POSTER

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A Tailored Textile Sensor-based Wrap for Shoulder Complex Angles Monitoring

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Figure 1: Overview of the wearable system. (a) A customized shoulder wrap equipping with five textile sensors, (b) The illustration of sensor placement. Five textile sensors were placed around the anterior and posterior fascicles of the deltoid, trapezius, pectoralis externus, and scapularis raisers.

ABSTRACT

The shoulder joint plays a crucial role in the recovery of upper limb function. However, conventional wearable technologies employed for monitoring shoulder joint movements predominantly rely on inertial sensing units (IMUs), which may suffer alignment errors and compromise the freedom and wearability experienced by patients during their daily activities. This paper contributes in two facets, first, it presents the design, implementation, and technical evaluation of a new wearable system, a customized unilateral shoulder wrap that utilizes flexible and breathable textile sensors. Diverging from earlier studies, our system not only facilitates the monitoring of glenohumeral joint angles but also concurrently tracks the movement angles of the scapula. Secondly, to estimate joint angles, we propose a specific model called the Channel-Temporal Encoding Network (CTEN), which leverages Transformer and Long Short-Term Memory (LSTM) architectures. In a preliminary technical evaluation, the results demonstrate root mean square errors (RMSEs) of 2.24°and 1.13°for the glenohumeral joint and scapula, respectively. This study is intended to contribute to the development of more advanced wearables tailored for shoulder joint rehabilitation training.

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CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

KEYWORDS

Wearable system; Textile sensor; Human motion monitoring; Shoulder joint angles

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1 INTRODUCTION

Monitoring shoulder joint angles, particularly for rehabilitation purposes, can be a challenging task. The shoulder complex encompasses various joints, including the sternoclavicular (SC), acromioclavicular (AC), glenohumeral (GH), and scapulothoracic (ST) joints. This implies that patients' shoulder issues may vary, requiring personalized rehabilitation plans or methods[1, 11]. Additionally, monitoring shoulder movements, at least, necessitates accurate measurements of joint angles and range of motion. However, the shoulder complex exhibits a wide range of motion patterns, making it difficult to obtain precise data through simple observation or manual measurements conducted by physiotherapists.

To address these challenges, prior studies have proposed several sensing technologies for the detection and quantitative measurement of shoulder movements[1, 2, 8]. Optical motion capturing technology is considered the gold standard in this domain, but it is costly and requires a laboratory environment. As an alternative, wearable sensors have gained attention due to their low cost, flexibility, and potential ubiquity. Among these sensors, inertial measurement units (IMUs) are commonly employed in wearable systems for human motion monitoring. However, IMUs suffer from drift errors, lack of comfort [6, 16], and difficulties in fitting acromial angle[12].

Smart textiles, also known as flexible textile sensors or e-textiles, are receiving attention from wearable computing community and being considered as a promising solution to alleviate the limitations of IMUs[9]. By incorporating conductive materials into elastic textile structures, these textile strain sensors can detect motion by adapting to changes in shape during human movement.

However, accurately monitoring shoulder joint angles using textile sensors for rehabilitation purposes remains challenging. One of the primary challenges is achieving desirable accuracy. For instance, Esfahani et al.[3] employed 11 textile sensors to detect trunk and shoulder (glenohumeral joint) angles, but the estimation error for the shoulder motion angle was found to be 9.4°, significantly higher than that for the trunk (1.3°). Another challenge lies in the simultaneous monitoring of multiple joints. Previous studies have commonly simplified the shoulder joint as a three-degree-of-freedom ball-and-socket joint centered at the glenohumeral joint. Examples include above-mentioned work by Esfahani et al.[3], and also the work by Jin et al.[7] presenting errors of 4.5°. However, individuals with shoulder dysfunction often exhibit abnormal movements during glenohumeral joint motion, such as limited or delayed scapular upward rotation during arm elevation. The simplified three-degree-of-freedom shoulder joint model fails to detect or monitor these harmful abnormal movements. While Lorussi et al.[10] investigated both scapulothoracic and glenohumeral movements, their use of textile sensors was limited to detecting scapular sliding rather than real-time angle estimation.

To address these challenges, this paper aims to develop a comfortable wearable system based on soft textile sensors for monitoring multiple joint angles around the shoulder with high accuracy. To this end, three key research components are undertaken:

- Clarifying design requirements and goals through interviews with both patients with shoulder dysfunction and physiotherapists.
- Designing and developing a wearable system featuring desirable wearability with textile sensors based on insights from the interviews.
- Establishing and evaluating algorithms to calculate joint angles using time-series signals from the textile sensors.

Ultimately, a unilateral shoulder wrap is presented, featuring easy donning and doffing. This wrap, as shown in Figure.1a, is equipped with five textile sensors to monitor the motion angles of both the glenohumeral joint and scapula. In the preliminary technical evaluation, it achieved promising results, demonstrating root-mean-square errors (RMSE) of 2.24° (R^2 of 0.98) and 1.13° (R^2 of 0.98) for the glenohumeral joint and scapula, respectively.

2 DESIGN REQUIREMENTS AND GOALS

2.1 Investigation of Design Requirements

To gain a comprehensive understanding of the shoulder rehabilitation process, we conducted semi-structured interviews with three physiotherapists and two patients undergoing shoulder rehabilitation at a community rehabilitation center. The interview topics mainly involved 1) the procedural aspects of patient recovery and rehabilitation training; 2) the common movements involved in rehabilitation, as well as the most prominent abnormal movement patterns observed during shoulder rehabilitation and 3) their perspectives and anticipations regarding wearable systems featuring soft textile sensors.

Each interviewee participated in the interviews individually. Furthermore, during the face-to-face interviews, we presented a demonstration prototype with textile sensors sewn onto it to elicit their insights and expectations regarding wearable systems and textile sensors. Through content analysis of the interviews, we derived the following design requirements:

- Monitoring of both scapula and glenohumeral joint movement is necessary, as numerous training exercises focus on restoring stability and coordination in these two joints.
- A real-time, quantifiable, and visible motion angle monitoring system is desired, as it holds promise for reducing the workload of physiotherapists and alleviating patient anxiety.
- The wearable system should be accurate, comfortable, and aesthetically pleasing. Consideration should be given to both comfort and social-contextual factors in the design.

2.2 Target Joint Angles for Monitoring

Based on the first design requirement mentioned above, this study aims to monitor the angles of both the scapula and glenohumeral joint involving X, Y, and Z axes. The shoulder coordinate system defined by the International Society of Biomechanics (ISB) is employed to determine these angles [14]. More specifically, the motion angles of the scapula, denoted as $\theta 1$ in this study, represent the difference between the scapular coordinate system and the thoracic coordinate system. Similarly, the motion angles of the glenohumeral joint, denoted as $\theta 2$, represent the difference between the humeral coordinate system and the scapular coordinate system. With the targeted angles identified, the design and implementation of our wearable system are presented in the following section.

3 WEARABLE SYSTEM DESIGN

3.1 Sensor Placement

Determining the placement of textile sensors is crucial for building an effective sensing and computing textile network. Following the methodology of previous studies[3, 7], three steps were taken to determine the final sensor placement. Firstly, a woven resistive textile sensor incorporating silver fiber was chosen for its good linearity and sensitivity, with a large range of resistance variation from 150Ω to 450Ω. Secondly, based on anatomical knowledge, five sensors were strategically arranged around the anterior and posterior bundles of the deltoid muscle, trapezius, ectopectoralis, and levator scapulae muscles, as these areas experience notable skin deformation during glenohumeral joint and scapula movements. Lastly, the sensor placement was refined through sensing performance testing, iteratively placing the sensors in specific locations and orientations that produced significant changes in sensor resistance. The sensor placement of our wearable system is depicted in Figure 1b.

3.2 System Design

During the development of the prototype, we learned that conventional long-sleeved garments were not user-friendly enough for individuals with upper limb impairments when it came to donning and doffing. Therefore, in contrast to previous studies that typically integrated textile sensors into tights, a customized unilateral shoulder wrap was designed with an asymmetrical structure in the front and back, as shown in Figure.1a. The wrap can cover the left scapula area on the back, while having a smaller area on the front to reduce contact area with skin and enhance comfort. To ensure better durability, we sewed textile sensors on the wrap with zigzag stitches. Additionally, the wrap features a velcro adjustment at the right underarm area, facilitating ease of donning and doffing and allowing for adjustments in tightness.

The above-mentioned prototype consists of a textile sensing unit, a sensing signal acquisition unit, and a data processing unit. Five textile sensors (width = 1cm) and conductive fibers were securely attached to the unilateral wrap using zigzag stitches. Each textile sensor was connected in series with a 220Ω resistor and then connected in parallel to a 5V supply circuit. The non-grounded ends of the textile sensors were linked to the analog port of an Arduino board to capture voltage changes resulting from the stretching of the textile sensors during movement. The real-time resistance of the textile sensors was recorded and processed using a laptop.

4 ALGORITHM CONSTRUCTION

4.1 Data Collection

To capture and calculate ground-truth angles, a total of 14 reflective markers were affixed to the garment around the shoulder, following the coordinate definition recommended by the International Society of Biomechanics (ISB) [14]. Both the OptiTrack motion capture system and the textile sensing system operated at a signal acquisition frequency of 120 Hz. A participant was recruited to wear the prototype and perform 9 sets of movements, including arm abduction (0°to 60°), extension, and flexion. Each set of movements was repeated 6 times. In total, we collected 54 movements of sensor data and corresponding shoulder joint angles. To enhance the model's robustness while preserving temporal consistency, we randomly shuffled these movements and concatenated them to create the dataset. Subsequently, the dataset was partitioned into training (70%), validation (10%), and testing (20%) sets based on frames. Additionally, a Savitzky-Golay filter was applied to mitigate high-frequency electromagnetic noise from the sensors, and min-max normalization was employed to enhance the optimization process's stability.

4.2 Regression Model

The utilization of flexible textile sensors in wearable systems for monitoring shoulder motion angles aims to establish a mapping function between the resistance variations of the textile strain sensors and the corresponding ground-truth joint angles. This allows for the prediction of real-time joint angles based on the resistance data from the textile sensors. We approach the estimation of shoulder joint angles as a multivariate time-series regression problem, seeking a regression model that can estimate the shoulder joint angle from the multivariate time-series collected by the sensors.

Inspired by the successful application of Long Short Term Memory (LSTM) [5] and Transformers [13] in wearable-based human activity recognition and extrinsic regression tasks [4, 15], we propose an innovative approach called Channel-Temporal Encoding Network (CTEN) that combines the strengths of both architectures to construct a robust model for estimating shoulder joint angles.

CTEN consists of three modular networks: a channel-wise encoding network (CwE), a temporal-wise encoding network (TwE), and a shoulder joint angle representation decoder. Given that resistive textile strain sensors exhibit different resistance changes for specific movements, with some sensors being more sensitive while others contribute to noise, the CwE is designed to selectively emphasize or suppress specific channels between each sensor at every time step. We adopt the encoder block from the original Transformer architecture [13] to construct the CwE, enabling explicit capture of channel-wise correlations through the attention mechanism. Furthermore, considering the temporal diversity and hysteresis of the sensors, we introduce the TwE to learn the temporal dynamics using LSTM. Finally, the output representation of the encoder is decoded into joint angles using two-layer fully connected layers. To optimize the model parameters, we employ the Mean Squared Error

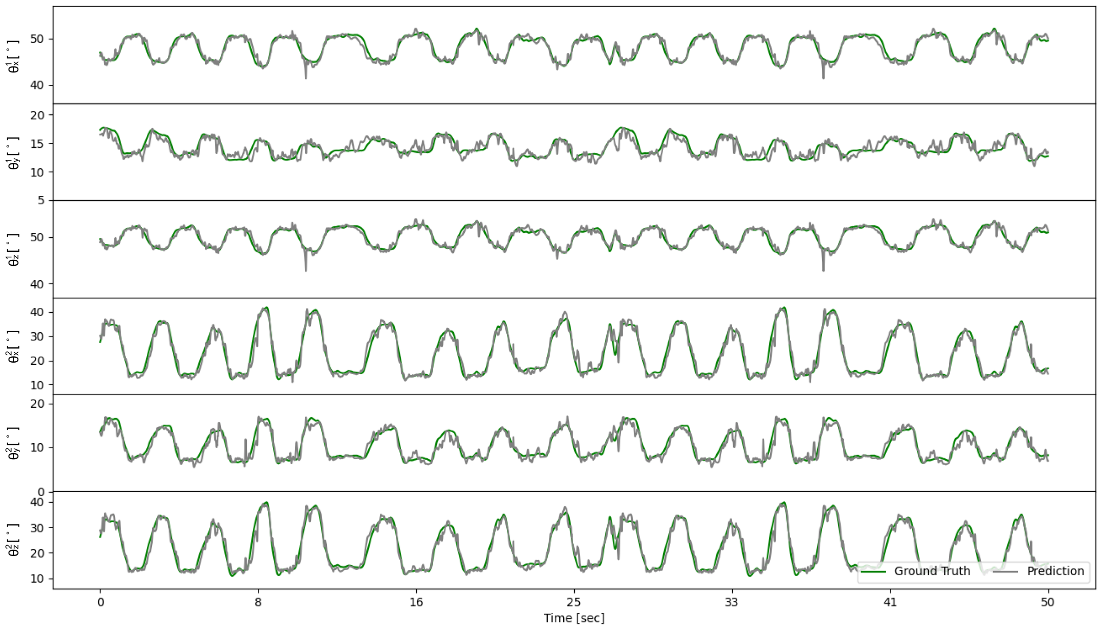

Figure 2: Visualization of estimation performance on tested shoulder movements.

(MSE) loss to minimize the prediction error between the estimated joint angles and the ground-truths.

4.3 Results

The performance of joint angle estimations were evaluated using Root Mean Square Error (RMSE) and R^2 respectively. The preliminary technical evaluation yielded promising results, with an overall RMSE loss of 1.68°and an R^2 value of 0.98 for the entire test set. When specifically considering the scapula angles ($\theta 1$) and glenohumeral joint angles ($\theta 2$), the RMSE losses were 1.13°and 2.24°, respectively, both with an R^2 value of 0.98. The estimation performance on tested shoulder movements is visually depicted in Figure.2, providing a clear visualization of the model's effectiveness in capturing the desired joint angles.

5 CONCLUSION AND FUTURE WORK

In this study, we introduced a novel wearable system, the unilateral shoulder wrap, which incorporates soft textile sensors for monitoring the motion angles of the scapula and glenohumeral joint simultaneously. The preliminary technical evaluation of the system has yielded promising results, demonstrating its potential effectiveness. Moving forward, there are three main steps for future work. Firstly, it is essential to conduct additional technical evaluations by involving a larger number of participants. This will help assess the robustness and generalizability of our system and algorithm across a wider range of individuals. Secondly, more efforts would be carried to evaluated the usability of this system, including comfort evaluation with feedback from more participants and durability of the prototype. Based on the results from above-mentioned evaluation, further iterations of the prototype should be carried out. Finally, a feedback interface with visible joint angles would be developed for patients and further clinical evaluation in real rehabilitation scenarios should be conduceted.

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