Smart Sensors, Measurement and Instrumentation 47

Robert LeMoyne
Timothy Mastroianni

Wearable and Wireless Systems for Healthcare I

Gait and Reflex Response Quantification

Second Edition

Springer

Smart Sensors, Measurement and Instrumentation

Volume 47

Series Editor

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ISSN 2194-8402 ISSN 2194-8410 (electronic)
Smart Sensors, Measurement and Instrumentation
ISBN 978-981-97-2438-3 ISBN 978-981-97-2439-0 (eBook)
https://doi.org/10.1007/978-981-97-2439-0

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The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

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In Memoriam:

Lori Mete-Mastroianni (1955–2005)
For Lori Mete-Mastroianni, my beloved wife and guiding star. Your wisdom and compassion as an educational counselor not only shaped countless lives but profoundly impacted mine. I would not be where I am today without your love and guidance.

David Peduto (Lt. Col. US Army) (1954–2016)
To a friend, valued research team member, and Patriot.

Jonathan Swift Ph.D. (1932–2017)
To an incredible teacher who made learning an adventure.
"Think globally, and act locally!"

Wes Stewart (1924–2017)
Cousin Wes you are a dearly cherished member of our family and the personification of America's Greatest Generation. You are deeply missed. I take comfort knowing everybody has an angel.

To my wife, thank you for everything. Love Always.

I would like to thank my Mother, Father, and brother for their support.

“Nothing transcends the power of the human spirit.”
from a homeless Vietnam Veteran and very loyal friend
And in the wind he’s still alive.

“To beat a tiger, one needs a brother’s help.”
Chinese Proverb
Thanks Tim.

Chiri mo tsumoreba yama to naru.
A favorite Japanese Proverb (in Romaji)
Translation:
Even dust piled up becomes a mountain.

Preface

The domain of wearable and wireless systems for biomedical and rehabilitation applications, such as through smartphones and portable media devices, is anticipated to grow exponentially. Even from the time of presenting the draft manuscript of this book to the time of publication, the prevalence of this subject is expected to undergo meaningful transformation and evolution. These devices enable wireless inertial sensor applications to an assortment of scenarios pertaining to rehabilitation and therapy.

Since 2010 when LeMoyne, Mastroianni, and our research team applied a novel smartphone application for quantifying Parkinson's disease tremor and gait quantification in the context of a wireless accelerometer, the opportunities have expanded considerably. The authors are delighted to provide a contribution to this exciting field with the anticipation of the considerable array of developments in years to follow. Please enjoy the knowledge and intellectual inspiration that our book provides with the goal of providing meaningful, robust, and optimal rehabilitation for many.

Flagstaff, AZ, USA — Robert LeMoyne
Pittsburgh, PA, USA — Timothy Mastroianni

Contents

Chapter 1
Wearable and Wireless Systems for Gait Analysis and Reflex Quantification

Abstract The capacity to quantify the movement features of a person undergoing the rehabilitation process enables therapists and clinicians to proactively optimize the therapy strategy. Wearable and wireless systems, such as the smartphone and portable media device, are equipped with accelerometers and gyroscopes that can readily quantify aspects of human movement pertinent to rehabilitation, such as gait and reflex response. The smartphone and portable media device can measure gait and reflex response through their inertial sensors, and the acquired data can be conveyed by wireless transmission to the Internet as an email attachment. This capability enables the experimental site and post-processing resources to be remotely situated. Three phases of the evolution of quantification techniques for the rehabilitation process are observed, which are characterized as a first, second, and third wave. The first wave pertains to the traditional ordinal scale approach used by expert clinicians. The second wave emphasizes the role of quantification systems that are generally constrained to a clinical setting. The third wave envisions the development of Network Centric Therapy through the application of wearable and wireless systems, such as smartphones and portable media devices, for quantifying movement characteristics, such as gait and reflex response. Network Centric Therapy encompasses a quantum leap in rehabilitation capability through Cloud Computing amalgamated with machine learning with patient and therapy team situated remotely anywhere in the world. A summary of each chapter is further presented.

Keywords Wearable and wireless systems · Smartphone · Portable media device · Accelerometer · Gyroscope · Gait · Gait analysis · Reflex response · Reflex response quantification · Ordinal scale · Quantification apparatus · Network Centric Therapy

R. LeMoyne and T. Mastroianni, *Wearable and Wireless Systems for Healthcare I*,
Smart Sensors, Measurement and Instrumentation 47,
https://doi.org/10.1007/978-981-97-2439-0_1

1.1 Introduction

The capacity to quantify trends in a patient's rehabilitation enhances the acuity for a team of clinicians to refine the therapy strategy and prescription [1–6]. Inertial sensors, such as accelerometers and gyroscopes, have been proposed for the quantification of human movement characteristics, such as gait and reflex [3–7]. With recent advances in microelectronics and wireless technology wearable and wireless accelerometer and gyroscope systems have permeated the fields of biomedical engineering and healthcare with previous arrangements, such as tethered sensor systems, becoming effectively obsolete [3–6, 8].

The progressive integration of wearable and wireless systems are envisioned to enable a quantum leap with regards to the capabilities of the biomedical and healthcare environment. Inertial sensors, such as the accelerometer and gyroscope, can facilitate a therapist's acuity with regards to the nature of the patient's movement quality in the context of the therapy response. In particular wearable and wireless devices are forecasted to considerably advance the rehabilitation experience, especially with regards to gait analysis and the associated quantification of reflex characteristics.

Essentially the presence of wearable and wireless systems with inertial sensors, such as the accelerometer and gyroscope, is representative of the Internet of Things for the biomedical community. The objective of the book is to provide a perspective of the role of wireless accelerometer and gyroscope sensor apparatus that are also wearable for the advance of rehabilitation and therapy in the context of gait analysis and correlated aspects, such as reflex quantification. This book sequentially advocates the evaluation to Network Centric Therapy, which is predicted to radically advance the efficacy of the rehabilitation experience.

An advantage of the wearable and wireless accelerometer and gyroscope system is the considerable flexibility of available devices for the scenario under consideration. One of the first and most fundamental pathways was with regards to the application of wireless accelerometer nodes for the domain of gait and reflex quantification. Wireless accelerometer nodes were successfully demonstrated for the accurate and reliable quantification of gait and reflex characteristics. At this level of technology evolution wireless accelerometer nodes would locally transmit data packages by wireless connectivity to a nearby situated PC [6, 9–22].

Further research and investigation respective of the technology pathway sought to acquire wireless capabilities that could better access the Internet directly. Equipped with the proper software application the smartphone is capable of functioning as a wireless accelerometer platform and also a wireless gyroscope platform. The recorded data package could be wirelessly conveyed to the Internet as an email attachment, and the data could be post-processed remote from the experimental location. Beginning in 2010 LeMoyne and Mastroianni have thoroughly researched, developed, tested, and evaluated the role of the smartphone for the accurate and reliable quantification of gait and reflex response features [3–5, 23–37]. With the

successfully demonstration of the smartphone as a gait analysis tool a multitude of clinically relevant applications have advocated its wireless inertial sensor capability [3–5].

Another similar wearable and wireless system relative to the smartphone is the portable media device. Using the same operating system as the smartphone the portable media device is readily capable of likewise functioning as a wireless accelerometer platform and wireless gyroscope platform. The primary differentiator between the portable media device and smartphone is the device cost and wireless accessibility to the Internet. A portable media device imparts a fixed cost; however, the smartphone generally requires a marginal cost to sustain the telecommunication package. The portable media device requires localized wireless Internet connectivity, and by contrast the smartphone can access the Internet through a broad telecommunication footprint. Research, development, test, and evaluation has demonstrated the ability of the portable media device as a wireless accelerometer and gyroscope platform for the quantification of gait and reflex response similar to the capabilities of smartphone [3–5, 37–49].

Further developments with respect to the capabilities of wireless and wearable systems for quantifying rehabilitation status are evident in light of local Bluetooth wireless connectivity. The concept of Bluetooth wireless offers the capacity to locally connect the inertial sensor node to the more broadly Internet accessible devices, such as a tablet, portable media device, and smartphone. This design perspective alleviates mass encumbrance and mounting complexity of the sensor node to the patient being monitored. For example, the relevance and acuity of the Timed 25 Foot Walk test has been considerably advanced through the application of a wireless accelerometer and gyroscope sensor node locally positioned about the ankle joint. The experimental trial data package is then streamed by Bluetooth wireless connectivity to a tablet, and the tablet then transmits the data to an Internet resource, such as a Cloud Computing database [50].

These available capabilities regarding the broad domain of wearable and wireless accelerometer and gyroscope sensors coalesce to promote the potential for Network Centric Therapy. Network Centric Therapy comprises the capabilities of rehabilitation and advanced therapy in consideration of the Internet of Things. In essence Network Centric Therapy would involve Cloud Computing level storage and post-processing of therapy and rehabilitation based on quantified data from wearable and wireless accelerometer and gyroscope sensors used by the patient.

There are a considerable array of utility that Network Centric Therapy offers for the biomedical and rehabilitation community, the therapist regarding enhanced acuity and awareness of the efficacy of the therapy strategy, and the patient's experience of optimal rehabilitation and timeliness of recovery. This concept promotes augmented patient intensive and focused therapy. The inherent nature of this envisioned rehabilitation technique is logistically robust.

A patient can provide the therapist ample quantified data as to the status of the rehabilitation experience from the convenience of a familiar and therefore highly relevant home bound environment through the application of wearable and wireless sensors systems, such as accelerometers and gyroscopes. For example, a therapist could

evaluate a patient from on the order of thousands of miles remote with respect to the quality of gait characteristics in consideration of a prescribed therapy strategy. A key feature to Network Centric Therapy is the observation that the patient and therapist can reside in considerably geographically remote locations, while proactively interacting for optimal rehabilitation. Data could be stored in a Cloud Computing resource for further post-processing, such as machine learning classification for prognostic acuity of therapy strategy progression.

Network Centric Therapy through the application of wearable and wireless systems to ascertain patient rehabilitation status integrates the therapy experience with bioinformatics and data science. This cloud based computing configuration would enhance trend assessment as to the efficacy of therapy strategy and suitability for alternative techniques. Such large scales of rehabilitation data for a vast number of patients would permit further optimization of the rehabilitation experience.

The available inertial sensor data provided through wearable and wireless systems for objectively quantifying patient rehabilitation feature sets can readily be consolidated for machine learning. Preliminary demonstration of the role of machine learning for wearable and wireless accelerometer and gyroscope sensor systems have been demonstrated for differentiating between hemiplegic affected and unaffected limbs with considerable classification accuracy [36, 48, 49]. Machine learning classification of rehabilitation status can augment the situational awareness and prognostic acuity for a therapist to progressively advance the sophistication of the therapy strategy. The implication is optimized therapy through machine learning in consideration of strategy efficacy and hastening time to a sufficient degree of convergence. The synergy of these capabilities should ameliorate strain on the limited availability of medical resources available for rehabilitation.

Furthermore the development of Network Centric Therapy through the application of patient focused wearable and wireless inertial sensor systems is envisioned to promote more geographically flexible application of medical resources. This is particularly apparent that the wearable and wireless accelerometer and gyroscope sensors have soundly established that the patient and therapist can reside remote [3–5]. For example, consider a scenario for which the most experienced group a therapists for a specific form of rehabilitation are uniquely located in Boston; however, a person in need of such expert resources lives far remote in rural Arizona.

In light of previous rehabilitation technologies the prospect of utilizing expert therapists in Boston to proactively instill a rehabilitation strategy for a person in a remote and rural part of Arizona would be logistically daunting. With wearable and wireless accelerometer and gyroscope sensor systems interconnected to the Internet to evaluate the quality of gait rehabilitation, a subject could readily utilize such a device to quantify the status of rehabilitation to the therapist situated far away in Boston. The therapist could then have the data samples post-processed with machine learning to distinguish the appropriate phase of the rehabilitation cycle or even propose an alternative intervention. This capability would be also highly relevant in the event that a group of expert therapists reside in a specific location with a growing patient need remotely situated.

Further implications of the value of wearable and wireless inertial sensors for quantifying rehabilitation status are the contextually realistic nature of the sensor data acquired in a patient's familiar environmental setting as opposed to a brief clinical snapshot of the recovery status. A clinical snapshot may not reveal the true nature of the patient's state of rehabilitation. By contrast the wearable and wireless inertial sensors can establish a progressive historical perspective of the patient's rehabilitation. More proactive intervention is enabled and the therapy strategy can be optimized. Advanced and future therapy strategies can be developed with the support of Cloud Computing data of multiple patients through the application of data mining techniques.

The internationally renown futurist Alvin Toffler envisioned the 'Third Wave', which may be compared to growing prevalence of wearable and wireless accelerometer and gyroscope sensors for gait and associated reflex quantification leading to Network Centric Therapy. To summarize Toffler's visionary Third Wave requires addressing the previous First Wave and Second Wave. The First Wave pertains to the advance of agricultural technology. The Second Wave encompasses the industrial revolution. Toffler's insight as to the Third Wave involves the expansion of the revolutionary developments of the Information Age [51].

The dawn of wearable and wireless systems, such as accelerometer and gyroscope sensors, for gait analysis and associated reflex quantification that facilitates the development of Network Centric Therapy draws analogies to Toffler's Third Wave. The First Wave comparative is discussed in Chap. 2 that involved the expert yet subjective interpretation of a highly skill clinician, which would provide relatively basic information as to the patient's rehabilitation status, such as a ordinal scale rating. The Second Wave metaphor is featured in Chap. 3. This Second Wave analogy as discussed in Chap. 3 provides clinically standard quantification techniques; however, they are confined to a clinical setting and require specialized resources.

The Third Wave analogy is the rise of wearable and wireless systems, such as accelerometer and gyroscope sensors, for gait analysis and associated reflex quantification. These devices link with Internet connectivity for the potential of Network Centric Therapy. This concept represents a true Information Age perspective that utilizes the Internet with patient intensive rehabilitation. Other associated technologies, such as remote post-processing and machine learning, are cornerstones to the application of wearable and wireless systems for gait analysis and associated reflex quantification. The cohesion of these capabilities is envisioned to provide a quantum leap regarding optimal rehabilitation while ameliorating strain on limited medical resources.

1.2 Summary of the Pending Chapters

The following chapters are sequentially organized regarding the evaluation of rehabilitation techniques and technology. They provide both historical perspective and insight as to future capabilities. The procession of each book chapter further

advocates and establishes the realization of wearable and wireless systems, such as accelerometer and gyroscope sensors, for gait analysis and associated reflex quantification in conjunction with the eminence of Network Centric Therapy.

Chapter 2: The most basic and standard means of quantifying a subject's rehabilitation status is with the application of an ordinal scale system. The highly trained and specialized clinician serves a critical role for this technique. There are multiple ordinal scale techniques that pertain to gait and reflex response quantification, for which each ordinal scale assignment corresponds to a specific series of criteria. In essence a clinicians expert, although subjective interpretation is critical for the determination of the patient's rehabilitation status.

Even through the ordinal scale ranking is specified by a highly skilled and expert clinician the reliability of the ordinal scale is a subject of controversy. As Chap. 2 demonstrates, even the reliability of five point and nine point scales for determining reflex response are contested. They discovery of a hemiplegic reflex pair is also a debatable topic.

Furthermore Chap. 2 advocates that the decrements of abnormal gait strategies are minute in nature. Clinical techniques for quantifying gait are highly related to clinical experience. More complex techniques for assessing neurodegenerative scenarios, such as Friedreich's ataxia, that are intrinsically related to gait quality, apply techniques like the Timed 25 Foot Walk test.

As future chapters advocating wearable and wireless accelerometer and gyroscope sensors demonstrate, these sensors can provide considerably more refined and thorough data, such as to augment the conventional Timed 25 Foot Walk test. Chapters 7 and 9 demonstrate that these wireless and inertial sensors can be worn during gait and provide signal data for the objective and quantified machine learning classification of subject health status. This quantum leap in biomedical and rehabilitation technology represents the considerable potential of Network Centric Therapy.

The historical evolution of clinical quantification techniques proceeds from the metaphorical First Wave of the ordinal scale approach to the Second Wave era pertaining to the development of electro-mechanical and optical systems that are generally confined to a laboratory environment. These devices are addressed in Chap. 3.

Chapter 3: Further technology evolution enabled the development of electromechanical and optical devices for the quantification of gait. This capability constitutes in effect the Second Wave metaphor for the quantification of human movement, such as gait. These devices promote meaningful quantitative feedback, which can be readily applied to the determination of rehabilitation efficacy. In particular there are six standard devices applied to the traditional domain of gait analysis:

- Foot switches
- Electrogoniometers
- Electromyogram (EMG)
- Metabolic analysis
- Optical motion cameras
- Force plates