Abstract: A flexible muscle contraction sensor comprising at least one light source for emitting light into muscle, and at least one detector for detecting light scattered from the muscle.
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG). Published: — with international search report (Art. 21(3))
Muscle Contraction Sensor

Field of the Invention
The present invention relates to a muscle contraction sensor and in particular a flexible muscle contraction sensor.

Background of the Invention
Muscle contraction sensors are particularly useful in providing the input signals to trigger the movement of active prosthetic devices such as artificial limbs. In the present available technique of electromyography (EMG) direct contact for a sustained period to a muscle or, more precisely, to the nerve signals actuating the muscle, is made, and the patient is trained to contract such muscles in given patterns in order to actuate the prosthesis. This is challenging, as the electrical contact is unstable, and therefore the contraction needs to be sustained for long periods of time. Moreover, the muscles can contract according to two patterns, called "isotonic" (i.e., the muscle shortens, at a constant exerted force) and "isometric" (i.e., the muscle length remains constant). As an example, lifting a dumbbell involves isotonic contraction, and pushing against a wall requires an isometric contraction. EMG does not distinguish between isotonic and isometric contractions, and therefore part of the information potentially present in the muscle contraction to be used for prosthesis actuation, is lost.

Optical sensing muscle movement is an attractive alternative, particularly appealing as it is non-invasive. Optical sensors can distinguish between isotonic (constant force - e.g. lifting a weight) and isometric (constant distance - e.g. pushing against a wall) contractions. Recently, an optical sensor for estimating upper limb force level by sensing the optical density of the muscle bundle was proposed. In an article by Chianuara and Giardini (An electrooptical muscle contraction sensor; ISSN 0140-01 18, Medical & Biological Engineering & Computing, Volume 48, Number 7) a rigid electrooptical muscle contraction sensor based on inorganic LEDs and photodiodes is described. This works on principle of the detection of the back scattered light from the muscle when light is shone on the muscle tissue. It records muscle contraction by measuring the change between the light scattered in direction parallel and perpendicular to muscle cells. The device is large, thick and rigid, and so requires a form of support (strap, bandage, embedding in a rigid or flexible shell) in order to make
contact with the muscle. It requires both electronic and mechanical assembly to be manufactured, thus presenting a non-trivial cost.

Summary of the Invention

The present invention relates to a flexible muscle contraction sensor. In particular, the invention relates to a flexible optical muscle contraction sensor.

According to the present invention, there is provided a flexible muscle contraction sensor comprising at least one light source for emitting light into muscle, and at least one detector for detecting light scattered from the muscle. Preferably, four detectors are provided for detecting light scattered from the muscle.

The light source may comprise an organic material. The light source may be an OLED. The at least one detector may comprise an organic material. The detector may be an organic photodiode. Using organic optoelectronic devices as the light source and photodiodes in muscle contraction sensing allows the sensor components to be developed with solution processable methods, such as inkjet printing or coating techniques on large areas or in multipixelated arrays, thus significantly reducing size, complexity, cost, ease of wearing.

The organic light emitting diode (OLED) and the large area organic photodiodes may be prepared on thin indium tin coated polyethylene terephthalate (PET) substrates separately. An electronic circuit printed on the thin black plastic may be used to integrate the light source and detectors. For example, a thin black plastic substrate may be used to integrate an OLED as a light source and four organic photodiodes as detectors with complete sensor thickness lower than 2 mm.

The sensor may include a flexible substrate on which the at least one light source and at least one detector are carried. The flexible substrate may be black. The flexible substrate may be made of plastic. The at least one light source and at least one detector may be embedded in the flexible substrate.

The flexible substrate may include electrical connectors for allowing external electrical connection to the at least one light source and at least one detector.
Brief Description of the Drawings
Various aspects of the invention will now be described by way of example only and with reference to the accompanying drawings, of which:

- Figure 1 is a schematic view of muscle in various different states;
- Figure 2 is a block diagram of a sensor system for measuring / detecting muscle contraction;
- Figure 3 is a plan view of a flexible sensor of the system of Figure 2 in place on a patient's muscle;
- Figure 4 is a photograph of a mask for making a flexible printed circuit for use in the flexible sensor of Figure 3;
- Figure 5 is a photograph of a flexible sensor of the system of Figure 2;
- Figure 6 is a circuit diagram of the control circuitry, and
- Figure 7 is a photograph of a robotic arm that has a single mechanical arm with six joints and an end effector at its tip.

Detailed Description
Muscles are shaped as elongated myofibril fiber along the main muscle axis. These myofibrils consist of thick filaments and thin filaments as shown in Figure 1. During muscle contraction thin filaments surrounded the thick filaments and all of them are pulled inward simultaneously. As a result the muscle becomes shorter and dense due to shortening and overlapping of each filament. In this scenario, the muscle tissue will scatter light anisotropically. In particular, the light scattered in a direction perpendicular to the muscle fibers differs from the light scattered parallel to the fibers. As the muscle contracts, the fiber aspect ratio changes, and the scattering anisotropy varies accordingly. The sensor of the invention is designed to detect such variation, responding to contraction with intrinsic rejection to non-anisotropic signals, such as those resulting from patient movement.

Figure 2 shows a schematic view of a sensing system. This has a flexible probe head connected to an electronic circuit for controlling and driving the probe. Figure 3 shows the flexible probe head in more detail. This has a point source of light for shining light on the muscle. Four photodiodes are positioned around the source to detect the back scattered signal from the muscle fibers. The photodiodes and equally spaced around the source. A red light source was chosen at 600 nm and longer wavelengths so that light can penetrate deep enough in the muscle tissue. The signals from the two pairs of
the photodiodes are subtracted and fed into a feedback loop which stabilises the output and reduced noise. The electronic box was designed to have a continuous LED driver and appropriate photodiodes preamplifier.

The light source is an organic light emitting diode source. The photodiodes are organic photodiodes. They are embedded on a flexible substrate that can readily be applied to a patient’s body. By using a flexible material, the sensor can conform to the patient’s body, thereby improving contact and so the quality of the measurements. The casing for the probe head is designed to minimise the cross talk. As an example, the casing may be a flexible polyethylene terephthalate (PET) material.

The organic light emitting diode source and organic photodiodes were prepared on 12 mm x 12 mm PET substrates with indium tin oxide (ITO) top anode layer of 120 nm. The substrates were carefully cleaned by ultrasound-assisted cleaning in water, acetone and isopropanol for 15 minutes. The organic layers on top of the anode were prepared by spin coating inside the glovebox with oxygen and water content less than 0.1 ppm. All the organic materials and solvents were used without further purification. For the organic photodiodes polymer thieno[3,4-b]thiophene/benzodithiophene (PTB7) was bought from 1 Material company and (6,6)-Phenyl C71 butyric acid methyl ester (PC70BM) was bought from Solenne BV. The additive 1, 8-octanedithiol (DIO) was bought from Fluka. For OLEDs the organic active layer Superyellow (PDY132) was bought from Merck-Covion. All the solvents used were bought from Sigma Aldrich. The buffer layer poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS) was bought from Clevios and was used without further purification.

The organic photodiode structure was: ITO coated PET, a 40 nm layer of PEDOT: PSS by spin coating at 4000 rpm, a 90 nm layer of polymer thieno[3,4-b]thiophene/benzodithiophene (PTB7) with PC70BM and 3% 1, 8-octanedithiol (DIO) additive as active layer by spinning at 1000 rpm followed by a layered metal cathode consisting of 20 nm Calcium and 200 nm Aluminium by using a thermal evaporator. The blend ratio of the polymer PTB7 and PC70BM was kept 1:1.5 with total concentration 25 mg/ml in the 1, 2, 4 dichlorobenzene solvent. Each photodiode consisted of a single pixel of dimensions 6 mm x 6 mm. The OLED structure was: ITO coated PET, a 40 nm layer of PEDOT: PSS by spin coating at 4000 rpm, a 70 nm layer of polymer Superyellow as a active layer by spinning at 1200 rpm followed by a layered
metal cathode consisting of 20 nm Calcium and 200 nm Aluminium by using a thermal evaporator. The SY polymer concentration was 5 mg/ml in chlorobenzene solvent. OLED source consisted of a single pixel of dimensions 3 mm x 3 mm. The active area of the photodiodes and OLEDs was encapsulated by PET substrate using UV curable epoxy (Norland 68) by shining 365 nm from low power UV lamp for 2 minutes. The total thickness of the devices was less than 1 mm. The 600 nm long pass gelatine filter was used to select the red light emission from the broad light emitting light source.

The organic light source and organic photodiodes are integrated onto a flexible circuit, thereby to form the fully flexible sensor head. The flexible circuit is preferably made of a black material to prevent guiding of light along the material from the source to any of the detectors. The design of the photomask to print the required circuit on plastic substrates was prepared by APM graphite software. The photomask was prepared by cutting Perspex PMMA sheets of thickness 3 mm using the laser cutting machine from CTR lasers UK. The printed circuit was designed by APM graphite software and the separation between the source and the photodiodes was chosen 2 cm so that light can penetrate deep enough inside the tissue. A 400 nm thick Aluminium was deposited on the plastic substrates using the photomask inside the thermal evaporator.

Figure 4(a) shows photographs of the Aluminium contacts on the black flexible substrate prior to inclusion of the optical components. The OLED source and all four photodiodes were integrated on the printed circuit using silver conductive epoxy circuitworks CW2400 to provide contacts to the devices, as shown in Figure 4(b). Thin copper wires were used to established contacts between the flexible probe head and the multicore cable which connects the photodiodes and the OLED to a photodiode preamplifier and a continuous-wave OLED driver. The final sensor may be covered or encapsulated in a flexible protective material. Figure 5 shows the complete flexible optical muscle contraction sensor in a bent configuration to illustrate the extent of its flexibility.

The amplitude of the scattered light from muscle tissue is low, only 1% of that of the injected light so a preamplifier is needed to get the good signal to noise of the collected signal from the sensor. The electronic design of the amplifier is based on the design of the inorganic sensor of the above mentioned article by Chianuara and Giardini. A simplified schematic diagram of the amplifier is shown in Figure 6. Photodiode 1 and 3
are connected opposite to photodiode 2 and 4. The resulting current $I_1$ and $I_2$ are of opposite signs and each of them is connected to a current amplifier and a current controlled switch. An inverter connected between the two switches ensures only one switch is on at a certain time. The background, filtered with time constant 'R-C2' is compared with a triangular signal to balance the photocurrents. The photocurrent is finally integrated on the capacitance 'C1' to yield the output signal. The amplification is controlled by the integrator. In practice, the actual electronic circuit may have multiple capacitances (C1) to achieve optimum gain.

The complete sensor was tested with DENSO robotic arm (Model VP-6242G, DENSO Wave Inc., Japan) to check its feasibility to be used as input signals in prosthetic devices. The robotic arm consists of a single mechanical arm with an end effector at its tip. It has 6 distinct joints, which are shown as the numbers in Figure 7. The signal collected by the probe is first sent through the electronic amplifier and then converted to digital signal by the I/O convertor. The digital signal is finally sent to the computer and analysed by the programme. The feasibility of the sensor was demonstrated by actuating a robotic arm on the signal detected on a volunteer, thus imitating on the robot the contraction of the volunteer's real arm in both isotonic and isometric contractions scenario.

The present invention provides a route to develop a thin, flexible, lightweight and potentially low cost muscle contraction sensor.

A skilled person will appreciate that variations of the disclosed arrangements are possible without departing from the invention. For example, although in the example described the control circuitry, such as shown in Figure 6, is provided separately from the flexible sensor, it could be provided as an integral part of the sensor, for example it could be formed on the flexible substrate. Equally, a signal processor could be provided integrally with the sensor. The signal processor could control the light source and/or process signals received from the detectors. Data could be transmitted wirelessly to a remote station, or a small flexible screen could be provided for showing results. Accordingly the above description of the specific embodiment is made by way of example only and not for the purposes of limitation. It will be clear to the skilled person that minor modifications may be made without significant changes to the operation described.
Claims

1. A flexible muscle contraction sensor comprising at least one light source for emitting light into muscle, and at least one detector for detecting light scattered from the muscle.

2. A flexible muscle contraction sensor as claimed in claim 1 comprising four detectors for detecting light scattered from the muscle.

3. A flexible muscle contraction sensor as claimed in claim 1 or claim 2 wherein the light source is arranged to emit light of wavelength in the range 500 nm to 700 nm, for example 600nm.

4. A flexible muscle contraction sensor as claimed in any of the preceding claims wherein the light source comprises an organic material.

5. A flexible muscle contraction sensor as claimed in claim 4 wherein the light source is an OLED.

6. A flexible muscle contraction sensor as claimed in any of the preceding claims wherein the at least one detector comprises an organic material.

7. A flexible muscle contraction sensor as claimed in claim 6 wherein the detector is an organic photodiode.

8. A flexible muscle contraction sensor as claimed in any of the preceding claims comprising a flexible substrate on which the at least one light source and at least one detector are carried.

9. A flexible muscle contraction sensor as claimed in claim 8 wherein the flexible substrate is black.

10. A flexible muscle contraction sensor as claimed in claim 8 or claim 9 wherein the flexible substrate is made of plastic.
11. A flexible muscle contraction sensor as claimed in any of claims 8 to 10 wherein the at least one light source and at least one detector are embedded in the flexible substrate.

12. A flexible muscle contraction sensor as claimed in any of claims 8 to 11 wherein the flexible substrate includes electrical connection to the at least one light source and at least one detector.

13. A flexible muscle contraction sensor as claimed in any of the preceding claims comprising one or more electrical components, such as an amplifier, and/or processor.

14. A flexible muscle contraction sensor as claimed in claim 13 wherein one or more electrical components, such as an amplifier, and/or processor are provided on the flexible substrate.
Figure 1
Figure 2

Flexible sensor head

Sensor controller
Figure 3
Figure 6
Figure 7
INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2014/052582

A. CLASSIFICATION OF SUBJECT MATTER

INV. A61B5/00 A61B5/11

According to International Patent Classification (IPC) onto both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data, BIOSIS, COMPENDEX, EMBASE, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>WO 2013/082156 A1 (UNIV LELAND STANFORD JUNIOR [US]) 6 June 2013 (2013-06-06)</td>
<td>1, 3</td>
</tr>
<tr>
<td></td>
<td>page 8, line 22 - page 10, line 3 page 20, line 21 - page 21, line 16 figure 1A</td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>US 5 954 053 A (CHANCE BRITTON [US] ET AL) 21 September 1999 (1999-09-21) column 11, line 13 - column 12, line 6 column 13, line 14 - line 67 figures 2, 5</td>
<td>1, 8, 9</td>
</tr>
</tbody>
</table>

[X] Further documents are listed in the continuation of Box C.  [X] See patent family annex.

* Special categories of cited documents:
*A* document defining the general state of the art which is not considered to be of particular relevance
*E* earlier application or patent but published on or after the international filing date
*L* document which may throw doubts on priority claim(s), even though cited to establish the publication date of another citation or other special reason (as specified)
*D* document referring to an oral disclosure, use, exhibition or other means
*P* document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"A" document member of the same patent family

Date of the actual completion of the international search: 11 November 2014
Date of mailing of the international search report: 18/11/2014

Name and mailing address of the ISA:
European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Gbrl ach, Tobi as

Form PCT/ISA/210 (second sheet) (April 2005)
<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patent document cited in search report</td>
<td>Publication date</td>
<td>Patent family member(s)</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------</td>
<td>-------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2013082156 A1</td>
</tr>
<tr>
<td>US 2006063995 A1</td>
<td>23-03-2006</td>
<td>NONE</td>
</tr>
<tr>
<td>US 5954053 A</td>
<td>21-09-1999</td>
<td>NONE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CN 101888808 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2011224553 A1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2009059412 A1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JP 2013514146 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TW 201129342 A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>US 2012157804 A1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WO 2011084450 A1</td>
</tr>
</tbody>
</table>