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Short communication

Can fabric sensors monitor breast motion?

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Abstract

To establish whether conducting polymer-coated fabric sensors could be used to monitor breast motion, vertical breast motion of two large breasted women (C+ bra cup) was simultaneously monitored using an OPTO*TRAK*® 3020 motion analysis system (200 Hz) and polymer-coated fabric sensors linked to a custom-made Bluetooth telemetry system (100 Hz) as the subjects walked and ran on a treadmill (7–10 km h^{-1}). Sensor strain, change in resistance and vertical breast displacement relative to trunk movement were output for analysis. It was concluded that, although polymer-coated fabric sensors may exhibit a small response lag due to textile geometry changes, they were able to accurately and reliably represent changes in the amplitude of vertical breast displacement during treadmill gait.

Keywords: Conducting polymers; Fabric sensors; Breast motion; Treadmill running; Biomechanics

1. Introduction

As an endocrine end organ, the female breast contains no supportive muscle or bone, although it is speculated that the main anatomical support structures for the breasts are the thin bands of connective tissue separating the lobules of the breast, known as Cooper's ligaments, and the surrounding skin (Van de Graaf, 1992). Due to this limited internal anatomical support, females are usually encouraged to wear external support in the form of a brassiere to reduce breast motion, particularly during physical activity (Mason et al., 1999).

Although effective in limiting breast motion, a consequence of current brassiere design is that the brassiere straps bear much of the load generated by breast momentum during physical activity. As breast mass increases, breast bounce momentum also increases, placing large loads on the straps and, in turn, excessive pressure on the wearer's shoulders. This excessive pressure has been known to cause deep brassiere strap furrows and can affect the neurovascular bundle, leading to malpostures and paresthesia of the fifth digit (Letterman and Schurter, 1980; De Silva, 1986). Apart from strap-related pain, many females, particularly large breasted women, are restricted from participating in physical activity due to exercise-induced breast pain associated with excessive vertical breast displacement (Lorentzen and Lawson, 1987). It is therefore imperative that brassieres designed for exercise can effectively limit excessive breast displacement without causing discomfort.

Due to the potential negative consequences associated with inappropriate brassiere design, it is imperative that brassiere designers have access to methods that can accurately and reliably quantify the effects of various brassiere design features on breast motion while not altering the material properties of the brassiere. However, most commercially available technologies that monitor the kinematics and kinetics characterising human performance have traditionally been comprised of rigid parts, such as strain gauges or buckle transducers, which can interfere with performance. However, advances in polymer science now enable inherently conducting polymers to be integrated into textiles, creating novel non-rigid biomonitoring options in the form of fabric sensors, which have strain gauge-like properties with a wide dynamic range (De Rossi et al., 1999). These unique fabric sensors are ideal to monitor human motion as, when integrated with

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conventional but wearable electronics, they can be integrated directly into existing clothing (De Rossi et al., 2003), such as brassieres, without changing the material properties or functions of these items and without interfering with normal human motion. Therefore, the purpose of this study was to determine whether these polymer-coated fabric sensors were suitable to monitor breast motion during locomotor activities.

2. Materials and methods

2.1. Subjects

Two women (age = 30 and 39 years, mass = 75 and 81 kg, height = 1.67 and 1.56 m), professionally sized to wear a 14C (36C USA sizing; 36D UK sizing) and 16D (38D USA sizing; 38DD UK sizing) brassiere, respectively, participated as subjects. As hormone levels can influence breast connective tissue, both subjects were premenopausal and were not breast feeding or pregnant at the time of the study. All study procedures were approved by the University of Wollongong Human Research Ethics Committee and both subjects gave written informed consent prior to participating.

2.2. Fabric sensor characteristics

A commercially obtained nylon (80%) lycra (20%) fabric (160×140 mm) was coated with the conducting polymer, polypyrrole (PPy), using a solution phase chemical polymerisation method adapted from Kuhn and Kimbrell (1989). Sensor strips (40×15 mm) were cut from the coated fabric and the mechanical and electrical characteristics of the strips were recorded using a custom-made dynamic calibration system (reference voltage = 5.0296 V), consisting of an Animatics Corporation SmartMotor™ (Santa Clara, USA; 10 cm s^{-1}), Linear Variable Differential Transformer (Schaevitz DC LVDT, 6000 DC-SE, Hampton, USA, linear range 0–150 mm) and load cell (Entran EL, Measurement Specialties Inc., Hampton, USA, 10 N). Each fabric sensor was subjected to increasing (stretch) and decreasing (relaxation) sinusoidal increments from 0% to 70% strain for a minimum of 20–25 cycles at 1 Hz. Average peak force and resistance data were plotted against strain to give a calibration curve. The linear range of the sensor and the gauge factor[1] were then determined from this curve. After being polymer-coated, the sensors displayed a maximum 0.35 N difference in extension force at 40% and 70% strain, electrical response linearity between 10% and 60% strain and minimal hysteresis (0.02 kΩ). The sensors were therefore considered adequate to be integrated with components of a brassiere and used to monitor breast motion.

[1]Gauge factor = $(\Delta R/R_0)/(\Delta L/L_0)$, where R_0 and L_0 are the initial resistance and length of the sample fabric at 0% strain, respectively.

2.3. Data collection and analysis

After familiarisation, each subject was asked to walk and run on a Powerjog CX100 treadmill (Expert Fitness UK, South Wales, UK) at 7 km h^{-1} (a comfortable self-selected walking pace) and 10 km h^{-1} (a recreational running pace), respectively. Two trials of data (10 s duration each) were collected for each condition after each subject had been walking or running for a minimum of 2 min and had achieved a consistent gait pattern.

During the experimental trials each subject wore a representative comfortable fashion brassiere (Berlei Touched: meryl nylon and elastane with brassiere cup underwire), shorts and athletic footwear. Two of the polymer-coated sensors were adhered to each subject's brassiere, using Velcro and adhesive tape and pre-strained 20% to ensure linearity. Sensors were placed on the right side of the brassiere on the strap (placed vertically from the most superior portion of the brassiere strap to 4 cm above the nipple; sensor length = 123 mm (14C); 132 mm (16D)) and the cup (placed vertically from the most superior portion of the brassiere cup to 2 cm above and 1 cm medial of the nipple towards the sternal line; sensor length = 37 mm (14C); 34 mm (16D); see Fig. 1).

Wires extending from the ends of each sensor were linked to a transmitter pack, worn around the waist of each subject, which sent the sensor strain data (V) to a Bluetooth Telemetry receiver (100 Hz; Sony Ericsson, Australia). Infrared emitting diodes (IRED) were placed directly above the wire connects to record change in sensor length (mm) and additional IRED were placed on each subject's right nipple under the brassiere and on the sternal notch to enable calculation of vertical breast displacement (mm) independent of torso motion (Mason et al., 1999). During each locomotor trial IRED positional data were monitored simultaneously with the sensor data using an OPTO*TRAK*® 3020 motion analysis system (200 Hz; Northern Digital, Waterloo, Canada). Intraclass correlation coefficients were calculated on the peak data output

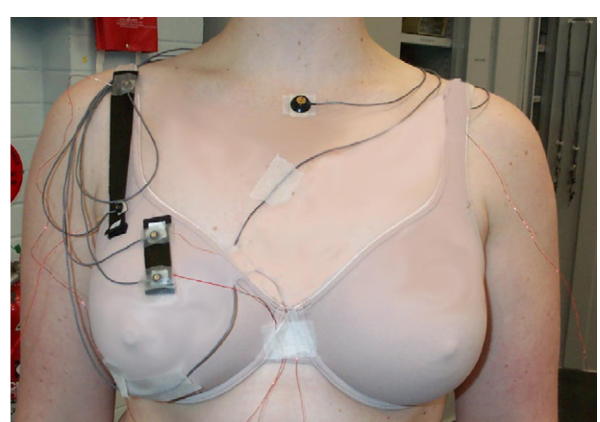

Fig. 1. The strap and brassiere cup fabric sensors attached to the right side of the fashion brassiere on the 14C subject with IRED attached to each sensor, under the brassiere on the nipple and on the sternal notch.