Sensors and Actuators A 213 (2014) 108–115

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Screen printed fabric electrode array for wearable functional electrical stimulation

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ARTICLE INFO

Article history:
Received 13 December 2013
Received in revised form 17 March 2014
Accepted 17 March 2014
Available online 18 April 2014

Keywords:
Functional electrical stimulation (FES)
Fabric electrode array
Screen printing
E-textile
Biocompatibility
Smart fabric

ABSTRACT

Functional electrical stimulation (FES) activates nerves using electrical currents, and is widely used in medical applications to assist movement of patients with central nervous system lesions. The recent emergence of small electrode arrays enables greater muscle selectivity and reduces fatigue compared to the use of traditional large electrodes; however existing fabrication techniques are expensive and have limited flexibility and comfort which limits patient uptake. This work presents a screen printed flexible and breathable fabric electrode array (FEA) which consists of four printed functional layers. Successful operation has been demonstrated by stimulating an optimised selection of electrodes in order to achieve clinically relevant reference postures ('pointing', 'pinch' and 'open hand'). The materials with skin contact used in FEA have been cytotoxicity tested to establish that they are biocompatible. The FEA demonstrates the potential for printable polymer materials to realise comfortable, wearable and cost effective functional systems in healthcare applications.

1. Introduction

Functional electrical stimulation (FES) is a technique to activate nerves using safe levels of electrical current in a coordinated manner in order to stimulate muscle activity [1]. It is widely used to assist the movement of patients with central nervous system lesions which may result from head trauma, spinal cord injury, stroke or other neurological disorders. FES uses electrodes to stimulate the neural tissues entering the muscle. The electrodes may either be implanted but are more commonly and conveniently placed on the surface of the skin. Surface electrical stimulation has widespread clinical use since the approach is non-invasive and comparatively straightforward to deploy.

Surface stimulation requires a sequence of electric charges to be delivered across an anodic and cathodic electrode pair, placed over the muscle body. Existing clinical surface electrodes are typically large and employ a self-adhesive hydrogel to improve electrical contact. The drawbacks of large electrode FES devices include insufficient selectivity and quicker patient fatigue due to the co-activation of various non-synergistic muscles [2]. Employing a large number of small surface electrodes has been found to address the lack of selectivity and a variety of different electrode arrays have recently emerged [3]. These have been found to assist patients with complex tasks through selective muscle stimulation [2–4]. In particular, electrode arrays have enabled the stimulation of functional wrist and hand gestures which are a critical component of the activities of daily living, involving at least 41 musculo-tendon units actuating a 16 joint system with 23 degrees of freedom [5].

The long-term goal is to produce wearable FES technology that provides maximum function, comfort and convenience. This necessitates exploiting the intrinsic properties of fabric (e.g. flexibility, breathability, light weight) by fabricating suitable electrode arrays directly on an appropriate fabric. To date, no fabrication technique has yet been demonstrated that can realise such an electrode array economically. Embroidery has been used by Keller et al. to manufacture smart fabric type electrode pads and electrode wiring on fabric for neuroprosthetic applications [6]. However, this required expensive high quality custom made silver sputtered yarns produced using plasma vapor sputtering since commercial metal coated yarns (e.g. silver coated Nylon 66 'ShieldX') showed low uniformity due to the degradation of the conductive yarn surface during the embroidery process [7]. Weaving and knitting have been used in fabricating smart fabrics for various wearable electronic applications (e.g. sensing, display, health monitoring, power generating) [8–10]. However, these methods are also not suitable for fabricating a wearable FES array. Weaving and knitting approaches impose limitations on the design of the array because the conductive path is constrained to follow the physical location of the yarns within the fabric. There is also a lack of homogeneity in the resistance

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http://dx.doi.org/10.1016/j.sna.2014.03.025
0924-4247/

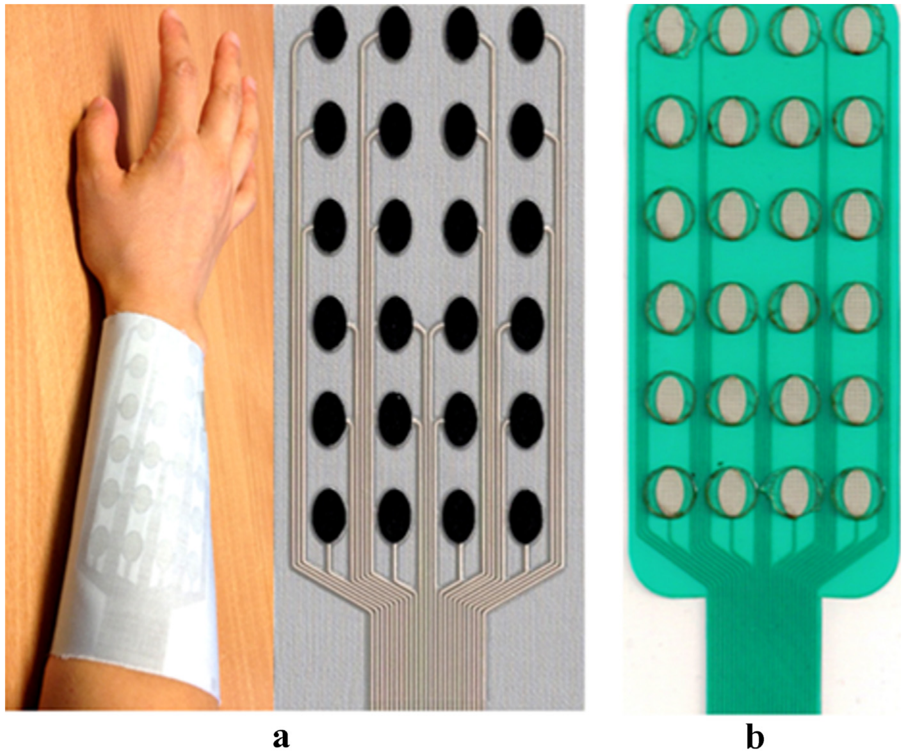

Fig. 1. Fabric electrode array (a) and flexible PCB array from Fatronik-Tecnalia (b).

of the conductive pattern due to the imprecise gaps between the conductive yarns.

This paper presents flexible and breathable fabric electrode array (FEA, Fig. 1a) fabricated entirely by screen printing the active electrode array directly onto a standard fabric. Screen printing is a straightforward and cost effective fabrication method which facilitates significant design freedom in terms of pattern geometries [11,12]. It is a well established technology in both the textile and printed electronic fields. The printed FEA has required the development of bespoke polymer based screen printable pastes that can be processed in a manner compatible with textiles. These materials are now commercially available from Smart Fabric Inks Ltd, UK [13]. A carbon loaded silicone rubber has been applied to form the electrodes which enable dry contact via the conductive pad–skin interface and avoids the need to use the hydrogel that is typically required by existing electrodes [14]. The materials with skin contact used in the FEA are biocompatible. The performance of the FEA has been compared to that of the leading alternative, which comprises a flexible printed circuit board (PCB) array on polycarbonate with a hydrogel layer (Fatronik-Tecnalia, Spain, Fig. 1b). The FEA can produce comparable angular joint movement compared to the PCB array; in addition, FEA has significant improvement on the flexibility, breathability and comfort. Critical postures of daily life have been achieved by stimulation of an optimised selection of elements.

2. Materials and fabrication

2.1. Materials

2.1.1. Fabric

The polyester/cotton (65/35, 2X1 twill, 210 g/m^2, 316 μm thick, provided by Klopman International) used in this study is a typical fabric for clothing. It combines the advantages of polyester fibre (e.g. wrinkle resistance, shape retention, durability, abrasion resistance, resistance to light damage) and the benefits of cotton fibre (e.g. comfort, softness, moisture absorption, light weight).

Table 1
Paste properties and curing conditions.

Pastes	Materials	Curing conditions
Fabink-UV-IF1004	Polyurethane acrylate paste	UV light
Fabink-UV-IF1044	Waterproof polyurethane acrylate paste	UV light
Fabink-TC-AG4001	Silver flake in vinyl resin polymer and solvent	10 min at 120 °C
Carbon rubber	Carbon filled silicone polymer paste	30 min at 80 °C

2.1.2. Pastes

The paste materials and their curing methods used in this study are shown in Table 1.

2.2. Fabrication process

2.2.1. Fabrication overview

A DEK248 semi-automatic screen printer was used to print the FEA which consists of four functional layers: (a) an interface layer on fabric to provide a smooth surface for subsequent printing; (b) a silver layer to form conductive pads and tracks; (c) an encapsulation layer over the conductive tracks to provide protection and electrical insulation, which leaves the silver tracks at the end open for connection as shown in Fig. 2; (d) a carbon loaded silicone rubber layer over the conductive pads to provide a good electrical connection with the skin. The printing processing steps are shown in Fig. 2.

2.2.2. Interface layer printing

Printing the silver conductor directly onto fabric is not ideal due to the rough surface of the fabric. In this work, the