PM R 10 (2018) S220-S232
www.pmrjournal.org

Innovations Influencing Physical Medicine and Rehabilitation

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

Franchino Porciuncula, PT, DScPT, EdD, Anna Virginia Roto, MS, MPH,
Deepak Kumar, PT, PhD, Irene Davis, PT, PhD, Serge Roy, PT, ScD, Conor J. Walsh, PhD,
Louis N. Awad, PT, DPT, PhD

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

https://doi.org/10.1016/j.pmrj.2018.06.013

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).

Table 1
Clinical applications of state-of-the-art technology in select neurologic and orthopedic populations

Clinical application		Sensor (model), associated technology	Findings
Assessment	Clinical instrumentation	IMU (Physilog, GaitUp, Lausanne, Switzerland)	High reliability and low measurement error for most measures taken when used for instrumented TUG in individuals after stroke [22]
	Falls management	Phone-based IMU (Xperia Ray SO-03C, Sony Mobile Communications, Inc, Tokyo, Japan)	Can identify differences in kinematic gait variables in those after stroke with and without a history of falls [26]
		IMU (Opal, APDM Inc, Portland, OR)	Can identify differences in dynamic gait stability between stroke and control cohorts and variables that could play an important role in increased fall risk [27]
	Identification of pathologic motor features	IMU (Kinesia ONE, Great Lakes NeuroTechnologies Inc, Cleveland, OH)	High test-retest reliability and sensitivity in measuring bradykinesia, hypokinesia, and dysrhythmia in those with PD [23]
		iPod-based IMU (iPod, Apple, Cupertino, CA)	Can detect significant differences in trunk control during static activities in people with HD compared with controls; found amplitude of thoracic and pelvic trunk movements was significantly greater in participants with HD [24]
	Activity recognition	IMU (Physilog, GaitUp, Lausanne, Switzerland)	Excellent ability to classify (90.4%) basic activities common to daily life in individuals after stroke (eg, lying, sitting, standing, walking, walking on stairs, and taking an elevator) [30]
		StepWatch Activity Monitor (Orthocare Innovations, Seattle, WA)	Can characterize activity levels without relying on self-report data or clinician opinion [31], assess real-world performance [32], and guide community-based treatments using goal setting [33] for individuals after stoke
		Phone-based IMU (Blackberry Z10, Waterloo, ON, Canada)	Good sensitivity and specificity in detecting immobile (standing, sitting, lying) vs mobile (walking) states, but poor ability to classify more complicated movements (walking up stairs and other small movements) [3] in people with stroke
	Characterization of disease stage	IMU (Opal inertial sensors, APDM, Inc, Portland, OR)	High correlation between disease severity and turning velocity, duration, and step number in those with PD tracked over 7 days [25]
Treatment	Biofeedback	Force sensor; Smart Shoes, custom made; IMUs; Smart Pants, custom made	Significant improvements in balance, mobility, strength, and range of motion comparable to improvements seen with therapist cueing only; suggesting potential use in at-home training for those with PD and after stroke [12]
		IMU (TecnoBody srl, Dlamine BG, Italy)	Improved BBS score and decreased mediolateral sway during standing in participants with PD who received biofeedback with Gamepad during training [28]
		Force sensor (not specified), pager motor (not specified)	Decreased KAM by 14.2% in people with OA [29]

IMU = inertial measurement unit; TUG = Timed Up and Go Test; PD = Parkinson disease; HD = Huntington disease; BBS = Berg Balance Scale; KAM = knee adduction moment; OA = osteoarthritis.

Stroke

Advanced signal processing approaches have enabled IMU instrumentation of popular clinical tests such as the 10-meter walk test [27] and the Timed Up-and-Go Test [22], providing clinically relevant data on movement quality in addition to the traditional outcome of "time to complete." Moreover, advanced AR algorithms have enabled IMU data to be used to identify and quantify gross movements with high sensitivity and specificity [30]. For example, data extracted from IMUs located in mobile phones have differentiated stroke survivors who are fallers from those who are not based on an estimate of inter-stride variability [26]. However, these analyses have been limited when used to quantify more complex movements [4], motivating further work in this area. Accelerometer-based step activity monitors also have been used to monitor physical activity in the home and the community, providing ecologically valid mobility data for the development of treatment-based classifications [31], the assessment of real-world performance [32], and to guide community-based treatment programs [33].

Wearable sensors also have enabled novel gait-training approaches, such as biofeedback-based interventions. For example, a custom body-worn sensor system composed of force sensors and IMUs was used to provide kinematic biofeedback during gait training, leading to improvements in balance, mobility, strength, and range of motion that were comparable to the treatment benefits obtained through therapist-directed gait training [12]. These results demonstrate the potential for wearable sensors to provide effective gait intervention without direct oversight by a clinician (eg, in real-world settings).

Parkinson Disease

As in stroke, AR algorithms have enabled IMU data to be used to identify pathologic motor features characteristic of PD. For example, periods of motor fluctuations between mobile and immobile states (ie, on-off periods) in levodopa-treated individuals were detected using IMU data analyzed with an advanced AR algorithm [34]. Other studies have demonstrated how IMUs can be useful in tracking primary physical symptoms of PD, such as tremor [35], dyskinesias, and bradykinesia [23] and in tracking disease progression [25]. For example, IMUs have been used to differentiate between tremor-dominant and non—tremor-dominant patients with PD [35]. Mancini et al [25] tracked features of turning performance (eg, velocity, duration, and step number) for 7 days and found a high correlation between disease severity and turning mobility. Additional studies have shown that IMU-enabled continuous monitoring of baseline gait metrics can predict disease progression and gait decline 1 and 2 years later [36]. Moreover, a recent large study of 190 patients with PD and 101 age-matched controls showed the feasibility for large-scale clinical trials to use IMUs to robustly track spatiotemporal parameters of gait [37].

As in stroke, sensor-enabled biofeedback interventions have gained popularity as noninvasive training tools in PD rehabilitation. For example, wearable sensors have been used to facilitate the delivery of rhythmic auditory or haptic cues during gait training, an approach shown to enhance motor learning in persons with PD [38]. Similarly, IMUs have been used effectively to provide haptic and visual biofeedback related to kinematic data during balance and gait training in persons with PD [28].

Knee Osteoarthritis

Wearable sensors have been used to understand population-level behavior in individuals with OA. Based on the Osteoarthritis Initiative, a large epidemiologic study on knee OA that used wearable sensors to track physical activity in 1,111 adults, only 12.9% of men and 7.7% of women with knee OA met aerobic physical activity guidelines [39]. The study showed that in people with knee OA, more sedentary behavior was associated with worse physical function [40] and greater risk of future functional decline [41]. The Multicenter Osteoarthritis Study, another large epidemiologic study enabled by wearable activity trackers, showed that disease severity and knee pain were not predictive of physical activity levels [42] and that older adults with high risk of knee OA did not meet physical activity guidelines despite walking at least 10,000 steps per day [43]. These wearable sensor-enabled studies have yielded critical insights into the factors related to decreased physical activity in persons with knee OA and the effects of decreased physical activity on health.

For individuals with knee OA, the most common therapeutic application of wearable sensors is directed toward altering kinematics to decrease knee joint loading during walking. People with medial tibiofemoral OA walk with greater medial compartment loading compared with individuals with knee OA [44]. Greater medial compartment loading is implicated in more rapid disease progression [45]. Thus, there is significant interest in interventions that can decrease medial compartment loading. The knee adduction moment (KAM) during walking, measured using 3-dimensional motion capture, is commonly used as a surrogate for medial compartment loading [44]. There are several examples in the literature of wearable sensors being used to decrease KAM. Dowling et al [29], for example, developed an active feedback system fitted inside a shoe. The system delivered haptic feedback if the pressure on the lateral aspect of the shoe exceeded a specific threshold, with the goal of producing a subtle medial shift in weight bearing to decrease KAM. Use of this innovative biofeedback system led to a mean decrease of 14.2% in KAM. Although encouraging, this study was performed in healthy individuals, in a controlled laboratory environment, using expensive motion analysis instruments, and with a prototype version of the device. Significant work is needed to translate these systems to free-living conditions for people with knee OA.

Running

Up to 79% of runners are injured in a given year [46]. There is emerging interest in the role that impact mechanics can play in running injuries. Accumulating evidence shows associations between impact loading, as measured with a force plate, and injuries in runners. Indeed, vertical load rates during the impact phase of running are associated with tibial stress fractures [47]. Runners with diagnosed injuries also have higher vertical load rates compared with those who have never been injured [48]. Similarly, vertical load rates are related to other common running injuries such as patellofemoral pain and plantar fasciitis [48]. Although vertical load rates are related to running injuries, peak tibial acceleration during landing has been shown to be related to these load rates [49]. Therefore, peak tibial acceleration, which can be measured with an accelerometer, has become a surrogate measure for vertical load rates (Figure 1A).

Wearable sensors also can assist in examining other gait characteristics that might contribute to running injuries, such as cadence and strike pattern. Among elite runners, achieving cadences near 180 steps per minute is believed to optimize performance [50].

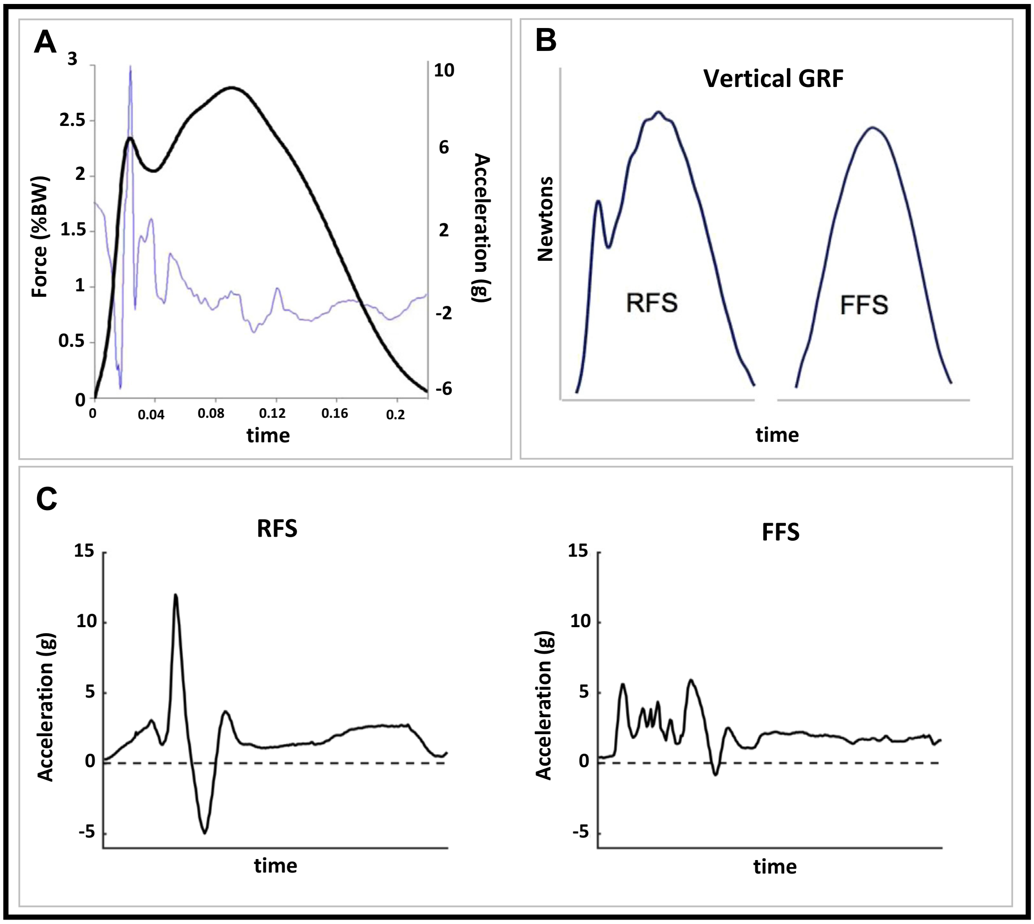

Figure 1. (A) Vertical GRF (dark line) with the tibial acceleration (light line) overlaid to demonstrate the similarity in timing of its peak with the vertical impact peak. (B) Vertical GRF curves of RFS pattern and FFS pattern. Note the distinct impact peak of the RFS pattern. (C) Representative trace of tibial acceleration pattern for an RFS runner and an FFS runner. Pattern recognition can be used to distinguish foot-strike patterns from these traces. Authors' original work. FFS = forefoot strike; GRF = ground reaction force; RFS = rearfoot strike.

Increased cadence has other benefits such as decreases in hip and knee energy absorption, patellofemoral stress, and hip adduction [51,52]. Further, increasing habitual cadences have demonstrated small decreases in vertical load rates [53]. In contrast, strike pattern influences ground reaction forces applied to the body. Rearfoot strike results in a very distinct impact peak in the vertical ground reaction force that is absent during forefoot strike [54] (Figure 1B). Transitioning to a forefoot strike pattern has been shown to resolve chronic patellofemoral pain [55] and chronic anterior compartment syndrome [56]. These distinct impact features can be seen in accelerometer data and can be used to differentiate a rearfoot strike from a forefoot strike pattern (Figure 1C).

Wearable sensors present an exciting opportunity in the prevention and treatment of running-related injuries by affording the ability to provide real-time feedback to the runner. Many commercial IMUs provide information on cumulative loads, which can be extremely helpful in preventing overload injuries in runners. Given the range of gait characteristics that can be measured (eg, strike pattern, lower extremity angles, tibial shock, etc), a wide variety of gait deviations can be addressed. Once the faulty aspect of gait is identified by the physical therapist, the runner can be instructed in how to alter the gait pattern. Then the therapist can set audible signals to remind the patient to attend to the gait when it begins to degrade beyond a certain threshold. Then feedback can be gradually removed with time. Runners can first practice these gait changes in the clinic; however, wearable sensors allow runners to translate the gait changes from the clinic into their natural running environment. This provides greater ecologic validity to the treatment and can decrease the number of clinical visits needed, thereby lowering overall health care costs.

IMUs have important limitations to note when assessing running. Impact magnitudes during running can often exceed 16*g*, which is the limit of some commercial devices. Similarly, accelerations during running include high-frequency components that require adequate sampling frequencies (500-1,000 Hz). These factors need to be considered when choosing IMU-based devices for running studies.

Clinimetric Properties of Sensors

The use of wearable sensors to inform neurologic and orthopedic rehabilitation practice warrants careful consideration of their clinimetric properties, which vary among devices [57], conditions, measures, and environments [58]. Information on reliability, validity, and sensitivity is available for some devices, but not all. For example, wearable sensors used for running have been shown to provide acceptable, valid, and reliable values for some measures [59]; however, IMU-derived measures of tibial acceleration magnitudes and determinations of strike patterns require validation. For PD, a recent review of sensor characteristics concluded that only 9 of the 73 devices considered could be recommended based on the availability and acceptability of their clinimetric properties [57]. Continued examination of the clinimetric properties of wearable sensor measurements could improve the standardization of data processing, definition of variables, and development of population-specific algorithms [57,58].

Emerging Clinical Applications of Commercially Available Technology

Emerging clinical applications using existing sensor technologies include their use (i) to identify biomarkers of disease onset and progression, (ii) to differentiate between restitution and compensatory mechanisms of motor recovery, (iii) to provide opportunities for telerehabilitation and big data collection, and (iv) in next-generation robotics.

Biomarkers

Tracking disease onset and progression is particularly valuable for those with chronic diseases. As such, there is increasing research effort directed toward identification of biomarkers. A biomarker is a measurable characteristic that represents a normal biologic process, a pathologic process, or a response to an intervention [60]. For example, there is emerging research on identifying motor biomarkers in genetic neurodegenerative diseases. The unobtrusive nature of wearable sensors coupled with their ability to measure subtle changes in mobility in ecologic settings makes them a highly promising tool for detecting subclinical motor changes that can signal disease onset and progression. Evidence for this emerging application follows.

PD is characterized by dopamine depletion in the basal ganglia, which results in motor disturbances such as tremor, postural instability, bradykinesia, and gait impairment. Although most cases of PD are idiopathic, a subset can be explained by genetic factors, of which the most common mutation is leucine-rich repeat kinase 2 (LRRK2) plus G2019S [61]. Accelerometers fixed on the low back have been used to identify increased stride time variability [62], arm swing asymmetry, and trunk axial jerk in asymptomatic carriers of the LRRK2-G2019S mutation (ie, at risk for PD) during dual-task walking compared with healthy controls [63].

The identification of motor biomarkers in HD also is an emerging area in which wearable sensors have strong potential. HD is an autosomal-dominant neurodegenerative disease that is characterized by a combination of hyperkinetic and hypokinetic motor features [64]. Pharmaceutical and rehabilitative interventions are being developed to delay the clinical onset or slow down progression of HD [65]. However, these efforts are attenuated owing to limited knowledge of optimal clinical endpoints that are needed for clinical trials. There is emerging evidence for the use of wearable sensors to identify alterations in motor control, which could serve as a worthwhile endpoint. As in PD, an IMU fixed on the low back of individuals with pre-manifest HD and healthy controls was effective in detecting subclinical decrements in the sensory modulation of postural control [67] and variability in trunk movement during walking [67]. Similarly, wearable iPOD sensors (IMU-based) fixed on the trunk and low back detected abnormal trunk movements in persons with manifest HD compared with controls [24]. Despite these exciting preliminary findings that support the use of wearable sensors to identify and monitor biomarkers of disease onset and progression in movement disorders, larger, multisite, and longitudinal studies are needed to catalyze this application.

Motor Restitution vs Compensation

An emerging clinical application of wearable sensor technologies is in differentiating restitution from compensation when assessing the nature of motor recovery [68]. Restitution refers to the reappearance of movement patterns that were present before the injury, whereas compensation refers to the emergence of a new set of movement patterns after injury resulting from substitution or adaptive mechanisms [68]. Elucidation of the mechanisms by which recovery occurs during rehabilitation allows for the development of computational models that can organize biological and behavioral data to inform clinical decision making [68].

Researchers also have begun to use wearable sensor technologies and analytical techniques to look beyond gross functional and biomechanical recordings, with a focus on the neural control of movement. An example is the use of surface electromyography (sEMG) in the examination of motor modules during functional activities [69] to identify neuromechanical differences between healthy and pathologic movement [70], evaluate the effects of neurorehabilitation intervention [71], and assess changes in neuromotor control resulting from robotic intervention [72]. Although more research is needed, this is a promising application of commercially available sensor technology. By differentiating between restitution and compensation mechanisms of recovery after neuromotor injury or dysfunction, sEMG analyses have potential to influence the prescription and evaluation of rehabilitative treatments.

Telerehabilitation

As the population ages and chronic disease rates and health care costs continue to rise, there is demand for increased access to health care services and decreased costs. Telerehabilitation is a relatively new branch of telemedicine that prioritizes developing and optimizing telecommunication technologies for rehabilitation services (eg, evaluation, monitoring, and treatment) [73]. The emerging use of wearable movement sensors to enable telerehabilitation services is exciting and timely.

It is not the goal of telerehabilitation to replace health professionals; rather, it is to elevate the level of care [74]. The remote monitoring afforded by wearable sensors allows for real-time movement tracking in real-world settings. This enables the continuous sampling of activity, rather than a finite series of collections taken during periodic clinic visits. Continuous remote monitoring of movement data could be used by clinicians to map progress and develop personalized interventions. The transmission of these data to clinicians through wireless communication systems could increase patient access to clinicians by bypassing the need to physically travel to a clinic. Similarly, for those with progressive neurologic conditions, personalized biofeedback or teletherapy can be administered in the comfort of home or community settings. These data coupled with supported human-computer interactions also could enable an assessment of quality of task practice and patient engagement and compliance with home-based interventions (eg, exercise programs). There is limited moderate evidence showing that telerehabilitation results in comparable improvements with that of conventional therapy. Additional research is needed to extend the evidence base [75]. Research also is needed to determine the reliability and validity of the wearable sensor data that might be used through telerehabilitation approaches [73]. Furthermore, challenges in privacy and security of information exist, warranting consideration of enhanced security protections based on policy, regulatory protocols [76], and security protocols [77].

Robotics

Wearable sensors have played an important role in enabling the development of next-generation assistive and rehabilitation robots. For example, during the past decade, portable rigid exoskeletons have emerged as an exciting tool to enable individuals who cannot walk to walk again [78]. These powerful systems use sensors such as encoders or potentiometers to measure their movement and provide an estimate of limb movement—information that is used to modulate the forces delivered to the wearer. However, such sensors are not compatible with a new class of wearable robots that are made from soft and compliant materials [79]. IMUs and force sensors have been shown to be more easily integrated into these soft robotic exo-suits, enabling their emergence for different biomedical applications, including decreasing the energy used during healthy walking [80] and running [81] and restoring more normal walking after a stroke [82,83].

Next-Generation Wearable Sensors

Noninvasive Monitoring of Neural Activity

Extending the discussion of sEMG-enabled assessment of motor module analyses, complementary sensor modalities are emerging that enhance movement measurement by monitoring underlying neural control mechanisms. Indeed, motor impairments arise from changes in neural control and degradation of the mechanical properties of muscles, and the relative contribution of each could be unique for each individual. Inherent to the control of movement are the firings of individual motoneurons that propagate toward the neuromuscular junction, where their activation and rate coding regulate muscle contraction force and quality of movement. Deficits in motoneuron control are known to underlie neurologic [84,85] and musculoskeletal [86] conditions, but have been difficult to discern using traditional techniques based on needle EMG recordings [87], which are invasive, yield the firings of relatively few motoneurons, and are not practical beyond monitoring highly constrained activities that result from isometric muscle contractions. With the advance of neural sensors and their underlying artificial intelligence concepts, methods for extracting motoneuron firing behavior from noninvasive sEMG during isometric contractions [88] and more recently during functional activities of everyday life [89] have been made possible (Figure 2A).

Recent work in this area has shown that groups of motoneurons are regulated differently when multiple muscles function in synergy to perform a functional task [90] and that abnormal motoneuron firing behavior underlies motor impairments after stroke [84,85]. Assessing motoneuron recruitment patterns across neurologic and orthopedic populations could provide valuable insight in determining whether rehabilitation efforts that target abnormalities in movement also have a measurable effect on reversing underlying deficits in motoneuron firing behavior.

Another emerging application of this technology includes assessing activation patterns of motoneurons specific to different training interventions. For example, a recent study showed that subjects could selectively activate different populations of motoneurons and thereby exercise components of the muscle with greater fatigue-resistance capabilities [91].

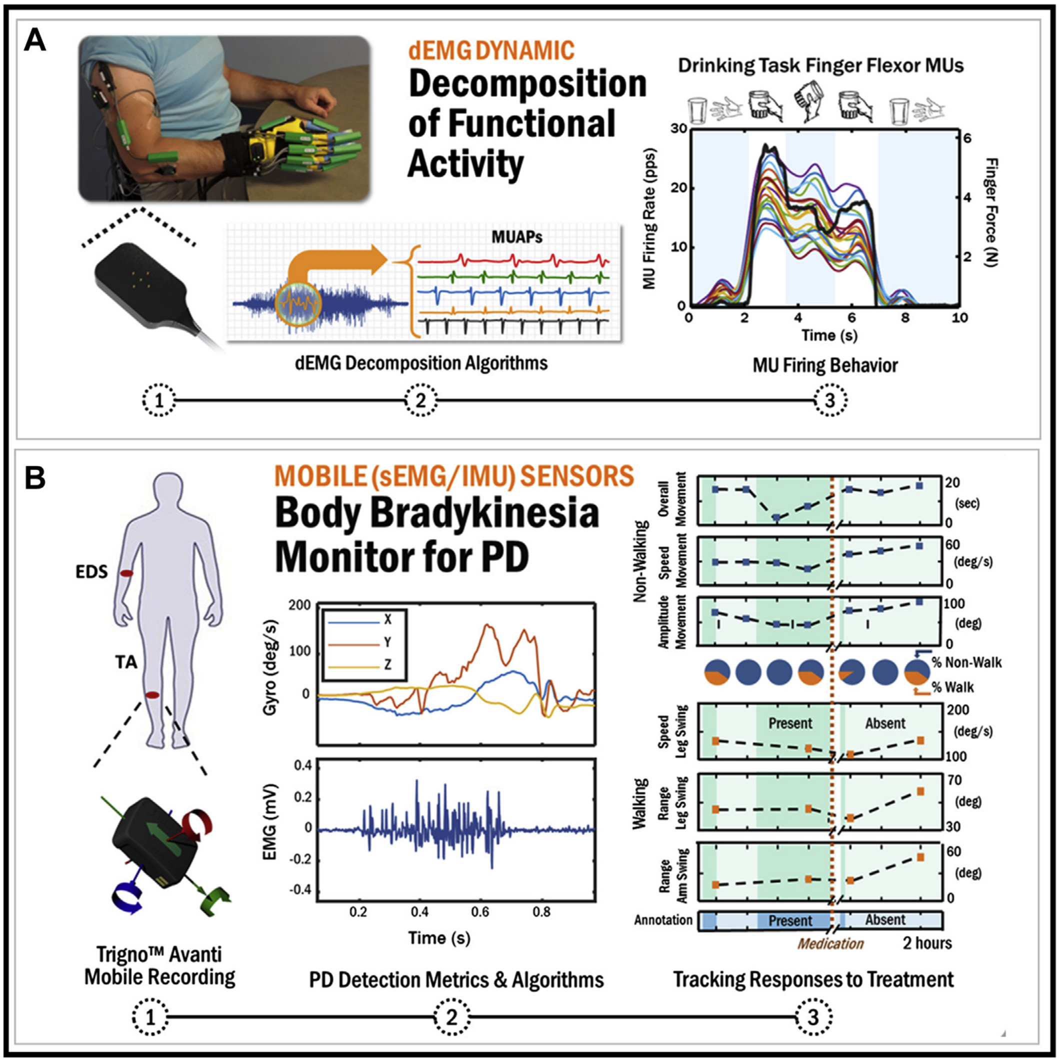

Figure 2. (A) Schematic of advanced surface EMG sensor technology that can extract the firings of individual MU activity during functional tasks, which can be used to study the underlying mechanisms of human movement in health and disease and provide a noninvasive neural interface as a real-time controller of a prosthetic or similar robotic device. (B) A schematic illustrating the use of hybrid sensor technology to autonomously monitor changes in the presence and severity of body bradykinesia in response to dopamine replacement medication in a person with PD. Authors' original work. dEMG = electromyography decomposition; EDS = extensor digitorum superficialis; EMG = electromyography; MU = motor unit; MUAP = motor unit action potential; PD = Parkinson disease; TA = tibialis anterior.

Subjects could increase the activation of relatively larger motoneurons that control higher forces with respect to relatively smaller motoneurons that control lower forces, in some cases by as much as 40%. Research is continuing to expand on these exciting preliminary findings to provide a basis for new strength-training protocols to mitigate muscle weakness in patient populations with muscle atrophy from normal aging, musculoskeletal injury, or long-term bedrest [92].

Hybrid Sensors for Monitoring Muscle Activity and Movement

Recent technologic advancements have enabled the integration of miniaturized sensor components into on-chip electronic systems with ultralow power consumption. This has fostered the development of "hybrid" wearable sensors that combine in a single encapsulation (i) motion sensing and (ii) EMG sensing of muscle activity. Hybrid sensors can be particularly advantageous for monitoring quality of movement when assessing and treating motor impairments. Indeed, the ability to measure characteristics of the wearer's movement and the underlying muscle activity responsible for regulating the movement provides a more holistic assessment of movement dysfunction. Hybrid sensors currently in use for movement monitoring include an EMG recording component and a motion component, such as an accelerometer or IMU [93,94].

The feasibility of this technology was initially evaluated for automated detection of functional activities of daily living in individuals with stroke [95]. Using a minimal subset of 4 hybrid sensors (combined sEMG and accelerometer sensors located on the 2 upper arms, 1 forearm, and 1 thigh), activities related to feeding,

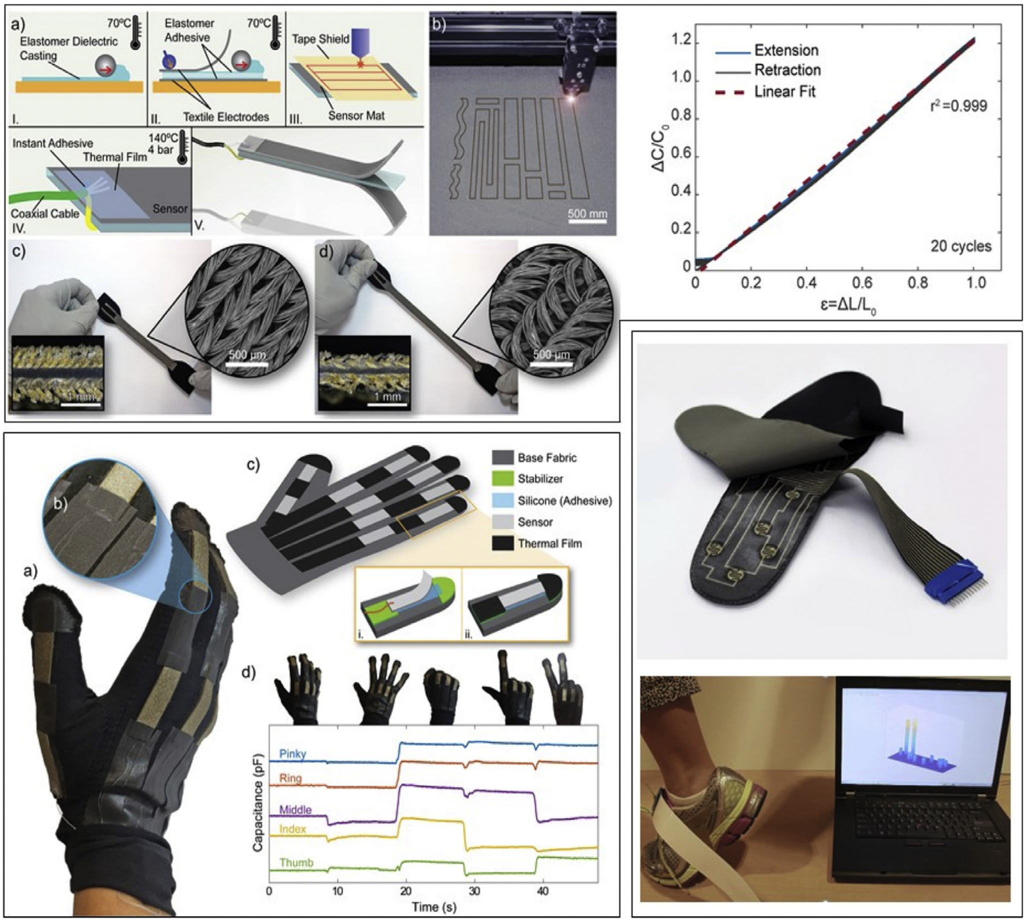

Figure 3. Preliminary work toward textile-based sensors. (Top) Capacitive fabric-based stretch soft sensor for measuring joint kinematics. (Bottom left) Demonstration of sensors in soft robotic glove for measuring finger movement. (Bottom right) Ongoing work to develop pressure-sensing insole using conductive textile traces and electrodes combined with a printed piezo-resistive film. Authors' original work.

grooming, dressing, transferring, locomotion, and toileting were detected with a mean sensitivity of 95.0% and a mean specificity of 99.7%. Significant improvements in sensitivity and specificity resulted when sEMG and accelerometer data were included, highlighting the value of a hybrid sensor approach for this application. Preliminary work in stroke demonstrated that a hybrid sEMG and accelerometer sensor could differentiate voluntary from spastic contractions [96]. Hybrid sensing also has been shown to be effective for the automated detection of involuntary movements associated with PD during unscripted activities of daily living [93,94]. Indeed, the use of 1 hybrid sensor (sEMG and accelerometer) per symptomatic limb was sufficient in achieving 94.9% sensitivity and 97.1% specificity for autonomous tracking of tremor and dyskinesia in that limb in response to levodopa treatment.

Hybrid sensors that combine sEMG and IMU sensing hold even greater opportunities for wearable activity monitoring of movement disorders. The availability of angular velocity measurement in such a hybrid sensor proved highly effective in providing the first whole-body bradykinesia detector for PD (with an average accuracy of 95.0% for combined walking and non-walking activities) during unconstrained activities of daily living before and after levodopa therapy [94] (Figure 2B). Similar technology has been shown to be effective when assessing the quality of movement in stroke [97] and to monitor athletic performance for prevention of injury [98].

Soft Sensors

Advances in materials science have enabled explorations into the development of soft sensors and their applications to rehabilitation. Soft sensors can be placed in locations not possible with current movement-monitoring devices. For example, stretchy sensors can be placed on the arch of runners with plantar fasciitis. Because runners with plantar fasciitis often have weak intrinsic foot muscles [99], there is resultant flattening of the arch and increased strain on the plantar fascia. Stretchy sensors can provide feedback to runners when their arch is lowering too much, reminding them to engage those muscles.

Because placement of sensors could be a source of imprecision in measurement [100], the prospect of soft textile-based sensors that could be worn like clothing is very attractive. For example, ultrathin, ultralight, and stretchable sEMG sensors that resemble a temporary tattoo and are mechanically unnoticeable to the user are being tested for use in evaluating exercise performance during rehabilitation [101]. In addition, elastomeric soft sensors have been integrated into a wearable sensing suit to measure hip, knee, and ankle kinematics [102]. Such sensing garments could be used for continuous kinematic monitoring in the community. More recently, an alternative stretchable capacitive sensor has been developed with conductive knit fabrics as the electrode layer and a dielectric layer made from a silicone elastomer [103] (Figure 3, top). These sensors can be rapidly customized through a layered manufacturing process using a film applicator and laser cutting has demonstrated scalable, fast, low-cost production and arbitrary shaping of strain [103] and pressure [104] sensors. The textile-based nature of these sensors makes them much more suitable for integration into apparel than existing sensor technologies. It has been demonstrated that these sensors can be integrated into a glove for measuring finger movements [103] (Figure 3, bottom left) and grip force [104]. Additional promising initial results with other textile-compatible sensors have demonstrated the ability to measure tension [105] and applied pressure [106] in wearable devices. Apart from making the transduction mechanism compatible with apparel, developments have focused on creating conductive traces within textile materials to eliminate wiring and enable systems to be washable. Figure 3 (bottom right) highlights adaptations of this early work to develop an insole for measuring contact pressure.

Limitations

First, this review does not provide a comprehensive systematic review of the literature, but rather a focused discussion of the current and emerging sensor technologies and their clinical applications. Therefore, studies presenting similar technologies and clinical applications might not have been included. Second, the clinical applications discussed are limited to stroke, PD, HD, OA, and running populations. Although these are only a few of the conditions that use and can benefit from wearable movement sensors, the conditions chosen illustrate the large spectrum of individuals with varying degrees of capabilities who could benefit from existing and emerging sensor technologies.

Conclusions

The central goal of physical rehabilitation is to facilitate the reacquisition of movement abilities after injury or onset of disease. Motor behavior is viewed as an output of the movement system based on its encompassing interaction with cardiovascular, pulmonary, endocrine, integumentary, nervous, and musculoskeletal systems [107]; thus, movement data have high potential in examining health and disease across systems. Wearable sensors are a promising rehabilitation technology because of their precision, noninvasiveness, and easy deployment compared with other methods. Their complementary measurement of kinematic motion, neural activity, and muscle dynamics offers a targeted approach for assessing and treating different neurologic and orthopedic conditions. In addition, more widespread monitoring of movement in clinical and ecologic settings and across different rehabilitation timescales could serve as a pathway to the development of computational models of recovery and precision medicine. Moreover, advancements in materials science are allowing for the development of next-generation sensors that can record biologic movements from device interfaces that are more fully transparent to the wearer.

Acknowledgments

We are grateful for the consultation and technical input provided by Jaehyun Bae. This work was funded in part by the National Institutes of Health (award numbers 1KL2TR001411, 1ULT1TR001430, 1K01AR069720, and R01HD088619) and the National Science Foundation (CNS-1446464).

References

1. Cook AM. Ethical issues related to the use/non-use of assistive technologies. Dev Disabil Bull 2009;37:127-152. Available at https://files.eric.ed.gov/fulltext/EJ920692.pdf.
2. Dhawan AP. Collaborative paradigm of preventive, personalized, and precision medicine with point-of-care technologies. IEEE J Transl Eng Heal Med 2016;4:2800908.
3. Dobkin BH. Behavioral self-management strategies for practice and exercise should be included in neurologic rehabilitation trials and care. Curr Opin Neurol 2016;29:693-699.
4. Capela NA, Lemaire ED, Baddour N, Rudolf M, Goljar N, Burger H. Evaluation of a smartphone human activity recognition application with able-bodied and stroke participants. J Neuroeng Rehabil 2016;13:1-10.
5. O'Brien MK, Shawen N, Mummidisetty CK, et al. Activity recognition for persons with stroke using mobile phone technology: Toward improved performance in a home setting. J Med Internet Res 2017;19:e184.
6. Döbrössy MD, Dunnett SB. The influence of environment and experience on neural grafts. Nat Rev Neurosci 2001;2:871-879.
7. Jonsdottir J, Cattaneo D, Recalcati M, et al. Task-oriented biofeedback to improve gait in individuals with chronic stroke: Motor learning approach. Neurorehabil Neural Repair 2010;24:478-485.
8. Hadjidj A, Souil M, Bouabdallah A, Challal Y, Owen H. Wireless sensor networks for rehabilitation applications : challenges and opportunities. J Netw Comput Appl 2013;36:1-15.

9. Reuterbories J, Spaich EG, Larsen B, Andersen OK. Methods for gait event detection and analysis in ambulatory systems. Med Eng Phys 2010;32:783-790.
10. Munoz-Organero M, Parker J, Powell L, Mawson S. Assessing walking strategies using insole pressure sensors for stroke survivors. Sensors (Basel) 2016;16(10).
11. Nolan KJ, Yarossi M, McLaughlin P. Changes in center of pressure displacement with the use of a foot drop stimulator in individuals with stroke. Clin Biomech 2015;30:755-761.
12. Byl N, Zhang W, Coo S, Tomizuka M. Clinical impact of gait training enhanced with visual kinematic biofeedback: Patients with Parkinson's disease and patients stable post stroke. Neuropsychologia 2015;79:332-343.
13. Owaki D, Sekiguchi Y, Honda K, Ishiguro A, Izumi SI. Short-term effect of prosthesis transforming sensory modalities on walking in stroke patients with hemiparesis. Neural Plast 2016;2016: 6809879.
14. Krishnan V, Khoo I, Marayong P, DeMars K, Cormack J. Gait training in chronic stroke using walk-even feedback device: A pilot study. Neurosci J 2016;2016:6808319.
15. Hurkmans HLP, Bussmann JBJ, Selles RW, Horemans HLD, Benda E. Validity of the Pedar Mobile system for vertical force measurement during a seven-hour period. J Biomech 2006;39: 110-118.
16. Tong K, Granat MH. A practical gait analysis system using gyroscopes. Med Eng Phys 1999;21:87-94.
17. Williamson R, Andrews BJ. Gait event detection for FES using accelerometers and supervised machine learning. IEEE Trans Rehabil Eng 2000;8:312-319.
18. Mayagoitia RE, Nene AV, Veltink PH. Accelerometer and rate gyroscope measurement of kinematics: An inexpensive alternative to optical motion analysis systems. J Biomech 2002;35:537-542.
19. Kavanagh JJ, Menz HB. Accelerometry: A technique for quantifying movement patterns during walking. Gait Posture 2008;28: 1-15.
20. Chen KY, Basset DR. The technology of accelerometry-based activity monitors: current and future. Med Sci Sport Exerc 2005; 37(Supplement):S490-S500.
21. Haji Ghassemi N, Hannink J, Martindale C, et al. Segmentation of gait sequences in sensor-based movement analysis: A comparison of methods in Parkinson's Disease. Sensors (Basel) 2018;18:145.
22. Wüest S, Aminian F, Aminian K, Gonzenbach R, de Bruin E. Reliability and validity of the inertial sensor-based Timed "Up and Go" test in individuals affected by stroke. J Rehabil Res Dev 2016; 53:599-610.
23. Heldman DA, Espay AJ, LeWitt PA, Giuffrida JP. Clinical versus machine; reliability and responsiveness of motor endpoints in Parkinson's disease. Parkinsonism Relat Disord 2013;31:1713-1723.
24. Kegelmeyer DA, Kostyk SK, Fritz NE, et al. Quantitative biomechanical assessment of trunk control in Huntington's disease reveals more impairment in static than dynamic tasks. J Neurol Sci 2017;376:29-34.
25. Mancini M, El-Gohary M, Pearson S, et al. Continuous monitoring of turning in Parkinson's disease: Rehabilitation potential. Neurorehabilitation 2015;37:3-10.
26. Isho T, Tashiro H, Usuda S. Accelerometry-based gait characteristics evaluated using a smartphone and their association with fall risk in people with chronic stroke. J Stroke Cerebrovasc Dis 2015; 24:1305-1311.
27. Bergamini E, Iosa M, Belluscio V, Morone G, Tramontano M, Vannozzi G. Multi-sensor assessment of dynamic balance during gait in patients with subacute stroke. J Biomech 2017;61: 208-215.
28. Carpinella I, Cattaneo D, Bonora G, et al. Wearable sensor-based biofeedback training for balance and gait in Parkinson disease: A pilot randomized controlled trial. Arch Phys Med Rehabil 2017;98: 622-630.e3.
29. Dowling AV, Fisher DS, Andriacchio TP. Gait modification via verbal instruction and an active feedback system to reduce peak knee adduction moment. J Biomech Eng 2010;132:071007.
30. Massé F, Gonzenbach RR, Arami A, Paraschiv-Ionescu A, Luft AR, Aminian K. Improving activity recognition using a wearable barometric pressure sensor in mobility-impaired stroke patients. J Neuroeng Rehabil 2015;12:1-15.
31. Fulk GD, He Y, Boyne P, Dunning K. Predicting home and community walking activity poststroke. Stroke 2017;48:406-412.
32. French MA, Moore MF, Pohlig R, et al. Self-efficacy mediates the relationship between balance/walking performance, activity, and participation after stroke. Top Stroke Rehabil 2016; 23:77-83.
33. Danks KA, Roos MA, McCoy D, Reisman DS, Program MS. A step activity monitoring program improves real world walking activity post stroke. Disabil Rehabil 2015;36:2233-2236.
34. Rodríguez-Molinero A, Samà A, Pérez-Martínez DA, et al. Validation of a portable device for mapping motor and gait disturbances in Parkinson's disease. JMIR Mhealth Uhealth 2015;3:e9.
35. Delrobaei M, Memar S, Pieterman M, Stratton TW, McIsaac K, Jog M. Towards remote monitoring of Parkinson's disease tremor using wearable motion capture systems. J Neurol Sci 2018;384:38-45.
36. Cavanaugh JT, Ellis TD, Earhart GM, Ford MP, Foreman KB, Dibble LE. Toward understanding ambulatory activity decline in Parkinson disease. Phys Ther 2015;95:1142-1150.
37. Schlachetzki JCM, Barth J, Marxreiter F, et al. Wearable sensors objectively measure gait parameters in Parkinson's disease. PLoS One 2017;12:e0183989.
38. Nieuwboer A, Rochester L, Müncks L, Swinnen SP. Motor learning in Parkinson's disease: limitations and potential for rehabilitation. Parkinsonism Relat Disord 2009;15(Suppl 3):53-58.
39. Dulop DD, Song J, Semanik PA, et al. Initiative: Are guidelines being met? Arthritis Rheumatol 2012;63:3372-3382.
40. Lee J, Chang RW, Ehrlich-Jones L, et al. Sedentary behavior and physical function: Objective evidence from the osteoarthritis initiative. Arthritis Care Res 2015;67:366-373.
41. Semanik PA, Lee J, Song J, et al. Accelerometer-monitored sedentary behavior and observed physical function loss. Am J Public Health 2015;105:560-566.
42. White DK, Tudor-Locke C, Felson DT, et al. Do radiographic disease and pain account for why people with or at high risk of knee osteoarthritis do not meet physical activity guidelines? Arthritis Rheum 2013;65:139-147.
43. White DK, Tudor-Locke C, Felson DT, et al. Walking to meet physical activity guidelines in knee osteoarthritis: Is 10,000 steps enough? Arch Phys Med Rehabil 2013;94:711-717.
44. Kumar D, Manal KT, Rudolph KS. Knee joint loading during gait in healthy controls and individuals with knee osteoarthritis. Osteoarthr Cartil 2013;21:298-305.
45. Bennell KL, Bowles KA, Wang Y, Cicuttini F, Davies-Tuck M, Hinman RS. Higher dynamic medial knee load predicts greater cartilage loss over 12 months in medial knee osteoarthritis. Ann Rheum Dis 2011;70:1770-1774.
46. van Gent RN, Siem D, van Middelkoop M, van Os AG, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: A systematic review. Br J Sports Med 2007; 41:469-480.
47. Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. Clin Biomech (Bristol, Avon) 2011;26:23-28.
48. Davis IS, Bowser BJ, Mullineaux DR. Greater vertical impact loading in female runners with medically diagnosed injuries: A prospective investigation. Br J Sports Med 2015;50:887-892.
49. Hennig EM, Lafortune MA. Relationships between ground reaction force and tibial bone acceleration parameters. Int J Sport Biomech 1991;7:303-309.
50. Daniels J. Daniel's Running Formula. Champaign, IL: Human Kinetics; 1998.

51. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc 2011;43:296-302.
52. Lenhart RL, Thelen DG, Wille CM, Chumanov ES, Heidershceit BC. Increasing running step rate reduces patellofemoral joint forces. Med Sci Sports Exerc 2014;46:557-564.
53. Willy RW, Buchenic L, Rogacki K, Ackerman J, Schmidt A, Wilson JD. In-field gait retraining and mobile monitoring to address running biomechanics associated with tibial stress fracture. Scand J Med Sci Sports 2015;26:197-205.
54. Rice HM, Jameson ST, Davis IS. Footwear matters: Influence of footwear and foot strike on loadrates during running. Med Sci Sports Exerc 2016;48:2462-2468.
55. Cheung RT, Davis IS. Landing pattern modification to improve patellofemoral pain in runners: A case series. J Orthop Sport Phys Ther 2011;41:914-919.
56. Diebal AR, Gregory R, Alitz C, Gerber JP. Forefoot running improves pain and disability associated with chronic exertional compartment syndrome. Am Coll Sport Med 2012;40:1060-1067.
57. Godinho C, Domingos J, Cunha G, et al. A systematic review of the characteristics and validity of monitoring technologies to assess Parkinson's disease. J Neuroeng Rehabil 2016;13:1-10.
58. Johansson D, Malmgren K, Alt Murphy M. Wearable sensors for clinical applications in epilepsy, Parkinson's disease, and stroke: A mixed-methods systematic review. J Neurol https://doi.org/10.1007/s00415-018-8786-y. Epub ahead of print.
59. Provot T, Chiementin X, Oudin E, Bolaers F, Murer S. Validation of a high sampling rate inertial measurement unit for acceleration during running. Sensors (Basel) 2017;17(9).
60. Biomarkers Definitions Working Group. Biomarkers and surrogate endpoints: Preferred definitions and conceptual framework. Clin Pharmacol Ther 2001;69:89-95.
61. Kumari U, Tan EK. LRRK2 in Parkinson's disease: Genetic and clinical studies from patients. FEBS J 2009;276:6455-6463.
62. Mirelman A, Gurevich T, Giladi N, Bar-Shira A, Orr-Urtreger A, Hausdorff JM. Gait alterations in healthy carriers of the LRRK2 G2019S mutation. Ann Neurol 2011;69:193-211.
63. Mirelman A, Bernad-Elazari H, Thaler A, et al. Arm swing as a potential new prodromal marker of Parkinson's disease. Mov Disord 2016;31:1527-1534.
64. Berardelli A, Noth J, Thompson PD, et al. Pathophysiology of chorea and bradykinesia in Huntington's disease. Mov Disord 1999;14:398-403.
65. Tabrizi SJ, Scahill RI, Owen G, et al. Predictors of phenotypic progression and disease onset in premanifest and early-stage Huntington's disease in the TRACK-HD study: Analysis of 36-month observational data. Lancet Neurol 2013;12:637-649.
66. Porciuncula F, Marder KS, Wasserman P, Rao AK. Sensory modulation of postural control in Huntington's disease. Mov Disord 2017;32(Suppl 2):S192-S193.
67. Collett J, Esser P, Khalil H, et al. Insights into gait disorders: Walking variability using phase plot analysis, Huntington's disease. Gait Posture 2014;40:694-700.
68. Reinkensmeyer DJ, Burdet E, Casadio M, et al. Computational neurorehabilitation: modeling plasticity and learning to predict recovery. J Neuroeng Rehabil 2016;13:42.
69. Clark DJ, Ting LH, Zajac FE, Neptune RR, Kautz SA. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. J Neurophysiol 2010;103:844-857.
70. Veerbeek JM, Koolstra M, Ket JCF, van Wegen EEH, Kwakkel G. Effects of augmented exercise therapy on outcome of gait and gait-related activities in the first 6 months after stroke a meta-analysis. Stroke 2011;42:3311-3315.
71. Ferrante S, Bejarano NC, Ambrosini E, et al. A personalized multichannel FES controller based on muscle synergies to support gait rehabilitation after stroke. Front Neurosci 2016;10:425.
72. Jacobs DA, Koller JR, Steele KM, Ferris DP. Motor modules during adaptation to walking in a powered ankle exoskeleton. J Neuroeng Rehabil 2018;15:2.
73. Winters JM. Telerehabilitation research: emerging opportunities. Annu Rev Biomed Eng 2002;4:287-320.
74. Polisena J, Coyle D, Coyle K, McGill S. Home telehealth for chronic disease management: A systematic review and an analysis of economic evaluations. Int J Technol Assess Health Care 2009; 25:339-349.
75. Chen J, Jin W, Zhang X-X, Xu W, Liu X-N, Ren C-C. Telerehabilitation approaches for stroke patients: Systematic review and meta-analysis of randomized controlled trials. J Stroke Cerebrovasc Dis 2015;24:2660-2668.
76. Hall JL, McGraw D. For telehealth to succeed, privacy and security risks must be identified and addressed. Health Aff 2014;33: 216-221.
77. Rezaeibagha F, Mu Y. Practical and secure telemedicine systems for user mobility. J Biomed Inform 2018;78:24-32.
78. Esquenazi A, Talaty M, Packel A, Saulino M. The ReWalk powered exoskeleton to restore ambulatory function to individuals with thoracic-level motor-complete spinal cord injury. Am J Phys Med Rehabil 2012;91:911-921.
79. Veale AJ, Xie SQ. Towards compliant and wearable robotic orthoses: A review of current and emerging actuator technologies. Med Eng Phys 2016;38:317-325.
80. Panizzolo FA, Galiana I, Asbeck AT, et al. A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking. J Neuroeng Rehabil 2016;13:43.
81. Lee G, Kim J, Panizzolo FA, et al. Reducing the metabolic cost of running with a tethered soft exosuit. Sci Robot 2017;2(6).
82. Awad LN, Bae J, O'Donnell K, et al. A soft robotic exosuit improves walking in patients after stroke. Sci Transl Med 2017;9: eaai9084.
83. Bae J, Siviy C, Rouleau M, et al. A lightweight and efficient portable soft exosuit for paretic ankle assistance in walking after stroke. In: IEEE International Conference on Robotics and Automation. Brisbane, Australia; 2018, pp. 2820-2827. (In press) Available at: https://biodesign.seas.harvard.edu/files/biodesignlab/files/0944.pdf. Accessed: August 28, 2018.
84. Chou L-W, Palmer JA, Binder-Macleod S, Knight CA. Motor unit rate coding is severely impaired during forceful and fast muscular contractions in individuals post stroke. J Neurophysiol 2013;109: 2947-2954.
85. Li X, Wang Y-C, Suresh NL, Rymer WZ, Zhou P. Motor unit number reductions in paretic muscles of stroke survivors. IEEE Trans Inf Technol Biomed 2011;15:505-512.
86. Kallenberg LAC, Hermens HJ. Motor unit action potential rate and motor unit action potential shape properties in subjects with work-related chronic pain. Eur J Appl Physiol 2006;96: 203-208.
87. Falla D, Lindstrøm R, Rechter L, Farina D. Effect of pain on the modulation in discharge rate of sternocleidomastoid motor units with force direction. Clin Neurophysiol 2010;121: 744-753.
88. De Luca CJ, Adam A, Wotiz R, Gilmore LD, Nawab SH, Luca D. Decomposition of surface EMG signals. J Neurophysiol 2006;96: 1646-1657.
89. De Luca CJ, Chang S-S, Roy SH, Kline JC, Nawab SH. Decomposition of surface EMG signals from cyclic dynamic contractions. J Neurophysiol 2015;113:1941-1951.
90. Kline J, Contessa P, Roy S, De Luca G. Coordination of motor unit firings during cyclic activities of the upper-limb. Paper presented at: ISB 2017 Congress XXVI; July 23-27, 2017; Brisbane, Australia.
91. De Luca CJ, Kline JC, Contessa P. Transposed firing activation of motor units. J Neurophysiol 2014;112:962-970.
92. Pope ZK, Hester GM, Benik FM, DeFreitas JM. Action potential amplitude as a noninvasive indicator of motor unit-specific hypertrophy. J Neurophysiol 2016;115:2608-2614.

93. Roy SH, Cole BT, Gilmore LD, et al. High-resolution tracking of motor disorders in Parkinson's disease during unconstrained activity. Mov Disord 2013;28:1080-1087.
94. Roy S, Shiwani B, Kline J, et al. Autonomous tracking of body bradykinesia during unconstrained activities in Parkinson's disease. Mov Disord 2017;32(Suppl2):448-449.
95. Roy SH, Cheng MS, Chang S-S, et al. A Combined sEMG and accelerometer system for monitoring functional activity in stroke. IEEE Trans Neural Syst Rehabil Eng 2009;17:585-594.
96. Ghaffari R, Jayarman A, Lonini L, Rogers JA, Shawen N. Automatic detection of spasticity from flexible wearable sensors. Paper presented at: UbiComp/ISWC Adjunct; September 11, 2017; Maui, Hawaii.
97. van Meulen FB, Klaassen B, Held J, et al. Objective evaluation of the quality of movement in daily life after stroke. Front Bioeng Biotechnol 2016;3:210.
98. Gilgien M, Spörri J, Kröll J, Crivelli P, Müller E. Mechanics of turning and jumping and skier speed are associated with injury risk in men's World Cup alpine skiing: A comparison between the competition disciplines. Br J Sports Med 2014;48:742-747.
99. Cheung RTH, Sze LKY, Mok NW, Ng GYF. Intrinsic foot muscle volume in experienced runners with and without chronic plantar fasciitis. J Sci Med Sport 2016;19:713-715.
100. Willemsen ATM, van Alsté JA, Boom HBK. Real-time gait assessment utilizing a new way of accelerometry. J Biomech 1990;23:859-863.
101. Constantinescu G, Jeong J-W, Li X, et al. Epidermal electronics for electromyography: An application to swallowing therapy. Med Eng Phys 2016;38:807-812.
102. Menguc Y, Park Y, Pei H, et al. Wearable soft sensing suit for human gait measurement. Int J Rob Res 2014;33:1748-1764.
103. Atalay A, Sanchez V, Atalay O, et al. Batch fabrication of customizable silicone-textile composite capacitive strain sensors for human motion tracking. Adv Mater Technol 2017;2:1700136. Available at https://onlinelibrary.wiley.com/doi/epdf/10.1002/admt.201700136.
104. Atalay O, Atalay A, Gafford J, Walsh C. A highly sensitive capacitive-based soft pressure sensor based on a conductive fabric and a microporous dielectric layer. Adv Mater Technol 2018;3:1700237.
105. Araromi OA, Walsh CJ, Wood RJ. Hybrid carbon fiber-textile compliant force sensors for high-load sensing in soft exosuits. In: International Conference on Intelligent Robots and Systems (IROS). In: 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, BC, 2017, pp. 1798-1803. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8205994&isnumber=8202121. Accessed August 28, 2018.
106. Araromi OA, Walsh CJ, Wood RJ. Fabrication of stretchable composites with anisotropic electrical conductivity for compliant pressure transducers. IEEE Sensors. Available at https://biodesign.seas.harvard.edu/files/biodesignlab/files/2016_araromi_-_ieee_sensors_-_fabrication_of_stretchable_composites_with_anisotropic_electrical_conductivity_for_compliant_pressure_transducers.pdf.
107. American Physical Therapy Association. Physical therapist practice and the movement system. Available at http://www.apta.org/MovementSystem/.

Disclosure

F.P. Paulson School of Engineering and Applied Sciences and Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA
Disclosure: nothing to disclose

A.V.R. College of Health and Rehabilitation Sciences, Sargent College, Boston University, Boston, MA
Disclosure: nothing to disclose

D.K. College of Health and Rehabilitation Sciences, Sargent College, Boston University, Boston, MA
Disclosure: nothing to disclose

I.D. Department of Physical Medicine and Rehabilitation, Harvard Medical School, Cambridge, MA
Disclosure: nothing to disclose

S.R. College of Health and Rehabilitation Sciences, Sargent College, Boston University, Boston, MA
Disclosure: Employed by Delsys, Inc; multiple patents related to wearable sensor technologies.

C.J.W. Paulson School of Engineering and Applied Sciences and Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA
Disclosures outside this publication: personal fees, ReWalk Robotics; Intellectual Property — Patents & Copyrights: pending/issued/licensed patent, C.J.W. is an author of a number of patents and patent applications related to soft exosuits (PCT/US2013/60225, Soft exosuit for assistance with human motion; PCT/US2014/68462, Assistive flexible suits, flexible suit systems, and methods for making and control thereof to assist human mobility; PCT/US2014/40340, Soft exosuit for assistance with human motion; PCT/US2015/51107, Soft exosuit for assistance with human motion)

L.N.A. College of Health and Rehabilitation Sciences, Sargent College, Boston University, Boston, MA; Paulson School of Engineering and Applied Sciences and Wyss Institute for Biologically Inspired Engineering, Harvard University, Cambridge, MA; Department of Physical Medicine and Rehabilitation, Harvard Medical School, Cambridge, MA. Address correspondence to: L.N.A.; e-mail: louawad@bu.edu
Disclosure: nothing to disclose

F.P. and A.V.R. contributed equally to this work.