power consumption and simple structure.

**Figure 17** An illustration of basic Shape Memory Alloys training: (a) original shape; (b) adding a reversible deformation; (c) heating the sample and (d) cooling it again (see http://en.wikipedia.org/wiki/Shape_memory_alloy) (see online version for colours)

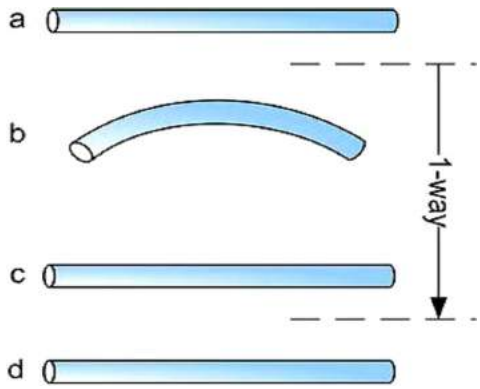
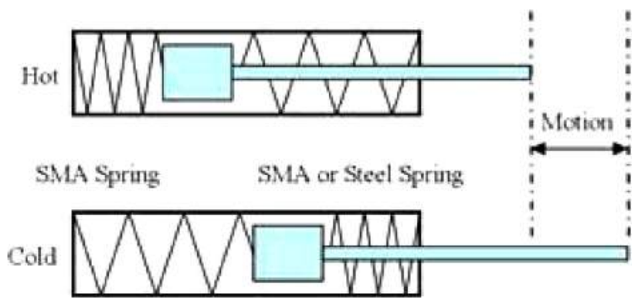



**Figure 18** The two-way linear actuator using SMA spring in Lee et al. (2004) SMA actuator (see online version for colours)



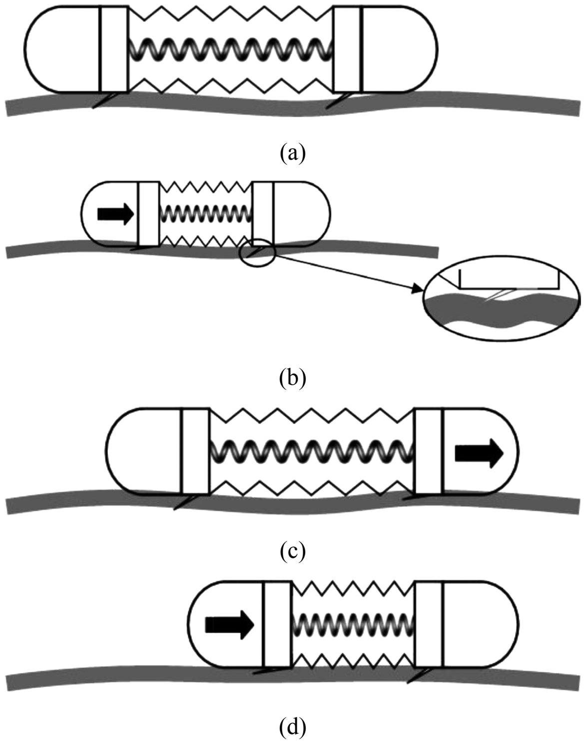

In case of artificial mobility prostheses, the adaptability to the form and size of the grasped objects can be achieved by articulation of the phalanges, coordination of the phalanges of each articulated finger, coordination of the fingers, especially, opposition and the coordination of the thumb. Ensuring these functions through tendon-driven mechanisms leads to the following advantages: lightweight, small size, actuators can be installed at a certain distance, low backlash, no shocks, overloading protection and good efficiency. The small size of the tendons permits large bending radius and thus large flexion-extension of the fingers. More, the tendon-driven mechanisms offer a gentler grasping compared with linkage-based pretension devices. Figure 19 shows a prototype of a two-finger prosthetic hand module (Mândru et al., 2008). Each finger has 1 DOF. An actuator based on SMA drives the finger corresponding to the index with two-antagonist helical spring active element, through tendon cables. Three parallel axis joints provide flexion-extension of the phalanx. The finger corresponding to the thumb is actuated via an actuator based on shape memory (SMA) wires. Both fingers are actuated by differential actuators. The drive and the control systems were also designed and developed.

**Figure 19** An artificial hand prosthetic device using SMA wires (see online version for colours)

*Source*: Mândru et al. (2008)

With microrobots, combining bioinspired actuation mechanisms with smart material technology can help with designing microrobots suitable for active diagnosis applications. Lee et al. (2004) and Kim et al. (2004) provide an interesting example. The locomotion mechanism is inspired from earthworm and is implemented using shape memory technology. An earthworm's body is made up of segments. On each segment, except the first and the last, there are pairs of tiny bristles called setae that help the worm move on the ground. The worm crawls by elongating to push the fore and by contracting to pull the hind part. The worm has two kinds of muscles used to crawl. Circular muscles, surrounding the body, can make the body shrink or expand radially. Longitudinal muscles, mounted along the length of the body, can shorten and spread out the length of the worm. If the circular muscle expands, the setae are erected and then they prevent the body from slipping. The longitudinal muscles play a two-way linear actuator role and the setae play a clamping device role. This mechanism is simple but effective. Such mechanism enables the earthworm to move on any environments. Figure 20 shows this same locomotive principle have been implemented in Lee et al. (2004) microrobot. Silicone bellows act as a bias spring to provide deformation force. The front needles clamp a contact surface and the rear body slides forward when SMA spring is contracted by heating. After the contraction of the SMA spring, the deformation energy of the silicone bellows makes the SMA spring elongate when it cools. At that time, the rear needles clamp the contact surface and the front body slides forward. Finally, the bellows' spring force is equal to that of SMA spring as initial equilibrium state. As the step from (a) to (d) in Figure 20 is repeated, the microrobot can move forward.

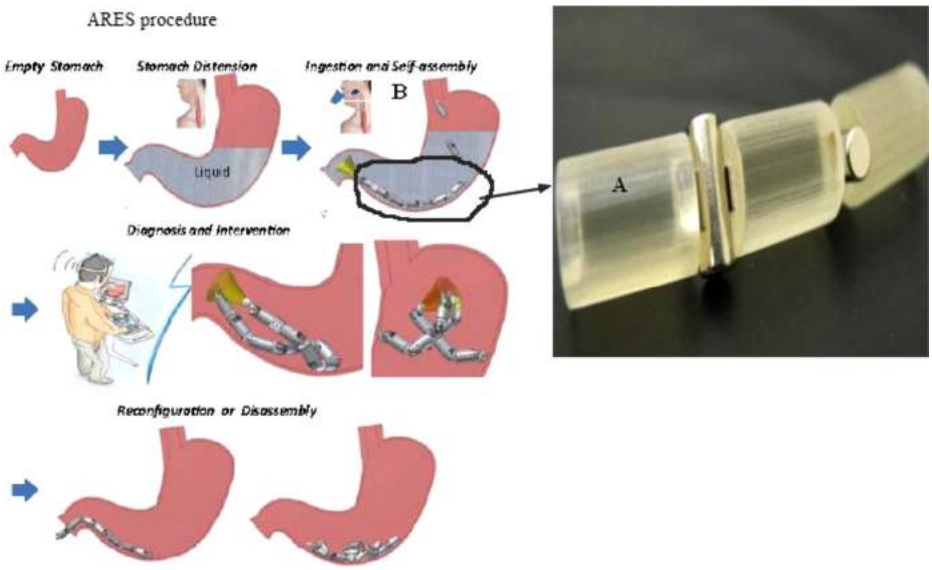
**Figure 20** The principle of locomotion in Lee et al. (2004): (a) initial state; (b) retraction state; (c) elongation state and (d) retraction state



The earthworm locomotion is not the only bioinspired useful locomotion. Snake like (Kassim et al., 2006), biomimetic swimming (Edd et al., 2003; Zhang et al., 2006) and amoeba-like (Hong, 2006) locomotions are all interesting worthy of careful investigation.

The current trials have not yet been sophisticated enough to reach commercialisation of active diagnosis and surgery microrobots. Combining these actuation mechanisms with principles from reconfigurable robotics (Nagy et al., 2009; Dorigo et al., 2004) is more likely to result in the degree of autonomy needed for active diagnostic and surgical procedures. The idea of reconfigurable microrobots has already been implemented by Nagy et al. (2009). To overcome the inherent limitation of a single robotic unit, an Assembling Reconfigurable Endoluminal Surgical (ARES) system is proposed (ARES, 2009, http://www.ares-nest.org). The surgical procedures using this kind of system are shown in Figure 21 (Nagy et al., 2009). In these procedures, miniaturised robotic modules are ingested and assembled in the stomach cavity. Thus, the size of a module should be such that it is ingestible, and at least as small as the current commercial capsule endoscopes (11 mm in diameter and 26 mm in length). During the assembly procedure, the stomach cavity can be filled with a liquid to distend the stomach up to 1.4 l and to aid in the self-assembly of the robotic modules either in the liquid or on its surface. The assembly needs to be completed before the liquid naturally drains away, which is in 10–20 min. The assembled robot can change its configuration according to the target location and target task, while the position of each module is monitored by a localisation system and the robotic structure is manoeuvred via wireless bidirectional communication with an external console operated by the surgeon. After the surgical task in the stomach cavity is completed, the robot might completely disassemble into individual modules. It could also reconfigure itself into another topology, e.g., into a snake-type structure, and move on to examine, for example, the small intestine, which cannot be reached by an endoscope. A possible application in this case would be the detection of bleeding sites in the small intestine.

**Figure 21** Nagy et al. (2009): (a) ARES system and (b) associated surgical procedure (see online version for colours)




However, the system is still a prototype and suffers from lack of the desired degree of autonomy as well as issues like biocompatibility and guaranteed reliable locomotion. The type of reconfigurable robots that we need to implement to achieve the desired dexterity and intelligence suitable for active diagnosis and complex surgical procedures is that reported by Dorigo et al. (2004) (see Figure 22). Swarm robotics is an emergent field of collective robotics that studies robotic systems composed of swarms of robots tightly interacting and cooperating to reach their goal. On the basis of the social insect metaphor, swarm robotics emphasises aspects such as decentralisation of the control, limited communication abilities among robots, use of local information, emergence of global behaviour and robustness. In a swarm robotic system, although each single robot of the swarm is a fully autonomous robot, the swarm as a whole can solve problems that the single robot cannot cope with because of physical constraints or limited capabilities. The disadvantage of such a system is in its size. However, if the swarm robots are made of microrobots with bioinspired locomotions implemented using smart material technology, the size will be reduced to the extent that is suitable for biomedical applications. Thus, we believe that a combination of swarm robotic system made of units like the inch-worm microrobot (Lee et al., 2004) within an ARES-like (Nagy et al., 2009) framework can solve the microrobot surgeon challenges.

Smart-material-based actuators can also help with designing more comfortable vehicles (for example, roll and pitch damping on ships can be controlled and reduced using stabilisers made from smart materials to improve comfort and sea keeping (Shenoi et al., 2009)). The structures using this technology are termed as smart structures (Monner, 2005). A smart structure involves five key elements: structural material, distributed actuators and sensors, control strategies and power-conditioning electronics. With these components, a smart structure has the capability to respond to changing environmental and operational conditions (such as vibrations and shape change). Microprocessors analyse the responses of the sensors and use integrated control algorithms to command the actuators to apply localised strains/displacements/damping to alter the elasto-mechanical system response. Actuators and sensors are highly integrated into the structure by surface bonding or embedding without causing any significant changes in the mass or structural stiffness of the system. To do so, a fundamental part of smart structures are solid state actuators and sensors based on smart materials. For active noise and vibration reduction tasks in smart-structures technology, piezoelectric ceramics are first choice. They generate large forces, have fast response times, are commercially available as fibres, patches and stacks and allow integration into structural components.

**Figure 22** An assembly of swarmbots connecting to take a shape suitable for a particular application (see online version for colours)

*Source*: Dorigo et al. (2004)

## 3.3 Developing new powerful learning algorithms

Intelligence is quite desirable in several biomedical engineering branches. It is required to in an artificial prosthesis, microrobots as well as automatic diagnosis systems. Artificial Neural Networks (ANNs) (Gonzalez, 2008) can be used to add this intelligence to an application. However, we need a new powerful learning (training) algorithm to suit the challenges associated with biomedical applications. Particularly, we need algorithms to be developed with three main features. The first is transparency. By transparency we mean that the reasons behind the ANN decisions should be clear to the system designer. This is important to gain confidence in the ANN reliability, which cannot be compromised in applications such as biomedical engineering where human lives are at stake. Therefore, fuzzy logic can be used to translate the gained knowledge in the trained weights and biases into if–then rules. If any inconsistencies are detected, more data can be gathered to improve the ANN 'understanding' of the problem and guarantee that it is generalised to an acceptable degree. The second feature is online adaptability. Consider for example the development of an intelligent prosthesis. The successful development of an online training algorithm for such prosthesis relies on the accurate capturing of high-level cognitive goal signals using suitable sensors (Guigon et al., 2007) (i.e., the signal issued by the brain when the subject attempts to move his or her limb a certain movement). If the error between desired move (encoded in the high-level cognitive input from the brain corresponding to a goal-intended move) and the actual move (as detected from feedback from sensors attached to the artificial limb or feedback from the muscles in case of healthy natural limbs) exceeds a certain level, online adaptation is triggered. Numerical optimisation techniques/non-linear control laws can be used to retune the ANN parameters (weights and biases) with the detected error being the objective function that is to be minimised. The third feature is real-time behaviour. This is important for both prostheses and microrobots. Naturally, an ANN exhibits this advantage. Although the training of an ANN may take a long time, running an ANN is instantaneous. However, to make sure that we will not need to re-train the ANN online frequently, a powerful initial offline training stage is necessary. This can be achieved using a multiphysics simulator in the training loop. For example, for a microrobot application, numerical optimisation with a multiphysics simulator in the loop can be used to teach an ANN the required mapping between available sensory inputs and the desired series of actions that is to be carried out by the microrobot and the corresponding correct input to its actuators. Initially, the ANN weights and biases can be assigned random values. The output from the ANN is fed into a multiphysics simulator, which includes both the microrobot and dynamics and body model. The multiphysics simulator results are used to calculate the error in performance. This error will be taken as the objective function that the numerical optimisation procedure is to find the values of the weights and biases that minimises it. Note that the advantage of ANN-based control over direct action tuning (direct action optimisation) is that you do not have to do the optimisation search for optimal action each time. ANNs are only retrained if their suggested actions lead to large errors in performance.

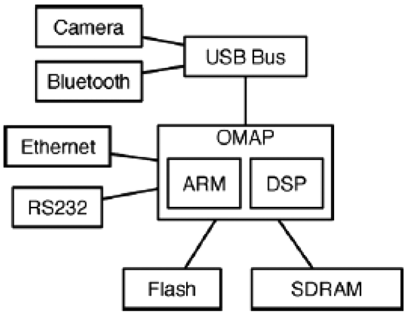
### *3.4 Developing new biofriendly powering methods*

RFID-Like Rectennas can be used for wireless powering of artificial prostheses (Tikhov et al., 2007). These are miniaturised antennas that capture electromagnetic radiation and transform it into DC power suitable for operating electronic devices. The technique is already employed in RFID tags. However, the range of frequencies that is safe to apply for remotely powering a device inside a human body makes designing a rectenna with a suitable size a challenge. Several other alternative energy-harvesting techniques may be considered. The flow of the blood as well as the electrical spiking signals within the body, heart rhythm, the change in temperature from part to another all represent forms of energy that may be harvested if suitable sensors are designed specifically for this task. This may be the safest way to power microrobotics and invasive implants if it is designed properly.

### *3.5 Powerful Miniaturised Processing Tools*

The processor proposed by Tsai et al. (2009) (see Figure 23) in particular seems to be quite promising for both vision and mobility prosthesis, although it has been proposed in context of the former. It is based on dual-core microprocessor architecture and runs the Linux operating system. At the heart of the processor is an OMAP5912 microprocessor (Texas Instruments, Dallas, TX, USA), which is primarily designed for embedded multimedia systems such as Personal Digital Assistants (PDAs), or portable medical devices. The OMAP5912 has a dual-core architecture composed of an ARM9TDMI general-purpose reduced instruction set microprocessor designed by ARM Limited (Cambridge, UK) and a TMS320C55x digital signal processor (DSP, Texas Instruments). During normal operation, the ARM core runs in host mode. It interfaces with most hardware components, executes the operating system and delegates mathematically intensive operations to the DSP. The DSP has a separate clock, so it operates independently of the ARM core, allowing for parallel processing. The processor has SDRAM and flash memory for data storage. An Ethernet port allows the system to be connected to a network. Peripherals may be connected to the device using RS232 serial or USB. The OMAP5912 has dedicated hardware pins for attaching a CCD camera.

**Figure 23** The OMAP-based processing unit in Tsai et al. (2009)




**System hardware of the image processor. Peripherals are connected through USB. The image processor can communicate with other devices via Ethernet, RS232 and Bluetooth. Furthermore, flash memory and SDRAM are available for data storage.**

## *3.6 Developing new intelligent bio-optimised communication protocols*

In addition to conventional general solutions to communication systems problems in biomedical engineering, like advanced modulation techniques, fibre optics and using metamaterial technology to produce miniaturised broadband antennas (Miranda et al., 2009; Palandoken et al., 2009), new bio-optimised communication protocols can be an important asset. For example, in telemedicine/telesurgery over links like the internet, latency, blackouts, lost packets and error bursts are to be expected. However, if the semantics of the operation performed by the physician are included in an intelligent high-level error-correcting protocol, these effects can be compensated for and the system can execute safe actions depending on the current state of the operation until successful reconnection is re-established. Moreover, in telemetry applications where neuronal signals are transmitted from inside the body to a remote receiver for further processing as well as in some artificial prosthesis, the body of the patient is part of the communication channel. Coding techniques less-prone to the types of noise that are to be encountered in such a medium need to be considered and optimised using an accurate model of the body as the communication channel.

## 4 Conclusion

This paper offered a review of the challenges facing some of the most exciting and important biomedical engineering research fields, discussed the current solutions pursued by researchers and suggested several additional solutions to these challenges. The solutions included methods for improving multiphysics simulators performance, methods to add adaptability to artificial prostheses and microrobots as well as better actuation, energy-harvesting techniques and new bioriented communication protocols.

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