Improved Control Over the Movement of a Hand Prosthesis’ Fingers Using Nanosensor Implants

by

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Abstract

In the first part of this paper I shall describe some of the principles of nanotechnology, a number of its current ‘building blocks’ and its possible applications in medicine. In the second part I shall propose how implanting a series of nanosensors into the residual muscle tissue of a limb end after an amputation of the hand could be used to control individual mechanical fingers of a hand prosthesis. This would greatly improve the functionality of a prosthesis that, currently, only allow the opening and closing of all fingers together. My design would also provide greater fine-motoric control and take less time to adjust to compared with currently available models.

Introduction

‘Nanotechnology’, a term first coined in 1974 by Norio Taniguchi from the Tokyo Science University to “describe the precision manufacture of materials with nanometer tolerances”[1], now refers to “technological developments on the nanometer scale, usually 0.1-100nm” [2], i.e. 0.1-100 x 10^-9 meters. For comparison, a mitochondrion, the structure of which can be made visible at the outermost magnification factor of current electron microscopes, ranges in size from 0.5-1µm in length [3], i.e. a mitochondrion is still a hundred times larger than the scale nanotechnology works at.

Nanotechnology seeks to investigate “individual molecules, such as proteins and the polynucleic acids RNA and DNA” with devices such as the atomic force microscopy and optical laser tweezers [4] as well as to manufacture “products that are made from atoms”[5].

Nanotechnology promises the discovery of materials with novel phenomena and properties, cheaper production cost and medicine on a molecular scale. [6]

Due to the small scale, physical properties change in three main areas:

1) Quantum-mechanic behaviour bringing about novel technical physics through changes in, magnetism, electrical conductivity, colour etc.;
2) Increased surface area with novel chemical processes “through changes in melting and boiling point, chemical reactivity and catalytic yield” and

Point 3) involves nanostructures to self-assemble, reflecting the self-assembly of molecules in living cells, e.g. in protein synthesis. [8]

Complex structures are build up from simpler units, such as super-crystals from nanoparticles. [7] This is the reverse process to the increasing miniaturisation in technology during the last decades in areas such as computer technology. Instead of making things increasingly smaller, nanotechnology makes it possible to build things up from individual atoms.

Some of the basic building blocks of nanotechnology so far are nanotubes (made of carbon atoms, arranged as alternate hexagons and pentagons, forming a hollow tube
T-junctions between nanotubes [10], nanogears [11], SnO$_2$ nanoribbon (making an ultra sensitive nanosensor for various gases, such as NO$_2$, O$_2$, and CO [9]), and spherical molecular structures called buckminsterfullerenes or bucky balls [12] as part of molecular shuttlecocks showing “liquid-crystal behaviours”. [13]

Some scientists hope to build nanorobots and nanocomputers with these basic building blocks. For instance, Robert A. Freitas Jr. (1999) discussed the future production and use of artificial red blood cells [15] and white blood cells (2001) [16].

In human medicine many diseases and ill-health conditions have their causes on a cellular and molecular level, e.g. viral and fungal infections, inhaled particles causing cancer through smoking and genetically conditioned diseases, e.g. cystic fibrosis [17]. Being able to address the mal-functioning cells specifically with a treatment, rather than the whole organism (including the majority of well-functioning cells) as is currently done with drugs applied to the whole body (e.g. with chemotherapy in cancer treatment [18]), would reduce the amount of drugs needed for treatment and reduce thereby its risk factors and side effects. Nano-biosensors could possibly recognise and analyse the cancerous cells and treat them, e.g. inject a toxic to kill them. [19]

Of particular interest for the discussion of this paper are nanosensors, MEMS (Micro Electro-Mechanical Systems) and NEMS (nanoelectromechanical systems). MEMS are currently used in automobiles, biomedical and electronics to detect pressure changes, e.g. in inkjet printers, which use piezoelectrics or bubble ejection to deposit ink on paper, accelerometers in modern cars for airbag deployment in collisions, car tire pressure sensors, and disposable blood pressure sensors. [20, 21] Of equal interest is nanowire (a wire of dimensions of the order $10^{-9}$ meters which may be used in future computing devices) which I shall propose to use too. [14]

In the following section I shall discuss the use of nanosensors to measure voltage changes in contracting muscle tissue of a limb end to control the motoric of a terminal device (such as an artificial hand) by the amputee.

**Discussion**

**Existing Systems**

For the purpose of this paper I am going to restrict my discussion on myoelectric below-elbow prostheses as this level of amputation provides sufficient residual muscle tissue necessary for my design. However, similar designs for prostheses of other body parts could be based on the same technology.
In general, functional prostheses fall into two categories: body-powered prostheses (cables) and myoelectric prostheses. [22] Typically, it has the following features:

“Myoelectric prostheses create movement based on electrical charges that naturally occur during muscle activation. Electrodes are placed on the surface of the muscle flexor and extensor to detect the electrical output. The outputs range from 5-200 microvolt and are then amplified to control a motor. That motor has the ability to control hand, wrist, and elbow movement depending on the specific design chosen. The device is powered by a rechargeable battery source.” [23]

This means that, currently, the motor may control only one (commonly a grip) of a range of pre-set movements, and not several in conjunction with one another. Also, these designs typically take the amputee several weeks to learn to control because different muscles need to be associated with the mechanical fingers’ (digits) movement from the original ones.

**Suggested Improvement**

My design proposes to manage the controlled flexing and extending of every digit individually using nanosensors implanted into the residual muscle tissue. Speaking about future prostheses, Hugh Herr pointed out in 2002, “Technologies such as BIONs and MEMS likely will play an important role in these systems.” [26]

**The Anatomy of the Lower Arm**
Anatomy of muscle fibres

Thousands of muscle fibres make up each particular skeletal muscle. The fibres are bound together by connective tissue through which run blood vessels and nerves. A number of fibres are controlled by one motor neuron which all contract fully when triggered. Muscle fibres are not capable of half contracting. The minimum unit of contraction, of all fibres activated by one neuron, is called the motor unit. The smaller the motor unit the more precisely controlled the motoric of the joints. In fingertips a motor unit contains about 10 fibres, whereas a calf muscle contains 1000-2000 fibres. [28]

The motor unit’s potential’s amplitude during contraction ranges between 0.3-0.2 mV. The duration of the amplitude change for a motor unit has been measured as 4-10 ms. [29]

I am proposing to implant a number of nanosensors into each muscle from the lower arm that either extends (extensor) or flexes (flexor) a digit, excluding intrinsic muscles of the hand controlling lateral movement. The nanosensors would register changes in voltage in the tissue when the fibres contract. I anticipate that learning how to use and control the mechanical digits of the prosthesis will be much briefer and give more refined control compared with current models as the muscles control ‘the same’ digits as before.

Even at rest, most of our skeletal muscles are in a state of partial contraction, called tonus. Tonus is maintained by the activation of a few motor units at all times even in resting muscle. As one set of motor units relaxes, another set takes over. [27] Using several nanosensors in each muscle enables the terminal device to distinguish between an increase in voltage caused by tonus and a willed contraction, as the likelihood of all motor units with a nanosensor contracting at the same time due to tonus decreases with an increase in the number of sensors per extensor or flexor.
The Nanosensor

The size of the nanoelectrodes of the proposed sensor could be in the range of 100nm. Since the current peak is directly proportional to the electrode size, however, reducing the electrode surface area brings about a problem in sensitivity. I am therefore suggesting to use an area of interlaced nanoelectrodes, increasing the surface area and the total size of the sensor to 50 µm, as described by Eric Finot [30].

Filaments, making up muscle fibres, contract by sliding over one another. They are 10-12 nm in diameter and 1.6 µm long. [31] The nanosensor would therefore cover an area of roughly 30 lengths and 4-5,000 widths of filaments, i.e. several muscle fibres.

Furthermore, the nanosensors would be made of an inert metal, such as gold, to avoid an immune or chemical reaction in the body’s saline environment. They would be connected with nanowire to the prosthesis’ voltage meter of the control unit and made of gold. At nanodimensions “the energy of the electrons going through a nanowire can assume only discrete values” [14], according to R. Landauer, 1989. [32] My design aims at continuous readings of voltage changes and I am therefore suggesting to ‘thicken’ the wire by weaving several strands together, similar to the making of a rope, thereby combining strength with flexibility and durability. This could provide continuous values by the nanowire.

The sensor (except for its electrodes) and the wire would be insulated with a coating of silicon rubber or PTFE, as described by Jerry Martyniuk for in vivo connections to biomedical implants, 1993. [33]

As the muscle strength varies from individual to individual, the nanosensors would be calibrated, setting a minimum threshold suitable to the amputee in question.

The voltage changes within each flexor and extensor would be registered and interpreted to power the prosthesis’ digits accordingly.
Conclusions

In summary, there are two major improvements over current prostheses designs achieved by my proposal.

Firstly, using biomedical nanosensors implanted in the residual muscle tissue of a limb end, the muscles of which are still able to contract and be controlled by the amputee, would greatly improve the functionality of current prostheses models by enabling the individual to control each finger’s movement individually.

Secondly, the learning period for mastering the control of such prosthesis would be minimised, as the same major muscle groups would be utilised as compared with before the amputation.

Future Improvements

Additionally, building MEMS and NEMS into the digits of the prosthesis that could detect pressure changes could make future improvements. They could then be connected to nanostimulators implanted into the muscle tissue to provide feedback. Thereby the motoric and control could be greatly refined. The amputee could directly control the speed of extension and flexion as well as the pressure for the first time.

Also, using the latest technique of anchoring prosthesis into the bone of the patient [34], the hand prosthesis could be anchored into the ulna and radius of the lower arm, providing pressure feedback through the living bone itself.

Limitations

The nanowires may prove not being durable and flexible enough for lasting use. According to Jerry Martyniuk the coating of silicon rubber proves to be somewhat stiff at the small scale and might not last longer than six months. [33] Further coating methods need to be developed.

Implanting the nanosensors along with the nanowires at the correct locations without damaging them is not solved yet. I anticipate that the present design of the nanoelectrode might still be too large to be comfortable to the patient for prolonged periods. Smaller designs of nanoelectrodes that are still able to take continuous readings in voltage changes would be desirable.
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