Medical Engineering & Physics 33 (2011) 546–552

Contents lists available at ScienceDirect

Medical Engineering & Physics

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

A durable, low-cost electrogoniometer for dynamic measurement of joint trajectories

Po T. Wang [a], Christine E. King [a], An H. Do [b,*], Zoran Nenadic [a,c,**]

[a] Department of Biomedical Engineering, University of California, Irvine, CA 92697, United States
[b] Department of Neurology, University of California Irvine Medical Center, Orange, CA 92868, United States
[c] Department of Electrical Engineering and Computer Science, University of California, Irvine, CA 92697, United States

ARTICLE INFO

Article history:
Received 23 June 2010
Received in revised form 3 December 2010
Accepted 13 December 2010

Keywords:
Articular goniometry
Transducers
Applied kinesiology
Joint range of motion
Regression analysis

ABSTRACT

This article introduces a method and step-by-step instructions for the design of a low-cost, flexible electrogoniometer, suitable for kinesiology, rehabilitation, and biometric applications. Two unidirectional flexible sensors are placed back-to-back, and a multivariate linear regression model was used to combine measurements from the two sensors. Following a short calibration procedure, the electrogoniometer can be reliably used for measurement of flexion/extension angles of various hinge joints. The performance of the goniometer has been tested on a population of 21 healthy subjects performing flexion/extension of index finger, wrist and elbow. The proposed device achieves the quality of joint angle measurements comparable to that of commercial electrogoniometers, while having a significantly higher durability-to-cost ratio.

1. Introduction

Flexible electrogoniometers are widely used to measure human joint movements [1], with applications ranging from medicine (e.g. kinesiology [2], rehabilitation [3], diagnostics [4]) to virtual reality interfaces and computer peripherals [5]. Their advantage over conventional potentiometric goniometers is that they adapt better to body parts and are not sensitive to misalignments concomitant with the movement of polycentric joints [1,6]. On the other hand, the major weakness of this technology is its relatively high cost [6]. At the time of publication, the typical cost of a commercially available flexible finger electrogoniometer is ~$700 for the sensor alone [7], with additional cost for accompanying cables and a transducer amplifier. Despite the high price (our group recently acquired a state-of-the-art two-endblock flexible goniometer and a transducer amplifier [8] for ~$1400), the durability of this device seems to be seriously compromised by the torsion of the flexible cable between the endblocks and the cable buckling that tends to occur as joints undergo a full range of motion.

Motivated by these limiting factors, we report on the development of a simple, durable and extremely affordable flexible electrogoniometer suitable for measurements of single axis joint movements in research applications. The cost of the device is at least an order of magnitude lower than that of commercial ones, with superior durability and comparable accuracy. Finally, the simplicity and low cost of the manufacturing process allow easy replacement of flexible sensors in the case of their electrical and/or mechanical failure.

2. Methods

2.1. Goniometer assembly

The basic sensing component of the electrogoniometer is a unidirectional flex sensor [9] shown in Fig. 1A. To achieve bidirectional sensing, two flex sensors are placed back-to-back (Fig. 1D). Each flex sensor consists of two layers of overlapping resistive films. When flexed, the amount of overlapped area changes, thereby changing the resistance with a nonlinear resistance–angle relation. The terminals on the flex sensors were too thin (0.16 mm) to form a tight fit with female headers (Fig. 1H). Therefore, to facilitate secure connection of the flex sensors, male headers (Fig. 1G) with 13 mm × 0.64 mm pins (Leoco USA Corporation, Fremont, CA) were soldered onto the flex sensor terminals (Fig. 1B).

Four 2.54 mm square female headers, obtained by cutting in half a computer CD-ROM drive SPDIF motherboard cable, were arranged in a 2 × 2 configuration (Fig. 1H) to accommodate the back-to-back arrangement of the flex sensors (Fig. 1D). Cyanoacrylate adhesive and 6.35 mm diameter heat-shrink tubing (Tech-Tron,

* Corresponding author.
** Corresponding author at: Department of Biomedical Engineering, University of California, 3120 Natural Sciences II, Zot Code: 2715, Irvine, CA 92697, United States. Tel.: +1 9498241548.
E-mail addresses: ptwang@uci.edu (P.T. Wang), kingce@uci.edu (C.E. King), and@uci.edu (A.H. Do), znenadic@uci.edu (Z. Nenadic).

1350-4533/$ – see front matter © 2010 IPEM. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.medengphy.2010.12.008

Fig. 1. (A) A 6.35 mm × 114.3 mm flex sensor before any modification (Spectra Symbol, Salt Lake City, UT), (B) with soldered male header pins (made from G), (C) with heat-shrink tubing for insulation. (D) Two flex sensors placed back-to-back, inserted into (E) expandable PET sleeving to enclose all electrical components (shown partially inserted). (F) Final goniometer assembly was plugged into (H) female headers. Sleeving was taped to female headers with duct tape to strengthen physical stability. The other end of sleeving was burned closed with fire. A plastic conduit made from transparency film was slid onto the sleeving to facilitate low-friction movement during use.

Santa Clara, CA) were used to fix the female headers in the 2 × 2 configuration. Prior to their insertion into the female headers, heat shrink-tubing was also applied to the flex sensors to insulate areas of potential exposure (Fig. 1C). The entire assembly was subsequently enclosed in 120 mm × 6.35 mm expandable polyethylene terephthalate (PET) sleeving (JT&T Products, Reno, NV) for insulation (Fig. 1E). The sleeving's low friction and flexible design facilitate the electrogoniometer's need to glide over skin and compensate for bending during use. The flex sensors' header pins were then snuggly inserted into the female headers (Fig. 1F). Finally, a plastic conduit which conforms to the external shape of the electrogoniometer's flexible end was made from transparency film. It was used to loosely enclose a portion (~2 cm) of the electrogoniometer's flexible end (Fig. 1E and F), thereby providing a point on which adhesive tape can be applied to fix the electrogoniometer to the skin, and allow for the sliding of its flexible portion during measurements. To increase grip to the skin, double sided tape was wrapped around the conduit.

The female headers corresponding to the two flex sensors were then connected to a voltage divider circuit (see Fig. 2) using four 1.2-m long segments of stranded wire (0.321 mm). The circuit was mounted on a standard breadboard and powered by 5 V DC. To prevent drawing of excessive current (e.g. by accidentally creating a short circuit), a 470-Ω resistor was placed in series to the power supply. To provide adjustable dynamic range of the outputs (V_1 and V_2), a potentiometer (0–20 kΩ) was placed in each branch. This also allows V_1 and V_2 to be balanced when the flex sensors are in neutral position (not deformed).

The outputs were connected to two channels of a data acquisition device MP150 (Biopac Systems Inc., Goleta, CA) with input impedance ≥1 MΩ. The data were sampled at 200 Hz and acquired using AcqKnowledge 3.8.2 software (Biopac Systems Inc.).

2.2. Goniometer mounting and calibration

The electrogoniometer was affixed to the joint of interest by straddling the approximate center of rotation, with the terminal end facing proximally and the flexible end facing distally to the

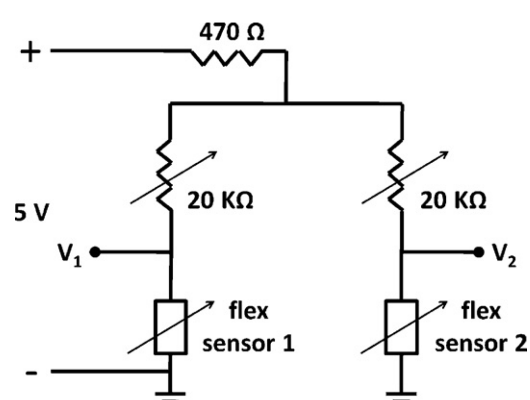

Fig. 2. Voltage divider circuit.