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Medical and Biological Engineering and Computing

48 (2010) 731-734

This is an author-generated version

The final publication is available at www.springerlink.com

DOI: 10.1007/s11517-010-0626-x

An electrooptical muscle contraction sensor

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The total number of words of the manuscript, including entire text from title page to figure legends: **1522**

The number of words of the abstract: **88**

The number of figures: **3**

(The number of tables: 0)

ABSTRACT

An electrooptical sensor for the detection of muscle contraction is described. Infrared light is injected into the muscle, the backscattering is observed, and the contraction is detected by measuring the change, that occurs during muscle contraction, between the light scattered in the direction parallel and perpendicular to the muscle cells. With respect to electromyography and to optical absorption-based sensors, our device has the advantage of lower invasiveness, of lower sensitivity to electromagnetic noise and to movement artifacts, and of being able to distinguish between isometric and isotonic contractions.

KEYWORDS

muscle contraction, optical device, infrared, isometric, isotonic

1. Introduction

In the design of an active prosthetic device, the detection of a signal suitable as a trigger or as a proportional controller for the prosthesis actuation is among the key issues. In current clinical applications, surface electromyography (EMG), that detects the electric signals that underlie muscle contraction, is in widespread use[1,2,3]. The patient is trained to contract appropriate muscles when he needs to actuate a specific movement in the prosthesis.

However EMG, based on the detection of low voltage signals at high impedance through electrodes applied on the surface of the skin, it is highly sensitive to electromagnetic interference[4]. Moreover, in order to reduce the impedance and to minimize movement artifacts, electrodes are put in direct contact with the tissue, often with a significant pressure, and the consequent tissue reaction and eventual reduction in tissue blood flow may cause malfunction and/or tissue damage[5,6].

For these reasons, in order to detect muscle contraction, optical techniques are particularly appealing, as they are intrinsically free from electromagnetic noise and, in principle, are not invasive on the tissues. As the near-infrared optical absorption of muscle is dominated by blood[7] and as, during contraction, the muscle undergoes blood depletion, it has been demonstrated that the contraction can be detected as a decrease in the optical absorption of the muscle[8,9]. Though this technique can indeed be used to generate a signal for prosthesis actuation, the sensitivity is low and, so far, viable sensor configurations have shown to be prone to artifacts due to patient movement[10].

2. Materials and methods

Our solution for the optical detection of muscle contraction is based on the observation that muscle cells are shaped as elongated fibers, aligned along the main muscle axis. In muscle tissue, we can therefore expect light to be scattered anisotropically. Namely, if we inject light into the muscle using a suitable point light source applied to the overlaying skin, the backscattered light, collected through the skin a few centimeters away from the source, depends on the collection point position with respect to the muscle fiber direction[11]. 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. We have therefore designed our sensor to detect such variation, responding to contraction with intrinsic rejection to non-anisotropic signals, such as those resulting from patient movement.

The sensor head is constituted of a round PVC housing, 50 mm in diameter and 8 mm thick, with five 5 mm PMMA windows arranged on the vertices and in the center of an ideal square with 40 mm diagonals. Such housing contains four photodiodes (BPW34, Siemens), arranged behind the peripheral windows, and a LED emitting at 880 nm (HIRL 8810, Rodan) behind the central one.

Using such configuration, the sensor collects light coming from a depth on the order of 2 cm under the skin surface[7].

A 1 m multicore cable connects the photodiodes and the LED to an appropriate photodiode preamplifier and a continuous-wave LED driver.

Inside the head, the cable is separated in its individual cores, that run in channels, held in place by an optically absorbing potting compound. This minimizes the optical crosstalk between each component. Figure 1 shows the lower part of the housing, with the channels, rendered from its CAD design (a), and a photograph of the assembled sensor head (b).

The sensor is placed directly on the skin, over a muscle. The LED emits light through the skin and into the muscle. It is oriented so that two photodiodes (1 and 3) collect the light scattered in the direction of the muscle fibers, while the other two photodiodes (2 and 4) collect the light scattered perpendicularly to such direction (photocurrents $I_{//}$ and $I_{\perp}$ respectively).

$I_{//}$ and $I_{\perp}$ are time-multiplexed, with opposite signs, on the input node of a current integrator. A feedback loop controls the duty cycle of the multiplexer balancing the output of the integrator for zero signal at steady state. Any imbalance between $I_{//}$ and $I_{\perp}$ faster than the loop time constant (22 s) appears as a non-zero signal on the integrator output. A simplified preamplifier schematic diagram is reported in Figure 2b.

3. Results and discussion

The sensor has been tested on a 28 year old male volunteer, placed over his biceps muscle, held in place by an elastic dark cloth bandage, taking care not to occlude blood circulation. The volunteer has then performed series of isotonic contractions (i.e., at constant muscle force), lifting a 8 kg dumbbell, and series of isometric contractions (i.e., at constant muscle length) against a fixed obstacle. Typical signals detected at the integrator output are reported in Figure 3.

Stable and consistent individual contraction signals can be easily distinguished against the steady-state baseline, and the shape of the signals corresponding to isotonic and isometric contractions is clearly different. In particular, in a first phase of the isotonic contractions, the muscle is rapidly depleted of blood, and then the differential optical scattering contribution due to the shortening of the muscular fibers prevails. Conversely, in isometric contractions, the muscle fibers are constrained to a quasi-constant length. Therefore, differential scattering contributes to a first phase of the signal only, and then haematic depletion dominates. As, in our configuration, differential scattering and blood depletion contribute to the signal with opposing signs, the isometric and isotonic signals present opposing leading and trailing edge slopes and steady-state values.

4. Conclusions

For the quality of the signals obtained, the device appears promising as an alternative to surface EMG for monitoring muscle contraction. As described, it enables a clear non-invasive detection of the contraction signal, with the substantial advantages on electromagnetic noise that optical methods present over low-signal electric detection, and with the additional capability to distinguish between isometric and isotonic contractions.

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Figure legends

FIG. 1. CAD rendering of the sensor head housing (a) and photograph of the assembled sensor head (b)

FIG. 2. Simplified schematic diagram of the sensor amplifier. (a): photodiodes D1 and D3 collect the light scattered parallel to the muscle fibers, D2 and D4 the light perpendicular to the fibers. (b): the photocurrents are integrated on C_i to yield the output signal V_s. The background, filtered with time constant R_fC_f is compared with a triangular signal V_t to balance the photocurrents.

FIG. 3. Sensor output for isotonic (a) and isometric (b) muscle contractions.

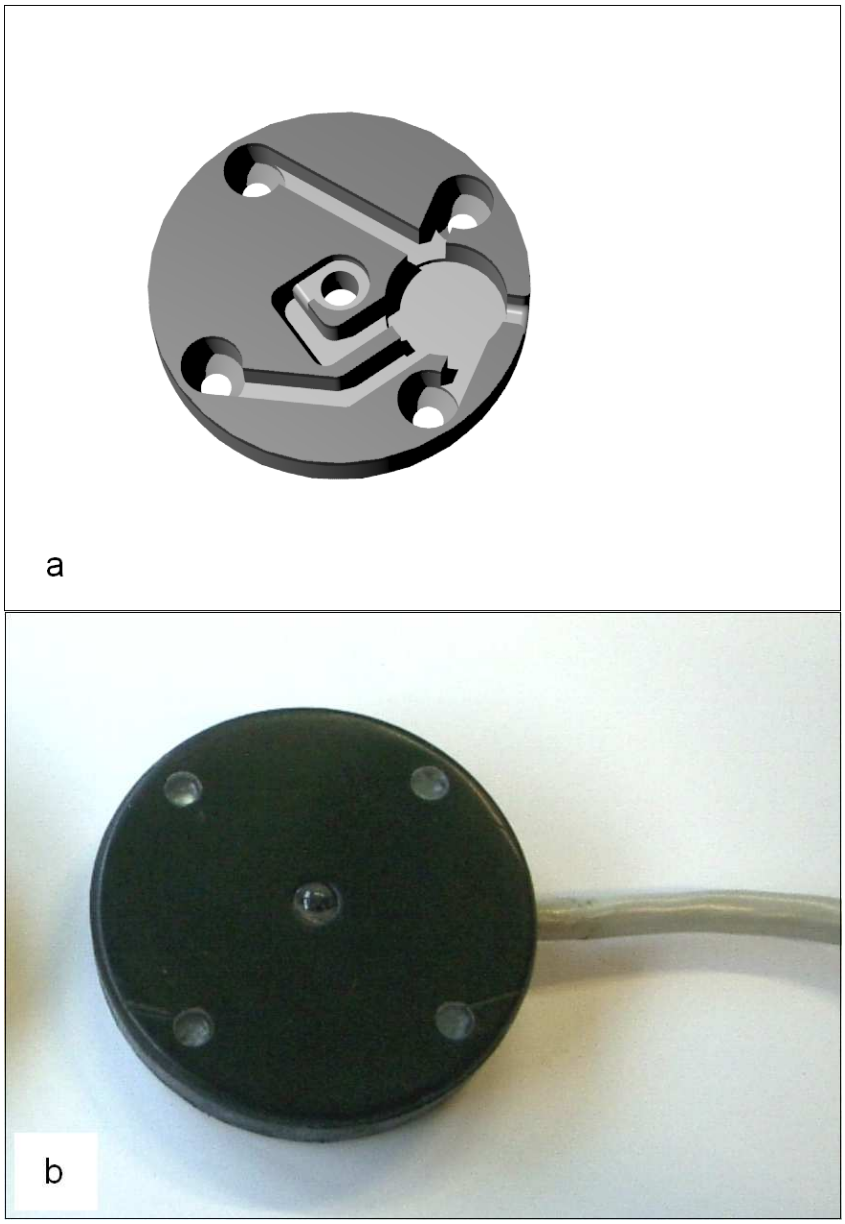


Figure 1

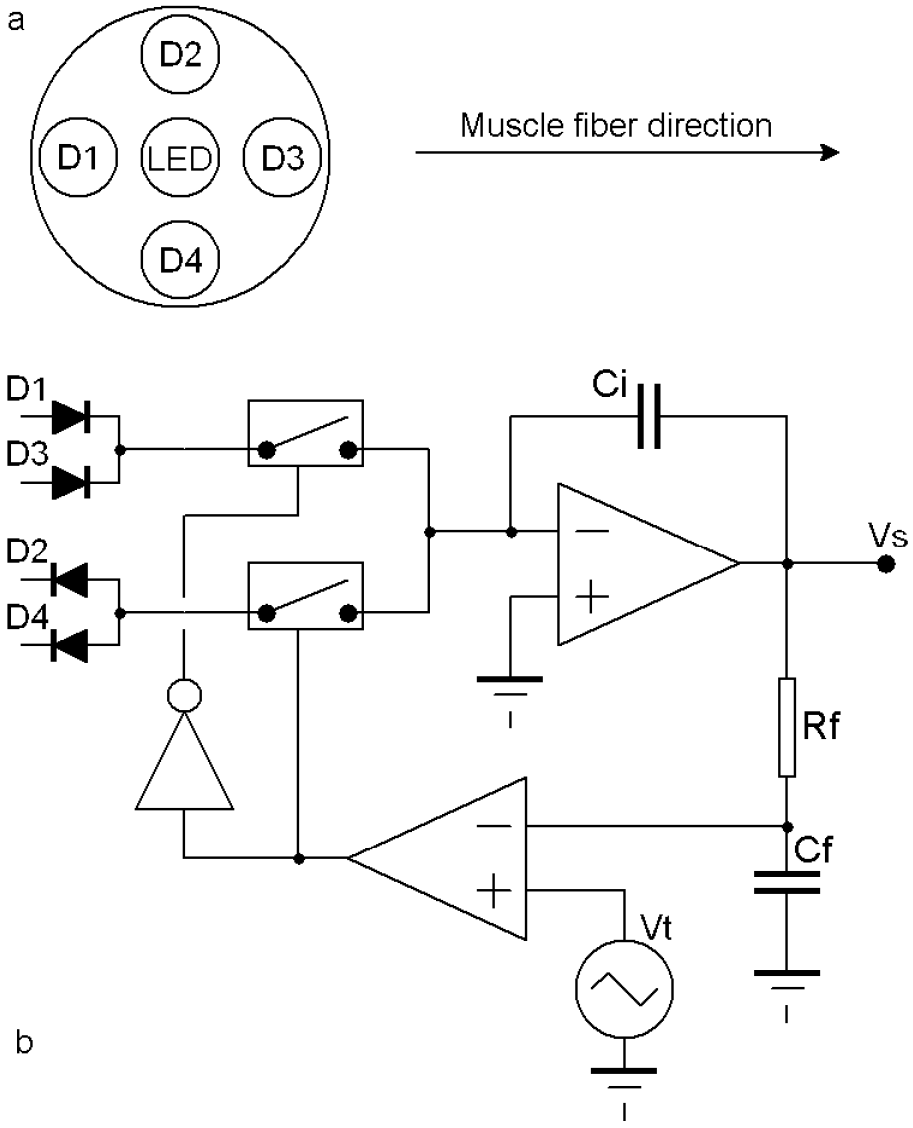
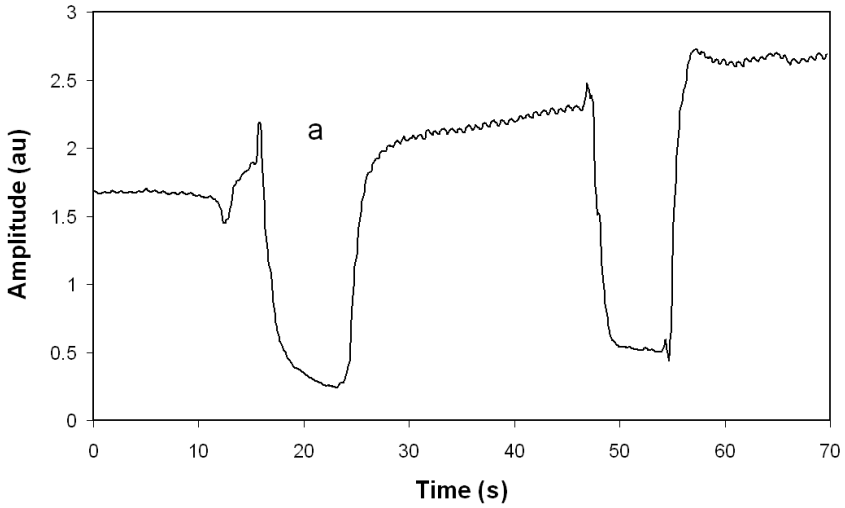

a
D2
D1
LED
D3
D4
Muscle fiber direction
D1
D3
D2
D4
Ci
Vs
Rf
Cf
Vt
b

Figure 2


a
Amplitude (au)
Time (s)
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0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70

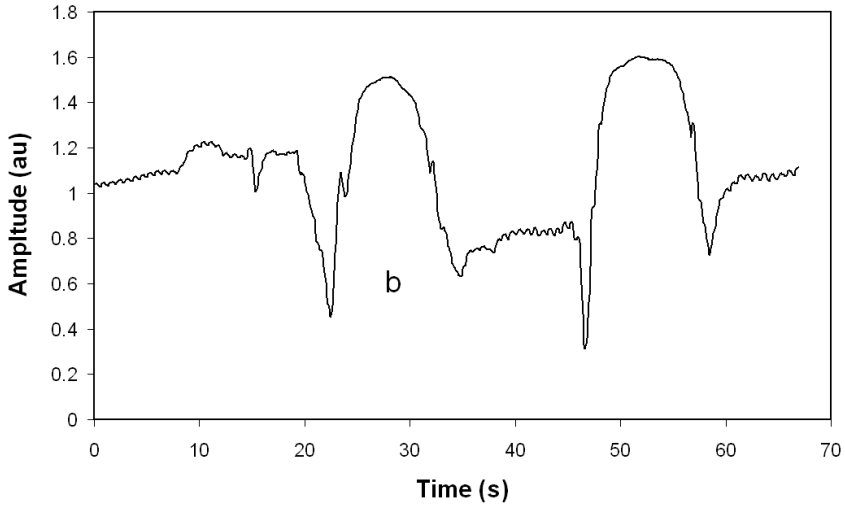
b
Amplitude (au)
Time (s)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
10
20
30
40
50
60
70

Figure 3