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Innovations Influencing Physical Medicine and Rehabilitation

Wearable Movement Sensors for Rehabilitation: A Focused Review of Technological and Clinical Advances

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Abstract

Recent technologic advancements have enabled the creation of portable, low-cost, and unobtrusive sensors with tremendous potential to alter the clinical practice of rehabilitation. The application of wearable sensors to track movement has emerged as a promising paradigm to enhance the care provided to patients with neurologic or musculoskeletal conditions. These sensors enable quantification of motor behavior across disparate patient populations and emerging research shows their potential for identifying motor biomarkers, differentiating between restitution and compensation motor recovery mechanisms, remote monitoring, telerehabilitation, and robotics. Moreover, the big data recorded across these applications serve as a pathway to personalized and precision medicine. This article presents state-of-the-art and next-generation wearable movement sensors, ranging from inertial measurement units to soft sensors. An overview of clinical applications is presented across a wide spectrum of conditions that have potential to benefit from wearable sensors, including stroke, movement disorders, knee osteoarthritis, and running injuries. Complementary applications enabled by next-generation sensors that will enable point-of-care monitoring of neural activity and muscle dynamics during movement also are discussed.

Introduction

Rapid advancements in electronics and computing have created an opportunity and responsibility [1] to translate these technologic advances to rehabilitation. In particular, wearable sensors have emerged as a promising technology with substantial potential to benefit a wide range of individuals, from patients living with mobility deficits to high-performance athletes recovering from an injury. Wearable sensors provide precise quantitative measurements of human movement, enabling tracking of the effects of disease or injury through their influence on the movement system. Importantly, the portability of wearable sensors allows their use in free-living environments, thus providing more ecologic and rich data related to health and disability. Wearable sensors provide an opportunity for the collection of big data across clinical and real-world settings, enabling the growth of personalized and precision medicine [2].

The field of wearable sensors has seen exponential growth during the past decade; however, widespread clinical use of this promising technology has yet to be realized. Clinical applications of wearable sensors include remote monitoring [3], mobile health [3,4], and expansion of health metrics beyond traditional clinical settings [5]. This focused review begins with a summary of the state of the art in wearable movement sensors and their current applications to neurologic and orthopedic rehabilitation, followed by emerging clinical applications. The review concludes with an overview of next-generation sensor technologies that expand motion sensing through hybrid sensors, neural interfaces, and soft sensors.

Literature Selection

To characterize (i) state-of-the-art, (ii) emerging, and (iii) next-generation wearable sensor technologies used in neurologic and orthopedic rehabilitation, a literature search was performed using the Medline, PubMed, and CINAHL databases. Studies published from 2013 through 2018 were the focus of this search. Search delimiters included studies published in English and

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studies with adult human participants. Discussion was steered toward stroke and movement disorders to exemplify applications in neurologic rehabilitation and toward knee osteoarthritis (OA) and running to exemplify applications in orthopedic rehabilitation. Sample keywords and their combinations included *sensors*, *rehabilitation*, *stroke*, *Parkinson's disease* (PD), *Huntington's disease* (HD), *osteoarthritis*, and *running*.

Review of Evidence

Recovery of motor function is a major goal of neurologic and orthopedic rehabilitation. Rehabilitation interventions facilitate motor learning by leveraging repetitive, progressive, and task-specific motor practice provided in sensory-enriched environments [6]—treatment parameters that enhance activity-dependent plasticity in the central nervous system [7]. Precise measurements of motor behavior over different timescales might assist in exploring and optimizing motor learning. Wearable motion sensors enable the objective measurement of body orientation, motion, direction, and physiologic state during movement in ecologic settings [8], thus providing clinicians with data that can be used to guide and enhance rehabilitation activities.

State-of-the-Art Technology

Force-based sensors are commonly integrated with footwear to measure the interaction of the body with the ground during walking [9]. These sensors include load-sensitive switches or force-sensitive resistors that characterize gait based on the configuration of the sensors. A single sensor attached to the heel allows detection of heel-strike and heel-off phases of gait, whereas multiple sensors within an insole enable examination of walking strategies [10], center of pressure translations [11], and the estimation of vertical ground reaction forces throughout the gait cycle [12]. Force-based sensors also are used to drive auditory [13,14] and visual [12] biofeedback during gait training [13,14]. Limitations of force-based sensors include their susceptibility to mechanical wear over time, limited direct measurements to events during the stance phase [9], and potential drift secondary to humidity and temperature inside the shoe [15] that can influence data quality.

Gyroscopes measure the rate of change of angular motion by detecting the Coriolis forces that act on a moving mass in a rotating reference frame. These forces are proportional to the rate of angular rotation of the limb. Gyroscopes are secured to body segments in line with the plane of movement that is being measured [16], and tri-axial gyroscopes allow 3-dimensional measurements. Particular strengths of gyroscope sensors are that their measurements are not influenced by gravitational forces [17] and vibrations during heel strike do not distort the signal [18].

Accelerometers measure body movements based on the rate of change of speed. The measurement principle underlying accelerometry is commonly explained by a mass-spring system [19]. Based on displacement of the mass element, the resultant acceleration is derived [19]. Although there are several classes of accelerometers, the most commonly used in rehabilitation research are strain gauge, capacitive, piezo-resistive, and piezoelectric [19]. Accelerometers used in rehabilitation commonly have 1 to 3 sensing axes, which allow motion detection in 1- to 3-dimensional space. Accelerometers are commonly used for continuous monitoring of gait, mobility, and activities of daily living. Accelerometer signals can be used to compute position or velocity; however, drift from integration decreases data quality [18]. Additional limitations associated with the use of accelerometers include poor reliability when measuring non-dynamic events [20] and the influence of gravity on the acceleration signal [9]. Various signal processing strategies are being developed to improve data quality [9].

Magnetometers are devices that detect the Earth's gravitation vector. Their measurements provide compass heading information and a reference measure for body orientation relative to gravity [9]. Because magnetometers are insensitive to acceleration during dynamic movements, their use alongside accelerometers allows separation of gravitational components from kinematic acceleration data. Moreover, given the qualities and limitations of gyroscopes, accelerometers, and magnetometers, these sensor types are often combined in self-contained devices called inertial measurement units (IMUs) to optimize measurement capabilities. Force-based sensors offer additional insight into a wearer's interaction with the environment and also have been used alongside IMUs. By and large, limitations in the quality of individual sensor signals can be addressed with advanced processing and intelligent algorithms [21]. The following section provides an overview of applications of these sensors across neurologic and orthopedic domains.

State-of-the-Art Clinical Applications

Wearable sensors are portable, low-cost, and unobtrusive tools that provide objective, quantitative, and continuous information about motor behavior in a range of environments. Clinically, wearable sensors have been used for assessment, including the instrumentation of common mobility tests [22], identification of pathologic movement [23,24], characterization of disease stage [25], falls management [26,27], and activity recognition (AR). They also have been used to augment treatments, such as enabling biofeedback-based gait training [12,28,29]. This section cites specific examples of these clinical applications (Table 1).