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Inertia sensor-based guidance system for upperlimb posture correction

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ABSTRACT

Stroke rehabilitation is labor-intensive and time-consuming. To assist patients and therapists alike, we propose a wearable system that measures orientation and corrects arm posture using vibrotactile actuators. The system evaluates user posture with respect to a reference and gives feedback in the form of vibration patterns. Users correct their arm posture, one DOF at a time, by following a protocol starting from the shoulder up to the forearm. Five users evaluated the proposed system by replicating ten different postures. Experimental results demonstrated system robustness and showed that some postures were easier to mimic depending on their naturalness.

1. Introduction

Demand on the healthcare system rises in proportion to the aging population. Technology can fill in the supply gap by providing automated systems to augment healthcare services [1]. For rehabilitation, the advent of small inertia-based sensors and feedback devices like vibrotactile actuators could help improve healthcare delivery.

Micromachined accelerometers, gyroscopes, and magnetometers are sufficiently small to be attached to the human body without interfering with movement. Accelerometers are used as inclinometer for motion where acceleration with respect to gravity are negligible while gyroscopes measure angular velocity and provide estimate in orientation change. Magnetometers determine the local earth magnetic field vector and provide additional information about orientation. These sensors are packaged together to form an inertial measurement unit (IMU), which is relatively cheap and consumes little energy.

IMU had been employed in posture measurement and rehabilitation: quantifying hemiparesis by measuring hand path in pointing tasks [2], treating idiopathic scoliosis [3], and detecting and assessing severity of Parkinson's disease [4]. Moreover, accelerometers had been used to detect trunk posture [5], and inertia sensors to measure full body motion [6] and determine gait kinematics [7]. Other technologies that have been proven effective in stroke patient rehabilitation include functional electrical stimulation (FES) for artificial activation of the skeletal muscles [8,9].

Interestingly, sensing user movement may not be sufficient. Feedback from therapists also plays an important role in informing patients of their progress leading to better chances of recovery [10]. Feedback can be audio, visual, tactile, or any combination thereof. Audio feedback was used in [11], where patients adjusted their trunk posture depending on feedback quality. In [12], audio and visual cues from the teacher were aided by a robotic suit that employed tactile feedback to guide the movement of the upper limb. Vibrotactile was used in [13] to improve dynamic gait of the elderly. Improvements in motion performance of Tai-Chi practitioners were realized using vibrotactile feedback complemented with audio feedback [14]. In [15,16], visual and tactile feedback were used to guide the subjects in replicating the target arm posture. A comparison of selected works is presented in Table 1.

The works cited demonstrate the robustness of inertia-based sensors in measuring limb, trunk, or full body posture and the importance of feedback in correctly replicating the desired postures. This paper presents a system that uses inertia-based sensors to measure arm posture and vibrotactile actuators to guide arm posture correction. Also presented is a protocol in measuring complete arm posture that requires only two IMUs and two vibrotactile actuators.

The optimized design combination of inertia sensors and vibrotactile feedback to correct arm posture is the main contribution of this paper. The system finds the balance between number of inertia sensors needed and the number of joints (DOFs) that has

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Table 1
Comparison of works that used vibrotactile feedback.

Work	Purpose	Body part measured	Measurement device	Vibrotactile device
[5]	Balance training	Trunk (mediolateral sway)	Microstrain Inertia-Link IMU	Tactaid VBW32 (4 units)
[12]	Motor learning	Arm (5DOF)	Vicon	Tactaid (8 units)
[13]	Risk fall indicator	Trunk (mediolateral sway)	IMU	Tactaid VBW32 (48 units)
[14]	Gesture correction	Upper body (14DOF)	Vicon	SHAKE
[16]	Motion replication	Arm (5DOF)	K-Health IMU	Solarbotics VPM2 (3 units)

to be measured. The key is the protocol that allows optimum conveyance of feedback information to the users while using the minimum number of vibrotactile motors. While other works have used inertia-based sensors and vibrotactile feedback in various applications, ours focuses particularly on rehabilitation, where accurate posture measurement and timely feedback could aid the patient in regaining lost muscular abilities.

The rest of the paper is organized as follows. Section 2 introduces the mathematical foundations of using IMU to measure and correct arm posture. Section 3 discusses the method for guiding arm posture correction while Section 4 presents the system design and method implementation. Section 5 details the experimental setup and Section 6 presents the experimental results. Section 7 concludes the paper and lists future work.

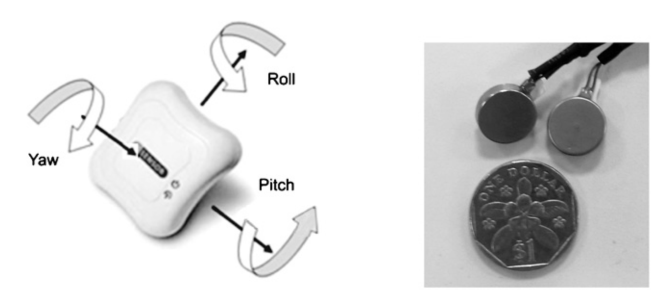
2. Measuring and correcting arm posture

2.1. Working principle of the IMU sensor

Each inertial measurement unit (IMU) sensor has an accelerometer, a magnetic sensor and two gyroscopes inside. The IMU's roll (φ) is the angle measured around the x-axis (parallel to the ground), its pitch (ρ) is the angle around the y-axis (parallel to ground), and its yaw (θ) is the angle around the z-axis (parallel to gravity). The IMU with its orientation axes is shown in Fig. 1(a).

The orientation of the IMU $[\varphi_{acc}(t)\,\rho_{acc}(t)\,\theta_{acc}(t)]$, is derived from the angular velocities $[\omega_x\,\omega_y\,\omega_z]$ about the three axes of the gyroscope. The angular displacements are calculated by integrating the angular velocities:

$$\begin{aligned}\varphi_{gyro} &= \int_{t_i}^{t_f} \omega_x\,dt \\ \rho_{gyro} &= \int_{t_i}^{t_f} \omega_y\,dt \\ \theta_{gyro} &= \int_{t_i}^{t_f} \omega_z\,dt\end{aligned} \tag{1}$$



(a) The inertial measurement unit (IMU) sensor, with its axes shown. (b) The vibrotactile actuators.

Fig. 1. The sensors and actuators.

Given the angular value at $(t-1)$ and Δt, the numerical approximation becomes:

$$\begin{aligned}\varphi_{gyro}(t) &= \varphi_{gyro}(t-1) + \omega_x \Delta t \\ \rho_{gyro}(t) &= \rho_{gyro}(t-1) + \omega_y \Delta t \\ \theta_{gyro}(t) &= \theta_{gyro}(t-1) + \omega_z \Delta t\end{aligned} \tag{2}$$

We use the accelerometer measurement to correct for the gyroscope integration error. Finally we obtain the rotation matrix:

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{3}$$

where,

$$\begin{aligned}
r_{11} &= \cos(\varphi)\cos(\rho) \\
r_{12} &= -\sin(\varphi)\cos(\theta) + \cos(\varphi)\sin(\rho)\sin(\theta) \\
r_{13} &= \sin(\varphi)\sin(\theta) + \cos(\varphi)\sin(\rho)\cos(\theta) \\
r_{21} &= \sin(\varphi)\cos(\rho) \\
r_{22} &= \cos(\varphi)\cos(\theta) + \sin(\varphi)\sin(\rho)\sin(\theta) \\
r_{23} &= -\cos(\varphi)\sin(\theta) + \sin(\varphi)\sin(\rho)\cos(\theta) \\
r_{31} &= -\sin(\rho) \\
r_{32} &= \cos(\rho)\sin(\theta) \\
r_{32} &= \cos(\rho)\cos(\theta).
\end{aligned} \tag{4}$$

2.2. Arm model

Fig. 2 illustrates the two arm segments (upper arm and forearm); each has distinct curvature and range of motion. Arm motion, particularly of the elbow and the wrist, can be modeled as a compound flexible pole (CFP). A flexible pole is capable of bending and rotating in three dimensions with no significant deformation along its length.

Each arm segment is modeled as a CFP, a rigid body with an IMU sensor attached, and treated as massless for orientation

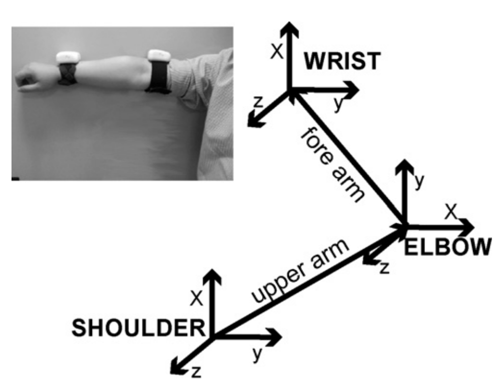


Fig. 2. A compound flexible pole model divides the arm into two main sections: the forearm and the upper-arm. The inset shows where the two IMU sensors are mounted on the arm.