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Feasibility of a wearable, sensor-based motion tracking system

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Abstract

The objective of this study was to develop and evaluate the feasibility of a wearable, sensor-based motion tracking system that provides an economical and quantitative means of recording upper limb motion for physical rehabilitation. The tracking system is comprised of a wirelessly connected network of inertial measurement units (IMUs), each containing a gyroscope and an accelerometer. Two IMUs were rigidly attached to each subject's forearm and upper arm. A trajectorizing algorithm was developed to estimate the three dimensional upper limb motion based on the measurements of the IMUs. A major advantage of the algorithm is that it allows the IMUs to be attached with arbitrary orientation to each limb and no manual anthropomorphic measurements need to be performed. By recording specific, known motions, the sensors can be calibrated with respect to their orientation in space and with respect to their orientation relative to their respective body segments. During the experiment, healthy subjects performed elbow flexion-extension motions that were recorded using the IMUs. To validate the system including the accuracy of recorded data and the correctness of the trajectorizing algorithm, an optical motion capture system was also used to record the same motions. Results showed that the proposed motion tracking system measured the elbow joint angles of the flexion-extension motions with high consistency with the measurements obtained from the optical motion capture system. Statistical analysis showed that joint angles between two systems are highly correlated. The error of elbow joint angles measured by our system yielded small root mean square error (RMSE) and small median absolute deviation (MAD). These results suggest that an IMU-based (more specifically, a gyroscope-based) motion tracking system can be realistically used to accurately track a patient's motion without the need of numerous sensors or an overly complicated set-up.

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Keywords: Healthcare; Motion tracking; Wearable wireless sensor

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1. Introduction

National health care spending in the United States is estimated to reach $4.8 trillion in 2021, which will consume nearly 20% of GDP (Centers for Medicare and Medicaid Services, National Health Expenditures Projections 2011-2021) [1]. The applications of wireless wearable sensors reduce healthcare costs and grant users flexibility and mobility [2]. In the past decade, there has been a rising interest in wearable sensor-based monitoring systems within the healthcare domain. Various publications have investigated healthcare systems focusing on monitoring physiological activities and motions. Typical hardware devices used in these systems employ the use of computers [3], mobile devices [4,5,6], and a wide range of sensors (heart rate monitor, blood pressure, body temperature, electrocardiogram (ECG), electromyogram (EMG), respiration monitor, accelerometer, gyroscope, etc.) [7,8].

Most of the healthcare systems were designed for different types of patients based on age, disease type, biological signals measured, and other factors. Target users of previous healthcare systems included patients, doctors, therapists and others. For example, Lee et al. developed a healthcare monitoring system for elderly clinical and trauma patients [9], Navarro et al. designed the monitoring system for elderly and infirm patients [10], and Suryadevara et al. integrated a wearable sensor-based healthcare system to monitor health perception and daily activity behavior for the elderly [8].

Motion tracking techniques are applied in many fields, ranging from animation [18] to clinical applications [3,6]. Current sensor-based motion tracking systems use a variety of sensors aimed to monitor the motion patterns of a patient. Although there are other motion tracking systems on the market (e.g., Xsens [18]), our motion tracking system is low cost, marker-free, and easy to install and use. Generally, gyroscope and accelerometer data are combined to determine the pose (orientation and position) of a tracked body segment, modeled as a rigid body [11]. Aside from the extra power consumed from continuously sampling multiple sensors, using an accelerometer can produce extra sources of errors, primarily because the accuracy of the measured acceleration is highly sensitive to the accuracy of the measured rotation. It was also necessary to correctly measure the location of the sensors on the body in these studies. In addition to the gyroscope and accelerometer, motion tracking systems may use other sensors such as magnetometers to calibrate the orientation of the sensor which can further increase the cost of these systems. To avoid these issues, the wearable sensor-based motion tracking system introduced in this paper minimizes the types of sensors used and is capable of calibrating without the need of additional equipment, performing additional anthropometric measurements, or measuring the location of the sensors.

This paper is structured as follows: Section 2 outlines our IMU system, experimental set-up, and the algorithm used to extrapolate the upper limb motion from IMU data. In Section 3, the experimental procedure and the method of analyzing the data is described in detail. Section 4 presents the results and discusses the findings. Lastly, Section 5 explains the significance of the research and describes its potential for further investigation.

2. Development of the wearable motion tracking system

2.1. Overview

We developed an upper limb motion tracking system using three low-cost SensorTag wireless sensor units from Texas Instruments. The onboard IMUs were used to track the upper arm and forearm, transmitting the sampled data via the device's Bluetooth module. The SensorTag uses the IMU-3000 gyroscope by InvenSense. Each gyroscope was set to a range of ±250 degrees per second with a sampling frequency of 50 Hz, which is sufficient to track a subject's motion with high accuracy. The SensorTag uses the KXTJ9 acceleromter by Kionix. Each accelerometer has its range set to ±4 G and its sampling rate set to 5 Hz. The bluetooth module used on the SensorTag is the CC2541 by Texas Instruments. It complies to Bluetooth Low Energy (BLE) specifications which was developed to address the need for robust wireless communication under low power settings with a focus on consumer and healthcare applications [12]. With this set-up, it is possible to use a Bluetooth enabled laptop to connect to and gather data from multiple SensorTags simultaneously.

To validate the accuracy of our system and model, we used the OptiTrack System, a commercially available, marker-based, optical motion capture system by NaturalPoint. It uses a Velcro suit to which 36 retroreflective markers were attached. These markers were tracked by 12 specialized cameras equipped with infrared LEDs. Fig. 1 outlines the underlying principle guiding the experiment through which our system's accuracy will be assessed. The