Interfacing Engineering Technology and Rehabilitation: A New Frontier for Physical Therapy

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ABSTRACT

Orthopaedic physical therapy uses a management approach focused on accelerating recovery after injury or disease. While physical therapists use a repertoire of techniques to manage different musculoskeletal conditions, there is still much to be learned about how physical therapy interventions can be applied to optimally link structure and function of the human movement system. Gaps in our understanding can be partially attributed to the fact that quantifying the impact of physical therapy applications at the molecular, cellular, and systems levels is complex and mostly unknown. In this monograph, we review concepts of sensing technologies and robotic interfaces that hold great promise in addressing our knowledge gaps, as well as expanding the possibilities of how physical therapy can evaluate, treat, and monitor complex interactions within the human movement system following disease or injury. Indeed, physical therapists will be vital in providing critical information for design and development of future generation of sensing technologies and robot interfaces, which will further enhance orthopaedic practice. Rather than the passive consumer of these technologies, physical therapists must evolve into proactive partners, working with engineers, to induce discoveries that will optimize best practice principles for our patients.

Key Words: sensors, robots, orthopaedic physical therapy

LEARNING OBJECTIVES

Upon completion of this monograph, the course participant will be able to:

1. Define 3 major fields establishing connections with physical therapy via engineering technologies.
2. Discuss different types of sensing technologies and their potential role in rehabilitation.
3. Define robotics and describe the advantages and challenges of using robots in orthopaedic physical therapy.
4. Describe how engineering technologies are expanding physical therapy practice.

INTRODUCTION

Medical referrals are routinely given for orthopaedic physical therapy to accelerate recovery after orthopaedic surgery, fractures, acute sports/work-related injuries, arthritis, sprains, strains, pain, neuromuscular disease or injury, and amputations. In such cases, the physical therapist uses a repertoire of techniques to manage these conditions. The management approach ultimately will engage complex interactions between the musculoskeletal, nervous, cardiovascular, pulmonary, and endocrine systems (ie, human movement system). Endogenous sensing (eg, spindles, vision, mechanoreceptors, etc) and actuating (eg, skeletal muscle) capabilities enables the human movement system to detect and elicit structural changes throughout the integumentary.[1] Although orthopaedic physical therapy outcomes are often favorable, there is little debate that there is still much to be learned about how, why, and when tools and techniques can be applied to further elicit more precise, efficient, and beneficial outcomes. Currently, physical therapists have limited knowledge about the extent to which their prescribed interventions result in long-term beneficial effects that optimally link structure and function of the human movement system.

Greater emphasis on ways to interface engineering technologies with physical therapy is a priority. Members from the American Physical Therapy Association (APTA), APTA Education Leadership Council, and APTA Orthopaedic Section and Academy of Neurologic Physical Therapy leaders suggest that collaboration between physical therapists and engineers will help to solve knowledge and technical gaps in justifying how and why our clinical services are vital. Indeed, the APTA-sponsored Physical Therapy and Society Summit (PASS) in 2009 urged interdisciplinary efforts to critically assess ways: (1) physical therapy induces physiological stressors on the human movement system that result in restoration of functional movements; and (2) engineering technologies can substitute, facilitate, and/or measure physiological responses to interventions at molecular, cellular, tissue, and system levels.[2] Few would disagree with the APTA PASS recommendations that using interdisciplinary collaborative strategies have the greatest potential to improve recovery after orthopaedic-related injury or disease.

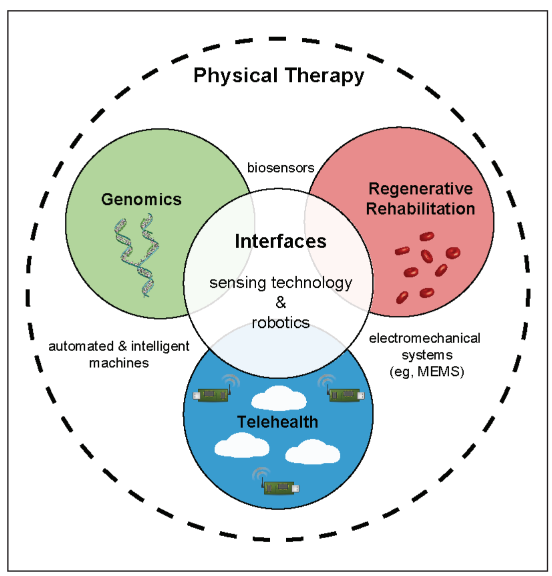
Quantifying the impact of physical therapy applications at the molecular, cellular, and system levels is complex, but very important for verifying efficacy. For instance, how does manual therapy alter molecular and cellular activity to enhance functional recovery? Studies using various biosensing technologies have shown that mechanical stimuli (eg, touch) transduces bioelectrical and/or biochemical changes including a broad range of protein-mediated coupling pathways and cellular cascades (ie, G-proteins, growth factors, ion channeling) that give rise to repair and regeneration of injured or diseased tissue.[3] Exogenous stimulation frequently used by physical therapists (eg, electrical stimulation, vibration) can also trigger molecular and cellular mechanisms that modulate muscle activity,[4-8] tissue remodeling,[9,10] angiogenesis,[11-14] and neural activity.[15,16] Engineering technologies capable of quantifying these targeted therapies with greater precision than measures currently at our disposal will eventually translate to more effective treatments and subsequently greater functional outcomes. Technologies that can shed light on the extent to which orthopaedic physical therapy techniques and tools affect mechanisms of recovery are vital for predicting outcomes, prescribing more precise care, preventing injuries from reoccurring, and in a most relevant sense, fostering better communication between the physical therapy and engineering communities.

Indeed, the U.S. health care industry is pushing orthopaedic physical therapists to provide greater evidence for their services.[17,18] To meet this demand, clinicians are becoming more interested in technologies that have the capacity to validate current treatments and predict future needs of patients. Here, we review concepts of sensing technologies and robotic interfaces that aim to expand the possibilities of how physical therapy can evaluate, treat, and monitor complex interactions within the human movement system following disease or injury. In a most realistic perspective, sensing technologies and other engineering feats are intimately linked to advances being made concurrently within other disciplines critical to our own maturation. Content related to genomics, telehealth, and regenerative rehabilitation, while each intricately implicated in present and future physical therapy applications and clinical decisions, have their unique contributions to the science and technology that is helping to define who we are and how our hands-on skills are to be informed (see next sections and Figure 1).

ENGINEERING TECHNOLOGIES THAT INTERFACE WITH PHYSICAL THERAPY

In light of this perception, one can safely conclude that engineering technologies are creating new opportunities for physical therapy. Many are emerging in the form of sensing technologies (eg, biosensors, haptics, and electromechanical systems) and robotics (ie, automated and intelligent machines) that can serve as interfaces to extend the boundaries for physical therapy to include fields such as telehealth, regenerative rehabilitation, and genomics. For example, the field of telehealth has established connections with physical therapy via a wide range of portable, low-cost sensors or automated machines. These wireless devices enable online and offline data-logging for performance tracking and biofeedback (eg, heartrate monitors). Using these devices, client data are stored, transmitted to internet servers, and then downloaded for remote monitoring by a physical therapist (http://www.apta.org/telehealth/). Another example is regenerative rehabilitation, an emerging field that routinely uses micro- and nano-scale technologies to identify biological markers (ie, biomarkers) and treatment delivery outcomes at the molecular (eg, viral vector actions), cellular (eg, stem cell fate), and system (eg, function) levels. These technologies have the capacity to provide fast and accurate ways to tailor treatments that best restore tissue function; interfaces that are directly congruent with the goals driving the field of physical therapy (http://www.apta.org/regenerativerehab/). Sim-

Figure 1. Interfacing engineering technology and rehabilitation.



ilar to regenerative rehabilitation, the field of genomics is applying biosensors and robotics to acquire and process biomarkers that can predict disease and injury prognoses. Establishing quantifiable metrics based upon genetic information will provide physical therapists with information on person-specific risk factors associated with injury propensity, disease development, and responsiveness to targeted therapy (http://www.apta.org/genetics/).

Sensing technologies and robotics will expand the decision-making capacity of physical therapists. For example, off-the-shelf wearable devices are effective in performing gait assessments in patients with a broad range of gait deviations due to various musculoskeletal pathologies. Many can accurately quantify body movements that are comparable in performance to that of laboratory-based tools, but have the advantage of being less expensive and more versatile (eg, allow for testing "in the wild," beyond the clinical laboratory). Accelerometers worn during overground walking can provide good estimation (ie, ~5% error) of body center of mass (COM) accelerations.[19] Bowden et al[20] offered an excellent example of how measurements of COM accelerations can bolster physical therapy decision-making during gait assessments. They point out that COM acceleration measures are effective in providing unique profiles of gait deviations. Since COM acceleration is proportional to force production, these data can help quantify how shaping of the COM profiles are useful in characterizing propulsion and breaking deficits during walking. Quantifying gait biomechanics via sensing technologies demonstrate a greater capacity to capture the effects of physical therapy on gait recovery. These objective measures provide better decision-making capacity for therapists. The measures can be used to assess walking behaviors that extend beyond the confounds of the clinic to real-world environments (eg, variations in terrain, distractions, and ambient conditions. This enables targeted therapies to address a patient's physical demands required for independent community walking at home or at work.[21]

The inherent versatility of these technologies enable more accurate, reliable methods for diagnostics, treatments, and monitoring across a broad range of orthopaedic-related disease and injury and can help predict changes in patient health, safety, responsiveness to treatment, and disease progression.[22] As illustrated in Figure 1, the use of interfacing technologies provides a connection between physical therapy and other interdisciplinary fields already exploiting these technologies.

Nevertheless, much still needs to be learned about the extent to which these technologies can provide viable improvements of physical therapist practice. There are outstanding concerns about whether benefits of these technologies exceed their costs. Many of these concerns emanate from clinicians and health care administrators who may not be adequately trained or prepared to prescribe or design and develop these technologies specific for physical therapy application. Thus, emphasis on ways to overcome this knowledge gap and foster greater interdisciplinary collaboration is crucial. To ensure effective translation of these interfacing technologies to orthopedic physical therapy practice, two key questions should be considered. (1) Do sensing technologies make "sense" for physical therapy? and (2) Is the field of robotics a viable interface for orthopaedic physical therapy?

Do Sensing Technologies Make "Sense" for Physical Therapy?

The intact human body has tremendous capacity to perceive external stimuli through a multitude of endogenous mechanisms. Beyond the 5 commonly recognized senses (eg, sight, smell, taste, touch and hearing), the human body uses an arsenal of receptors and transducers for detecting and processing internal and external stimuli. These receptors include thermoceptors for detecting temperature, proprioceptors for kinesthetic sense, nociceptors for pain, equilibrioceptors for balance, mechanoreceptors for pressure and vibration, and chemoreceptors to detect gas concentrations within the blood. Due to the importance of these sensing mechanisms in ensuring normal homeostasis, any disruption in their feedback can have catastrophic consequences on how humans move and recover after injury or disease. Thus, physical therapists often target these endogenous mechanisms to enhance feedback during critical stages of recovery. For example, therapists use visual (eg, mirror), auditory (eg, voice), and tactile (eg, touch) cues and "props" to encourage goal-directed functional movements and provide patients with feedback on performance. Although these tools can be cost-effective and efficient options in rehabilitation, they lack objectivity, specificity, and standardization. For example (and somewhat jokingly), has anyone ever figured out the metrics underlying the verbal command, "try harder"?

In recent years, engineers have developed cost-effective, automated, sensing devices that provide objective and standardized information to help enhance, restore, or even replace endogenous mechanisms of sensing. Typically, these sensors are comprised of: (1) receptors that record from biological tissue, (2) transducers that amplify and transmit electronic signals, and (3) computer software that converts electronic signals to physical parameters that describe the biological process under evaluation.[23] Collectively, these systems perform a broad range of physical operations and provide reliable and valid platforms for precision care.

Many biological sensors compliment the actions of endogenous sensing mechanisms and convert molecular, cellular, and system level stimuli-induced responses into quantifiable signals for medical diagnostics and treatments (ie, biosensors). Such sensors are commonly recognized for a broad range of tests that include blood, pregnancy, movement disorder, and genetic testing. More recently, small-scale sensing technologies are combining biosensors with “big data” algorithms and additional hardware to acquire, transmit, and process physiological data in real time. These devices can acquire information via epidermal recording, optical sensing, oral sensing, implantable materials, and encapsulated sensors that are ingested. The result is more versatile sensors that can provide fast and accurate evaluation of patient outcomes, as well as provide objective outcomes that can optimize treatment needs and reduce health care costs.

Noninvasive sensors enable clinicians to acquire and transmit continuous physiological data for highly efficient patient monitoring and evaluation. These technologies are cheap, transportable, and wirelessly communicate with a computer or phone. Reducing the size and energy consumption for signal amplification, acquisition, processing, and transmission has drastically improved the capacity of sensors for long-term monitoring use. Indeed, wearable sensing technologies are becoming quite popular in various sports and leisure activities. For example, healthy able-bodied persons are using wearables (eg, Fitbit, Apple watch, phones, etc) to track day-to-day steps, various motions (walking, jogging, running), and heart rate. Computer-aided enhancements enable these devices to provide fast acquisition and consolidation of large quantities of data in meaningful ways.

With continuous advancements in the power of personal computers and handheld devices (eg, phones and tablets), clinicians will have opportunities to use wearable sensing technologies in their clinical-decision making process. For example, microelectromechanical systems (MEMS) can serve as non-invasive, wearable sensors that can detect vital signs (eg, heart rate, electrocardiogram, respiration) with little to no plugs (wireless), as well as measure biomechanics (eg, forces, kinematics, and electrical potentials from muscle [ie, electromyography]). These devices aid in day-to-day monitoring of physiological signals using micro-scale integrated circuits for sensing, processing, and wireless communication on a single chip set.[24] The result is a portable, lightweight system to monitor and transmit physiological and/or biomechanical data to a computer or phone using wireless technologies (ie, Wi-Fi or Bluetooth) for further processing.

The use of MEMS interfaces has expanded the capabilities of off-site, at-home physical therapy services (eg, telerehabilitation) due to their generous storage capabilities and rapid data-logging via wireless interfacing. A recent study demonstrated a proof-of-principle sensing device that used MEMS-based inertial measurement units (IMU) to quantify gait impairment parameters in elderly adults at risk of falls.[25] Colleagues embedded IMU sensors in participant shoes to provide a cheaper alternative to clinic-based gait diagnostics involving sophisticated motion capture systems. Gait analysis based on wearable sensors can provide clinical and instrumented data to help with detection of gait abnormalities, assessment of patient progress before or after orthopaedic surgery, prevention of sport injury, enhancement of athletic performance, and fall risk estimation.[26] Similarly, engineers developed a wearable sleeve to record knee joint kinematics, as well as patient compliance during prescribed home-based exercises.[27] Wearable sensors may also be used to detect improper exercise movements related to rehabilitation exercises commonly prescribed for knee osteoarthritis,[28] thus improving patient management of the rehabilitation process and enabling off-sight monitoring of therapeutic accuracy and progress. Computer software and network server solutions often accompany these technologies so they can help manage and consolidate large clinical data sets, extract useful biomarkers (eg, genomics and regenerative rehabilitation) for personalized physical therapy, and provide a source of data-logging and data-sharing between caregiver and client. In many instances, these software applications can also identify trends related to diagnostics and treatments as well as corresponding outcomes following physical therapy interventions.[29]

Advances in MEMS have led to implantable biosensors that provide ways to more readily quantify the mechanobiology of cells and tissues. Due to the small size, light weight, and low energy consumption, MEMS represent new possibilities for monitoring physiological parameters inside the human body. For implantable joints and tissue, these devices can provide real-time detection of possible infection and component wear, as well as implant loosening and alignment. Implantable MEMS offer information about ligament tensioning that can reduce postoperative pain in persons with total knee replacements. For example, newly instrumented knee joint implants measure biomechanical metrics to identify optimal implant placement, to predict potential loosening, and to assist in precision physical therapy. Microelectromechanical systems can also provide feedback to embedded noninvasive stimulation systems for instrumented implants that induce and control bone growth, while assessing changes in joint mechanics.[30] Using im-