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The merits of artificial proprioception, with applications in biofeedback gait rehabilitation concepts and movement disorder characterization

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1. Introduction

The advance of wireless accelerometer technology has become increasingly integrated with respect to biomedical applications. With the amalgamation of wireless technology and MEMS applications, the synthesis of wireless accelerometer technology has yielded the biomedical/ neuroengineering artificial equivalent of proprioception. The merits of artificial proprioception are addressed in tandem with recent and novel applications incorporating wireless accelerometers as an artificial form of proprioception. Recent and novel applications span concepts such as virtual proprioception, a real-time biofeedback system for gait rehabilitation; gait analysis and quantification; quantification of Parkinson's disease status; and reflex characterization. The steady evolution of accelerometers has enabled the permeation of the technology from initial conceptualization to recent integration of the technology for biomedical applications (Saunders et al., 1953; Culhane et al., 2005; LeMoyne et al., 2008c).

Accelerometers were initially proposed for the quantification of movement characteristics during the 1950's; but the supporting technologies for developing robust accelerometer applications were not sufficiently evolved (Saunders et al., 1953; Culhane et al., 2005). During this era accelerometers were actually characterized as too expensive, unreliable, and cumbersome, which could perturb the actual nature of human movement (Culhane et al., 2005). Throughout the decade of the 1990's the accelerometer technology space obtained the capability for movement quantification. Essentially lateral technologies, such as airbag release systems for the automotive industry, provided the basis for the evolution of the accelerometer technology space. Successive developments of accelerometer devices demonstrated high levels of quality and reliability, while attributed with high volume capacity and low-cost production. The implications are that current accelerometer systems are capable for clinical applications, such as the characterization and quantification of human movement (Culhane et al., 2005; LeMoyne et al., 2008c).

The current technology status for accelerometer systems provides the capability for quantitative evaluation of locomotion and movement disorder with greater autonomy of application (Culhane et al., 2005; LeMoyne et al., 2008c). Sensors are extremely useful for movement analysis, such as gait, in both clinical rehabilitation applications and biomedical research, as provided by accelerometer technology (Wong et al., 2007). With micromachining technology, accelerometers produce a signal capable of measuring acceleration, representing both dynamic movement and static gravity. A general strategy for developing an accelerometer is to utilize a mass capable of producing a signal representative of the acceleration based on the deflection of the mass (Culhane et al., 2005).

The evolving technology applications for accelerometer devices provide the fundamentals for expanding the functionality of accelerometer systems as wearable proprioception applications. Accelerometer components provide the spatial representation imperative for the inertial navigation system of robotic applications, which is analogous to a proprioceptive system in humans. Spatial representation of proprioception for human beings is enabled through afferent systems, such as Golgi tendon organs and muscle spindles (Bekey, 2005).

The application of accelerometers as a wearable form of proprioception has an exceptional utility. A wearable accelerometer system can record and store the resultant accelerometer signal (LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d). The afferent proprioception of a human experience may be difficult to recall over an extended period of time and possibly especially difficult for a patient to communicate to a clinician. In contrast, wearable accelerometers are capable of providing artificial proprioception, which can be efficiently stored in a database and post-processed for potential diagnostic interpretation (LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d). The paradigm of wearable and wireless accelerometer systems providing artificial proprioception enables the foundation for current and unique applications.

Four novel applications utilizing wearable and wireless accelerometer devices as a form of artificial proprioception are quantification of Parkinson's disease status, reflex quantification and characterization, gait analysis quantification and classification, and virtual proprioception. Virtual proprioception is a real-time biofeedback application suitable for gait rehabilitation, especially for hemiparetic subjects. In essence the virtual proprioception system enables a subject to engage in real-time adjustment of gait disparities. Two wearable and wireless accelerometers are mounted to an anatomical anchor on each leg. The acceleration waveforms of both the affected and unaffected leg are provided to the subject. With the disparity of acceleration waveforms presented, the subject can modify gait during real-time of the gait cycle so that both legs are closer to parity of the acceleration waveforms as gait cycle continues (LeMoyne et al., 2008e; LeMoyne et al., 2008f).

Gait analysis quantification and classification incorporates wearable and wireless accelerometers with expanded application autonomy. Current applications of the system have been applied to a home-based setting and the outdoor environment. The value of the system is autonomy of the application beyond clinical confines. The concept is even relevant to situations for which the patient and clinician reside at distant locations. Subsequent post-processing techniques can characterize the current status and quality of gait for a subject (LeMoyne et al., 2009b; LeMoyne et al., 2009d).

Reflex quantification incorporating wireless accelerometers provides unique insight as to the neurological status of a subject. In essence the application is an extension from current methods for evaluating deep tendon reflexes as an integral aspect of the traditional neurological examination. As a form of artificial proprioception, the reflex response is characterized as a three dimensional acceleration waveform. With a tandem wireless accelerometer positioned to a potential energy derived reflex hammer evoking the reflex, the latency can also be derived given the temporal disparity of the tandem accelerometer acceleration waveforms. The wireless reflex quantification system enables a unique strategy for evaluating central nervous system and peripheral nervous system status, potentially reducing strain on critical economic resources (LeMoyne et al., 2008a; LeMoyne et al., 2008h; LeMoyne et al., 2009c).

Artificial proprioception through the application of wireless accelerometers also provides insight and autonomy for the assessment of Parkinson's disease status. Traditional evaluation for the response of a patient with respect to therapy strategy is performed by a clinician, tasked with the endeavor of qualitatively examining the patient and applying the findings to an ordinal scale (www.mdvu.org; LeMoyne et al., 2008c). Presumably the clinical assessment is conducted during an appointment, not continuously evaluated in the autonomous environment of the patient. In contrast the application of wireless accelerometry as a form of wearable proprioception may enable continual tracking for the Parkinson's disease status in the autonomous environment of the patient. The application of wireless accelerometers enables the opportunity for long-term data reduction and advanced insight as to the efficacy of treatment strategy (LeMoyne et al., 2009a).

The applications for virtual proprioception, gait analysis, reflex quantification, and Parkinson's disease status classification demonstrate the present and future capabilities that artificial proprioception has for advancing biomedical engineering and the medical industry. Artificial proprioception is attributed as wearable and equipped with the capability to store and convey information through wireless transmission. The integration of artificial proprioception can potentially advance clinical acuity and perceptivity as to the status of a patient with movement disorder, while reducing rampant strain on the medical economy. Gait rehabilitation biofeedback concepts, such as virtual proprioception, can be amenable to homebound environments. The diagnostic capabilities of wireless gait analysis and Parkinson's disease classification through wireless accelerometer devices are amenable to autonomous home settings. Wireless accelerometer reflex quantification systems may provide advanced acuity and perceptivity for clinicians with respect to the neurological status of a patient, while alleviating strain on medical resources, such as electrodiagnostic evaluation (LeMoyne et al., 2008a; LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d).

Fundamental demand for artificial proprioception through wireless accelerometers is initially illustrated through the consideration of people with trauma to the central nervous system undergoing motor control therapy, such as gait rehabilitation, possibly in tandem having a disparity in proprioceptive afferent representation, respective of both limbs. Ordinal scales, which are currently standard for clinical evaluations, are subject to controversy, especially in consideration of the qualitative basis for deriving the ordinal scale value. In particular ordinal scales lack the capacity to fully address the temporal nature of the movement characteristics being evaluated (LeMoyne et al., 2008c). With the accelerometer technology recently evolving to a sufficient capacity for biomedical applications, initial applications of accelerometer systems, such as activity monitors, are addressed. Other standard technologies for characterizing gait are contrasted to previous and current accelerometer gait analysis applications; and the successful test and evaluation results of the accelerometer systems pertaining to gait are considered.

2. Natural biological inspired proprioception contrasted to artificial proprioception

A contrast of the proprioceptive afferent sensory receptors relative to artificial proprioception establishes the fundamental utility of artificial proprioception. Proprioception is defined as the afferent representation for the spatial position of the body (Nolte & Sundsten, 2002; Seeley et al., 2003). Two proprioceptive afferent sensory receptors are selected for contrast: the muscle spindle and Golgi tendon organ (Kandel et al., 2000; Nolte & Sundsten, 2002; Seeley et al., 2003).

The muscles spindle is a predominant proprioceptive afferent, enabled with the ability to ascertain muscle length status. Consideration of the muscle spindle requires defining the disparity between the intrafusal and extrafusal class of muscles fiber. "Fusus" is Latin for spindle. Therefore intrafusal muscle fiber is within the muscle spindle, and extrafusal is outside of the muscle spindle. Intrafusal and extrafusal fibers are attached to each other (Nolte & Sundsten, 2002). The muscle spindles are parallel to their respective muscle fibers (Clark et al., 2008). Intrafusal fibers representing the muscle spindles are classified by two distinct types: nuclear bag fibers and nuclear chain fibers (Nolte & Sundsten, 2002).

Further consideration of the nuclear bag fibers establishes two disparate subclasses: the static nuclear bag fibers and dynamic nuclear bag fibers. The type 1a afferent fibers innervate all three forms of intrafusal fibers: nuclear chain fibers, static nuclear bag fibers, and dynamic nuclear bag fibers. Type 2 afferent fibers innervate static nuclear bag and nuclear chain fibers. The disparity in terms of afferent innervation enables the muscle spindle to measure two distinct types of muscle stretch characteristics (Kandel et al., 2000).

The muscle spindle is equipped with the ability to convey information pertinent to both muscle length rate of change and length status. The dynamic nuclear bag fibers innervated by the type 1a nerve fiber contribute to acquiring rate of muscle length change. The nuclear chain and static nuclear bag fibers are capable of conveying the steady state status of the muscle length and are innervated by both type 1a and type 2 afferent fibers (Kandel et al., 2000).

The Golgi tendon organ also provides afferent feedback, with respect to spatial representation of the body. In contrast to the muscle spindle, the Golgi tendon organ is aligned in series to the relevant muscle fiber. The Golgi tendon organ is innervated by 1b afferent fibers, which are activated in response to muscle contraction inducing tension on the pertinent tendon (Kandel et al., 2000; Nolte & Sundsten, 2002).

In contrast to biological (natural) proprioception, artificial proprioception using accelerometry enables a recordable modality for movement status. The accelerometer derives an accelerometer signal through a representative mass (Culhane et al., 2005; LeMoyne et al., 2008c). With the introduction of wireless technology, artificial proprioception has been synthesized into a fully wearable system through the incorporation of small wireless accelerometers. In the event of disparity of proprioceptive representation for affected and unaffected legs during hemiparetic gait, artificial proprioception can inform the user of the limb disparity during locomotion and also the efficacy of real-time compensatory strategies. Gait, reflex, and Parkinson's disease status can be characterized and stored on a database using artificial proprioception, and acquired data can be post-processed (LeMoyne et al., 2008a; LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d).

3. Ordinal scale classification of movement quality

Clinicians can apply ordinal scales as a strategy to classify their findings during an examination. The clinician is tasked with the goal of selecting a relevant ordinal parameter with an associated subjective qualitative definition. In consideration of a reflex evaluation during an examination, the clinician may rate the reflex response of a subject as 2+ representing normal reflex, 3+ representing brisker than normal reflex, and 1+ representing diminished relative to normal reflex. The ordinal reflex scale described above includes a 0 and 4+ ordinal component to classify the extreme bounds of the reflex response (Bickley & Szilagyi, 2003). Notably, the above reflex scale is highly dependent on the clinician's interpretation of 'normal' along with the interpretation of delineating acuity for the ordinal scale values.

There are other types of reflex scales, such as the broader Mayo Clinic scale. The Mayo Clinic scale is based on a 9 point ordinal interpretation. The clinician may classify an above normal reflex as +1 classified as brisk and +2 classified as very brisk (Manschot et al., 1998). Likewise the 9 point scale is extremely dependent on the clinician's interpretation and differentiation between the qualitative classification of 'brisk' and 'very brisk'. Another concern is the comparability and compatibility of multiple scales with a different number of ordinal classifying components. Two clinicians with preference for disparate scales may even be prone to prescribing disparate therapy protocols.

Ordinal scales are applied to other movement classification scenarios. Mobility can be classified through the incorporation of the modified Rivermead Mobility Index (Lennon & Johnson, 2000). Parkinson's disease status is characterized through the Unified Parkinson's Disease Rating Scale (www.mdvu.org).

Another issue of the ordinal scale method is the need for a clinician to conduct the evaluation. Parkinson's disease is neurodegenerative in nature (Kandel et al., 2000). The degenerative cycle can possibly persist between clinical appointments, for which the frequency of appointments may be correlated to the ability to modify therapy strategy in coherence with the potentially variant severity of the degenerative cycle. Essentially a prolonged duration between clinical appointments may lack the timely feedback with respect to the progressively degenerative cycle. However, for instance daily clinical appointments for tracking the status of the neurodegenerative disease might impart a rampant strain on limited medical resources.

The controversy of the accuracy of ordinal scale evaluation methods is demonstrated in consideration of reflex quantification. Litvan assessed the reliability of the five point ordinal NINDS Myotatic Reflex Scale. The results obtained substantial to near perfect reliability for intraobservers and moderate to substantial reliability for interobservers (Litvan et al., 1996). The findings of Manschot contradict the findings of Litvan. Manschot investigated the reliability of the five point NINDS scale and the nine point Mayo Clinic scale. In consideration of both scales interobserver agreement was bound by a fair level of agreement (Manschot et al., 1998). Further investigation by Stam shows an extensive level of interobserver disagreement while using the nine component Mayo Clinic scale. The study discovered that for 28% of the examination neurologists disagreed by a minimum of two ordinal scale units. For 45% of the reflex pairs there was disagreement as to the existence of asymmetry (Stam & van Crevel, 1990).

Artificial proprioception institutes a paradigm shift from the traditional ordinal scale evaluation technique. With the selection of defined anatomical anchors, the application of accelerometers can reliably characterize movement attributes (Kavanagh et al., 2006; Saremi et al., 2006). A wireless three dimensional accelerometer node can be positioned at a specified anatomical location, acquiring an acceleration derived bio-signal. The acquired acceleration signal can be post-processed for computing significant quantification parameters for augmented classification.

4. Evolution of accelerometer technology for biomedical applications

Accelerometer technology has progressively evolved respective of biomedical applications. Current technology innovations enable the application of wireless accelerometers, which are highly portable and even wearable. The synthesis of the wireless accelerometer technology space has resulted in the biomedical/ neuroengineering equivalent of biological derived proprioception termed artificial proprioception (LeMoyne et al., 2008c).

Technology applications for accelerometer systems have been applied to fields correlated with locomotion, such as the quantification of movement status (Bouten et al., 1997;

Uiterwaal et al., 1998; Zhang et al., 2003). A device developed by Aminian termed Physilog integrated accelerometers, successfully demonstrating the capability of measuring physical activity (Aminian et al. 1999). Applications using accelerometers have been developed for characterizing physical activity status for children (Busser et al. 1997; Hoos et al., 2004). Accelerometer devices incorporating classification techniques have reliably ascertained posture and activity status (Fahrenberg et al., 1997; Lyons et al., 2005).

Given the inherent autonomy of accelerometer synthesized devices, the spatial-temporal relationships of specific aspects of the body during gait cycle has been acquired (Moe-Nilssen, 1998; Menz et al., 2003a). Accelerometer systems have characterized important gait parameters: velocity, stride frequency, and gait symmetry (Auvinet et al., 2002; Menz et al. 2003b). Accelerometer systems have been evaluated as feedback modalities for augmenting functional neuromuscular stimulation (Willemsen et al., 1991; Veltink & Franken, 1996). Given the light weight and portable qualities of accelerometers, triaxial accelerometers have been placed on the trunk and head to contrast gait strategy for young and elderly people (Menz et al., 2003b; Kavanagh et al., 2004). The research endeavors further establish the relevance of accelerometer systems for the quantification of locomotion and movement characteristics, especially enabled given their minimally intrusive nature and attributes.

4.1 Research validation of accelerometers for gait quantification

Testing and evaluation of accelerometers is imperative for the validation of applications involving the quantification of movement characteristics. A subclass of general movement status is relevant to gait. The validation and confirmation for the efficacy of accelerometers to evaluate locomotion has been conducted with the evolving accelerometer technology space, with applications using uniaxial, integrated biaxial, and wireless triaxial accelerometers (Mayagoitia et al., 2002; Kavanagh et al., 2006; Saremi et al., 2006; LeMoyne et al., 2009d). The process for validating the ability of accelerometers to quantify gait has been established through the contrast to standard gait analysis systems, such as optical motion analysis (Mayagoitia et al., 2002).

4.2 Body mounted sensors incorporating uniaxial accelerometers

Mayagoita developed a body mounted sensor device, which integrated uniaxial accelerometers. The body mounted sensor system was represented with a series of uniaxial accelerometers operating in tandem, which was contrasted to the Vicon® system for optical motion analysis. The body mounted system incorporating uniaxial accelerometers yielded similar results in contrast to the Vicon® optical motion analysis system. Mayagoita envisions future applications, which instill portable data-logger systems for enhanced operational autonomy (Mayagoitia et al., 2002).

4.3 Biaxial accelerometer applications for gait analysis

As accelerometer technology is continuously evolving, the logical procession of the technology space would be from uniaxial to biaxial to triaxial accelerometer applications. The ultimate would be the evolution of a wireless triaxial accelerometer node (LeMoyne et al., 2008c). Subsequent research involving biaxial accelerometer technology also advances the application through the use of highly specified anatomical mounting positions for the accelerometer devices (Kavanagh et al., 2006; Saremi et al., 2006).

4.4 Biaxial accelerometers with portable microprocessor

Saremi evaluated an accelerometer based system termed the Intelligent Device for Energy Expenditure and Activity (IDEEA) created by MiniSun for the capacity to evaluate gait parameters. The device integrated five biaxial accelerometers mounted at highly specified anatomical positions. One accelerometer node was mounted 4cm below the sternum top. The other four accelerometers were allocated in pairs of two for both legs: under the medial forefoot and the anterior aspect of the thigh. With respect to the medial forefoot, further anatomical specification defined the position as below the 4th metatarsal head by a distance of 2cm. The anterior aspect of the thigh was further classified as the midpoint in terms of the distance between the anterior superior iliac spine and the knee. The selection of the anatomical mounting points for the accelerometer nodes enabled the acquisition of data relevant to the sagittal plane. The sampling rate for the accelerometer components was established at 32Hz (Saremi et al., 2006). The fundamental objective of the MiniSun IDEEA device was to measure the energy expenditure for physical activity in a more autonomous application relative to the laboratory environment (Zhang et al. 2003; Zhang et al., 2004). The IDEEA device represents the integration of multiple accelerometers with the capacity to obtain spatiotemporal data relevant to gait. The IDEEA system is applicable in both community and clinical settings (Saremi et al., 2006).

The accuracy of the IDEEA device was compared to multiple traditional systems for gait analysis, such as EMG, a footswitch device, and a video gait analysis system using infrared markers. The investigation amended a triaxial accelerometer positioned on the thigh as contrast to the biaxial accelerometers of the MiniSun device. Relative to the MiniSun biaxial accelerometers, the triaxial accelerometers mounted to the thigh produced nearly identical waveforms. No statistically significant difference was ascertained for the parameters acquired from the footswitch device in comparison to the MiniSun device. The temporal aspect of gait parameters familiar to clinicians, such as EMG bursts, hip, knee, and ankle joint angle were characterized through the MiniSun device. The MiniSun accelerometer system demonstrated a high test to retest reliability. The reliable acquisition of leg acceleration waveforms during gait cycle could augment therapist insight in consideration of patient rehabilitation (Saremi et al., 2006).

4.5 Tandem biaxial accelerometers with wireless connectivity from processor box to PC

Another study evaluating the reliability of an integrated biaxial accelerometer system was conducted by Kavanagh. The accelerometer system involved four nodes consisting of two biaxial accelerometers positioned orthogonally. The accelerometer nodes were wired by shielded cable to a processor box mounted to the waist of the subject. The subcomponents of the processor box were a power regulation system, microprocessor, Bluetooth system enabling wireless connectivity, and two AAA batteries. With the Bluetooth component, the system could transmit wireless information to a local PC (Kavanagh et al., 2006).

The objective of the research was to ascertain the reliability of the gait analysis system using accelerometers in consideration of intra/inter-examiner and stride to stride reliability. Four well defined anatomical positions were selected for the mounting of the accelerometer nodes: the C7 and L3 spinous process, 3cm proximal to the lateral malleolus, and the occipital pole of the skull. The study ascertained comparable reliability for intra/inter-examiner evaluations and for individual stride to stride reliability. The conclusion was the accelerometer node reapplication errors for the same or different examiner were minimal. The research implicates the reliability of accelerometer systems for the quantification of gait (Kavanagh et al., 2006).

The investigations by Saremi and Kavanagh have a significant implication. With the use of highly specified anatomical mounting points for the accelerometers, such as the L3 spinous process or 4cm below the sternum top, reliable data could be acquired (Kavanagh et al., 2006; Saremi et al., 2006). Essentially such highly specified anatomical anchor positions are suitable for a clinician with a considerable degree of anatomical specialization, rather than a subject applying and wearing the accelerometer systems in an autonomous and personalized environment.

Wearable proprioception is represented by even more autonomous applications, such as wireless three dimensional accelerometer nodes. Since the concept is envisioned for the operation by the actual subject in a fully autonomous setting, more simplified and robust anatomical mounting positions are considered. For gait related applications, such as virtual proprioception and gait quantification, the anatomical mounting points are the lateral malleolus and lateral epicondyle of the femur, secured by an elastic band. These two mounting positions can be readily identified as above and adjacent to the ankle joint and the top of the knee joint (LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2009b; LeMoyne et al., 2009d). Reflex quantification has also advocated the mounting position adjacent to the lateral malleolus, also described as the lateral aspect of the leg to the medial malleolus, which is essentially the ankle joint (LeMoyne et al., 2008a; LeMoyne et al., 2008h). With respect to the quantification of Parkinson's disease, the anatomical position is the dorsum of the hand, secured through a flexible strap and readily identifiable as the top of the hand (LeMoyne et al., 2009a).

4.6 Accelerometer systems for Parkinson's disease evaluation

Accelerometer systems have enabled the potential for automated and quantitative evaluation of Parkinson's disease motor status uniquely specified for an individual patient in an effectively autonomous environment while conducting daily activities. The accelerometer device was amalgamated with a neural network algorithm for classifying 'on' and 'off' Parkinson's disease states. Information acquired from the signal of the accelerometers was transmitted to a data-logger also mounted to the subject. The research study ascertained a high level of specificity for classifying the disparity between the 'on' and 'off' states for Parkinson's disease subjects based on the capabilities of the accelerometer system and associated algorithm. The advancement of accelerometer systems providing automated and quantified evaluation under autonomous conditions for Parkinson's disease status can potentially lead to individually optimized medication strategy and quantified measurement for the efficacy of novel therapy strategies (Keijsers et al., 2006).

The synthesis of an accelerometer system with neural networks was applied to classify the attributes of Levodopa-induced dyskinesia for subjects with Parkinson's disease. Given the findings of the research, the integrated system, equipped with accelerometers as the sensor and neural networks as the algorithm, was demonstrated as a means for classifying severity of Levodopa-induced dyskinesia. Future concepts based on the study would address the attributes of Levodopa-induced dyskinesia spanning the complete dose cycle (Keijsers et al., 2000). The system also could quantify the temporal feature for Parkinson's disease progression.

For patients with advanced pathologies, the establishment of a prudent drug therapy strategy may be obfuscated with both positive and negative outcomes. Accelerometers have been introduced for studies to evaluate the efficacy of drug therapy for patients with both dementia and Parkinson's disease. The medication could potentially improve cognitive function while amplifying tremor characteristics. The incorporation of accelerometers enables an advancement of diagnostic acuity, especially in light of conflicting effects from the presumptive therapy strategy (Gurevich et al., 2006).

With accelerometer data quantifying the characteristics of tremor, the efficacy of drug therapy can be analyzed through the incorporation of advanced numerical methods. Spectral analysis has been applied to the elucidation of accelerometer data derived tremor attributes. Research integrating the processing of the accelerometer signal through spectral analysis has been applied for ascertaining the efficacy of medication strategies for reducing tremor (Schrag et al., 1999).

Another unique application of accelerometer technology is as a feedback modality for deep brain stimulation efficacy. In a study involving patients with Parkinson's disease or essential tremor, accelerometers were used to quantify the effectiveness of deep brain stimulation. The study ascertained a significant improvement in tremor attributes with the stimulator in the 'on' mode (Obwegeser et al., 2001). Other research incorporated accelerometers for the determination that deep brain stimulation induces improved motor function characteristics (Kumru et al., 2004).

4.7 Integrated wireless three dimensional accelerometer systems for gait analysis

A wireless accelerometer system consisting of integrated subcomponents was produced and evaluated by Lee. A footswitch device was operated in tandem with the wireless accelerometer system, serving as a standard contrast for the acquisition of temporal parameters for gait. A triaxial accelerometer subsystem was integrated with the wireless accelerometer system, and the data was sampled at 61Hz. Other aspects of the integrated device were a battery powered subsystem and subsystem for conveying data wireless to a local PC, with a maximum operating range of 15 meters. The system mass was 50 grams. The attributes of the integrated wireless accelerometer system enabled mounting of the device at the lateral aspect of the ankle. Both ankles were mounted with an integrated wireless accelerometer system. The research by Lee confirms the temporal parameter correlation acquired from the footswitch device and the accelerometer system using integrated components for achieving wireless capability (Lee et al., 2007).

4.8 Wearable shoe integrated wireless gait quantification system integrating multiple biaxial accelerometers

A gait analysis device termed GaitShoe integrates multiple devices for quantification of locomotion attributes into a wearable system by integrating the components of the GaitShoe into a typical shoe. The shoe effectively represents the mounting point for the anatomical position, greatly reducing the need for even basic knowledge of anatomy. The GaitShoe device consists of multiple gait analysis sensors: pressure sensors, electric field height sensors, force sensors, bend sensors, gyroscopes, and accelerometers. Multiple biaxial accelerometers are integrated into the GaitShoe application. Acquired gait quantification data is conveyed from the GaitShoe through wireless transmission (Bamberg et al. 2008).

The GaitShoe device and integrated wireless accelerometer application by Lee represent evolutions of gait analysis and quantification. Wearable artificial proprioception further evolves the technology space for the more global application of movement analysis and quantification, for which the topic of locomotion is a subset. Wearable artificial proprioception is demonstrated by a fully integral wireless three dimensional accelerometer node, such as the G-Link® Wireless Accelerometer Node (www.microstrain.com).

In contrast to the device developed by Lee, the G-Link® Wireless Accelerometer Node is equipped with signal strength for wireless transmission spanning a range of 70 meters (www.microstrain.com). Even with a wireless range of 4-5 times the range for the system developed by Lee, the G-Link® Wireless Accelerometer Node has a mass of 46 grams, which is about 10% less than the system mass for the device composed by Lee. Also the G-Link® Wireless Accelerometer is powered by a rechargeable system as opposed to a battery, which would presumably need periodic replacement (www.microstrain.com; Lee et al., 2007).

The GaitShoe introduces a unique concept for evaluating gait, through the integration of multiple sensors into the wearable application of a shoe. However inherent limitations may exist with the incorporation of 6 sensor components, such as requirements for packaging the sensors and providing sufficient power. With the integration of the sensor apparatus, the integrated device has a volume on the scale of the actual shoe (Bamberg et al. 2008). The GaitShoe apparatus has a mass 6-7 times greater than the G-Link® Wireless Accelerometer Node. The GaitShoe provides accelerometer data through biaxial accelerometers, as opposed to the G-Link® Wireless Accelerometer Node that utilizes triaxial accelerometers (www.microstrain.com; Bamberg et al. 2008). The mounting of gait quantification sensors to a wearable shoe application may limit perceptivity as to locomotion quality and status, since the spatial temporal aspects of the foot during gait cycle are the result of a triple joint system represented by the ankle, knee, and hip joint.

4.9 Wireless three dimensional accelerometers and future technology

As demonstrated by the previous research, accelerometer technology has become increasingly integrated for applications of movement quantification, such as gait. As illustrated in figure 1, the accelerometer technology has progressed from uniaxial to biaxial to triaxial accelerometers with volumetric packaging decreasing with advances in miniaturization as a function of year (www.enablingmnt.com; LeMoyne et al., 2008c).

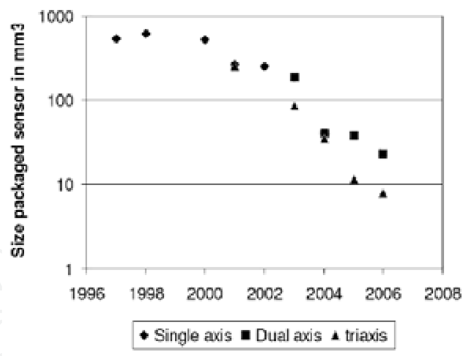

Fig. 1. Evolution trend progress for accelerometer miniaturization versus year (www.enablingmnt.com; LeMoyne et al., 2008c)

Multiple technologies support and affect the evolution of accelerometer systems (Culhane et al., 2005; LeMoyne et al., 2008c). Evolution of microelectronics based on the principle of Moore's Law establishes a basis for the advance of accelerometer technology. Moore's Law asserts that with respect to a chip the number of transistors doubles roughly within a two year duration. Basically Moore's Law implicates cost reduction with expanding performance (www.intel.com). The trend defined by Moore's Law should also pertain to advances in performance and decrease in cost for accelerometer technology.

4.10 Wireless accelerometers for artificial proprioception

The implementation of wireless technology has further advanced accelerometer systems (www.microstrain.com; www.sparkfun.com; Jafari et al., 2005; LeMoyne et al., 2008c). Wireless accelerometer systems provide expanded autonomy for the characterization of movement disorder and gait analysis (Lee et al., 2007; Bamberg et al. 2008; LeMoyne et al., 2008a; LeMoyne et al., 2008c; LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009d). In essence a compact, lightweight, and minimally intrusive wireless accelerometer provides an artificial type of proprioception.

The utility of a wireless accelerometer node functioning as artificial proprioception has numerous benefits to the biomedical field. While a non-intrusive wireless accelerometer node can measure human movement such as reflex response and latency, Parkinson's disease tremor, and gait quality; the quantified measurements can also be stored on a database of a local PC (Lee et al., 2007; Bamberg et al. 2008; LeMoyne et al., 2008a; LeMoyne et al., 2008c; LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009d). Downloading the resultant measurements of artificial proprioception through a wireless accelerometer node enables the implementation of subsequent post-processing algorithms and tracking of status progression.

The G-Link® Wireless Accelerometer Node currently represents the state of the art for artificial proprioception. The device is capable of sampling data at a rate of 2048Hz in a wireless activated data-logger mode, using tandem wireless accelerometer nodes. The sampling rate for the G-Link® Wireless Accelerometer Node, using tandem activated accelerometers, may be set to alternative sampling rates, such as 512Hz, according to the discretion of the operator and the research scenario requirements (www.microstrain.com).

Subsequently the wireless technology has been integrated into sensors, such as accelerometers (www.microstrain.com; www.sparkfun.com; Jafari et al., 2005). Advances in wireless technology may substantially benefit the accelerometer technology space, such as greater autonomy for research applications (LeMoyne et al., 2008c). The next logical step for the advancement of the technology is for the development of fully wireless and portable three dimensional accelerometer sensors.

The G-Link® Wireless Accelerometer Node represents the frontier of the wireless three dimensional accelerometer technology space with features such as a real-time streaming rate of up to 4kHz and wireless activated data-logger mode with 2MB of data storage capacity (www.microstrain.com). The variable sampling rates for the G-Link® Wireless Accelerometer Node provide flexibility in light of the Nyquist rate, which the is the minimum sampling rate required to prevent aliasing. Aliasing is known as the scenario, for which sampling disparate continuous signals becomes indistinguishable. Aliasing can be avoided through defining a sampling rate greater than the Nyquist rate, which is twice the maximum bandwidth frequency of the signal (www.vias.org).

The gait analysis study conducted by Saremi incorporated a sampling rate of 32Hz (Saremi et al., 2006). During the study by Lyons a sampling rate of 50Hz was considered to exceed the Nyquist criterion applicable to mobility data (Lyons et al., 2005). The G-Link® Wireless Accelerometer Node is certainly capable of exceeding the above sampling rates. Another advantage of the G-Link® Wireless Accelerometer Node is the sampling rate can be modulated at the discretion of the researchers. For instance the 2048Hz sampling rate may be reduced to 512Hz, which would reduce the data size of the sampling event by a factor of four (www.microstrain.com).

There are many other advantages for the G-Link® Wireless Accelerometer Node. The device is powered by rechargeable batteries integrated into the node, negating the need for battery replacement. The wireless accelerometers have a wireless transmission range of 70 meters. If the potential for a break in wireless signal continuity exists, the nodes can utilize a wireless activated data-logger mode. The G-Link® Wireless Accelerometer Node can store up to 2MB of data in the data-logger mode, and data can be downloaded to a PC by wireless transmission. G-Link® Wireless Accelerometer Nodes have a mass of 46 grams (www.microstrain.com). These attributes make the wireless accelerometer technology ideal for applications in reflex response and latency quantification, Parkinson's disease tremor evaluation, gait analysis, and real-time biofeedback of hemiparetic gait disparity (LeMoyne et al., 2008c; LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d).

5. Applications for artificial proprioception

Wireless three dimensional accelerometers have demonstrated the ability to serve as an artificial form of proprioception. There are numerous biomedical applications for which wireless three dimensional accelerometers are relevant. Recent research has been successfully applied to aspects of the classification and quantification of movement characteristics, such as the evaluation of tendon reflex, Parkinson's disease status, gait analysis, and virtual proprioception, which is a real-time biofeedback system for gait rehabilitation (LeMoyne et al., 2008e; LeMoyne et al., 2008f; LeMoyne et al., 2008h; LeMoyne et al., 2009a; LeMoyne et al., 2009b; LeMoyne et al., 2009c; LeMoyne et al., 2009d).

5.1. Reflex quantification using wireless accelerometer system as artificial proprioception

The tendon reflex, such as the patellar tendon reflex, is a standard aspect of a typical neurological examination (Kandel et al., 2000; Bickley & Szilagyi, 2003). The tendon reflex can provide insight as to the status of both central and peripheral nervous system function and possible trauma (Bickley & Szilagyi, 2003). Ordinal scales have been developed for evaluating reflex response, for which some researchers assert the validity of the ordinal scale system (Litvan et al., 1996). However, other studies contradict the validity of ordinal scale systems (Stam & van Crevel, 1990; Manschot et al., 1998). One notable aspect of the ordinal scale system is the lack of temporal parameters to characterize the temporal aspect of the reflex response (Stam & van Crevel, 1990; Litvan et al., 1996; Manschot et al., 1998). The tendon reflex can also indicate latency (Frijns et al., 1997; Voerman et al., 2005). The reflex loop may provide a less resource intensive first screen alternative to electrodiagnostic evaluation. The appropriateness of electrodiagnostic evaluation has been demonstrated as a subject of controversy (Mondelli et al., 1998; Podnar et al., 2005; Cocito et al., 2006). An alternative solution could be provided through a reflex quantification system.

Some reflex quantification systems have emphasized quantification of response, such as a load cell tethered to the ankle by a cable using an instrumented hammer; a strain gauge system measuring reflex response using a manual sweep triggered hammer for input; and EMG measurement of response while evoking the reflex with a motorized component (Van de Crommert et al. 1996; Faist et al. 1999; Pagliaro & Zamparo, 1999; Cozens et al., 2000; Lebiedowska & Fisk, 2003). Other systems have synchronized the reflex input and reflex response aspects of the reflex quantification system, deriving the effective latency as the temporal disparity between input and reflex response signals. Synchronized reflex quantification systems without the requirement of EMG have incorporated instrumented reflex hammers synchronized with a wired accelerometer; an instrumented hammer with a torque sensor locked in a defined position; and a motorized reflex hammer input functioning in tandem with a strain gauge sensor measuring response (Koceja & Kamen, 1988; Kamen & Koceja, 1989; Zhang et al. 2000; Mamizuka et al., 2007). Such strategies for quantifying tendon reflexes are noteworthy of credit; however the proposed wireless accelerometer reflex quantification system enables advances in terms of portability, flexibility, ease of use, scalability, and functional robustness. The proposed wireless accelerometer reflex quantification system has been progressively evolved over the course of three evolutionary cycles, with a modified third generation system applied to an artificial reflex configuration (LeMoyne et al., 2005b; LeMoyne & Jafari 2006a; LeMoyne et al., 2007b; LeMoyne et al., 2008a; LeMoyne et al., 2008g; LeMoyne et al., 2008h; LeMoyne et al., 2009c).

5.1.1 Wireless accelerometer reflex quantification device (first generation)

The initial concept of wireless reflex quantification, conceptualized and developed in 2005, consisted of two global system requirements: quantification of reflex response and reflex input for the patellar tendon (LeMoyne, 2005a; LeMoyne et al., 2005b; LeMoyne & Jafari 2006a). Eventually the system was evolved to successfully quantify both patellar tendon reflex input, reflex response, and reflex latency (LeMoyne et al., 2007b; LeMoyne et al., 2008a; LeMoyne et al., 2008h). Further confirmation of the wireless accelerometer reflex quantification system was obtained through the use of an artificial reflex device, which also demonstrated a high degree of accuracy and reliability (LeMoyne et al., 2008g; LeMoyne et al., 2009c).

The first generation wireless quantified reflex system was envisioned in 2005, and demonstrated the ability to contrast disparity of reflex response for a hemiparetic affected/unaffected leg in comparison to a nominal neurology control, through a wireless two dimensional accelerometer device. The prime objective of the first generation wireless quantified reflex system was to demonstrate the capacity of the system to objectively quantify the disparity of hemiparetic reflexes, contrasting affected leg to unaffected leg. The numerical algorithm strategy used for the application was the ratio of time averaged acceleration for affected versus unaffected leg (LeMoyne et al., 2005b).

The first generation wireless reflex system consisted of a Mednode two dimensional wireless accelerometer mounted near the ankle and coplanar to the sagittal plane for the reflex response of the subject. The signal of the Mednode wireless accelerometer was transmitted to a local PC for later post-processing of the data. The reflex input evoking the patellar tendon reflex was based on a hinged device with a reflex hammer attached to the moment arm, enabling consistent potential energy derived reflex input. The results indicated a significant disparity for the hemiparetic subject with an affected to unaffected leg patellar tendon reflex ratio of 1.5; in contrast the ratio was effectively parity at 1.0 for the nominal neurology subject (LeMoyne et al., 2005b).

5.1.2 Wireless accelerometer reflex quantification device (second generation)

The test and evaluation of the first generation wireless accelerometer reflex quantification system established the evolutionary insight for the second generation wireless accelerometer reflex quantification system developed in 2006. A more application robust three dimensional wireless accelerometer Mednode was integrated into the system, with the acquired data conveyed wirelessly to a local PC for post-processing. The reflex input component has evolved by developing a potential energy derived swing arm mounted to the reflex hammer incorporating aluminum parts with adjustable knobs for expanded simplicity of operation (LeMoyne & Jafari, 2006a; LeMoyne & Jafari, 2006b; LeMoyne et al., 2008a). Similar to the research of Kavanagh and Saremi, an anatomical mounting point was selected for optimizing accuracy for multiple evaluations (Kavanagh et al., 2006; Saremi et al., 2006). The anatomical location selected was the above the lateral malleolus, which is also the lateral aspect of the leg in consideration of the medial malleolus (LeMoyne & Jafari, 2006a; LeMoyne & Jafari, 2006b; LeMoyne et al., 2008a).

Given the expanded capacity of the second generation wireless accelerometer reflex quantification system to evoke the patellar tendon reflex with specified potential energy settings, multiple potential energy increments were incorporated. Three subjects comprised the test and evaluation experiment; consisting of one chronic hemiparetic and two subjects without any neurological traumas. The experiment was comprised of three sets of six reflex input settings (45, 30, 15, 15, 30, and 45 degrees) for each leg. Each set was conducted on a different day, obtaining 108 measurements. The objective of the test and evaluation of the second generation wireless accelerometer reflex quantification system was to provide proof of concept from an engineering perspective, ascertaining the accuracy and reliability of the system for quantifying the patellar tendon reflex (LeMoyne & Jafari, 2006a; LeMoyne & Jafari, 2006b; LeMoyne et al., 2008a).

Of the 108 measurements acquired by the second generation wireless accelerometer reflex quantification system, 107 of the measurements were bound by a 10% relative variation, with respect to the amplitude of the quantified reflex response. Only one measurement exceeded this 10% bound requiring a bound of 15%. The test and evaluation of the second generation reflex system using three dimensional accelerometers implicates a considerable level of reproducibility and accuracy (LeMoyne & Jafari, 2006a; LeMoyne & Jafari, 2006b; LeMoyne et al., 2008a).

5.1.3 Wireless accelerometer reflex quantification device (third generation)

The third generation wireless accelerometer reflex quantification system further evolves the application by integrating two tandem activated wireless accelerometers. Testing and evaluation was commenced during 2007. The primary modification for the third generation system was the incorporation of the G-Link® Wireless Accelerometer Node (LeMoyne et al. 2007b; LeMoyne et al., 2008h).

The G-Link® Wireless Accelerometer Node advanced the capacity of the wireless accelerometer reflex quantification system. The wireless accelerometers were capable of conveying a real-time data stream with a sampling rate of 100Hz. Two G-Link® Wireless Accelerometer Nodes were capable of tandem activation with a temporally synchronized data stream. The real-time data stream was subsequently conveyed to a local PC for post-processing (www.microstrain.com).

Tandem and synchronized operation of two accelerometer nodes enables event detection based on the temporal disparity of both acceleration waveforms. One wireless accelerometer was mounted to the swing arm of the third generation reflex quantification system, with the respective acceleration waveform indicating reflex hammer strike initiating the reflex loop. The other tandem and synchronized wireless accelerometer was mounted to the lateral malleolus, indicating the reflex response acceleration waveform. With both wireless accelerometers functioning in synchronicity and activated in tandem, the temporal disparity between the acceleration waveforms can derive latency of the reflex loop. The objective of the test and evaluation of the third generation wireless accelerometer reflex quantification system was to accurately and reliably acquire both quantified reflex response and latency of the patellar tendon reflex (LeMoyne et al. 2007b; LeMoyne et al., 2008h).

The following experimental protocol was used for the test and evaluation of the third generation wireless reflex quantification system:

1. Mount the wireless three dimensional accelerometer using an elastic band adjacent and above the lateral malleolus.
2. Aim the reflex hammer for evoking the patellar tendon reflex at the level of the tibial tubercle.
3. Retract the swing arm to a 30 degree setting relative to gravity vector.
4. Release the swing arm.
5. Save the acquired data from the wireless three dimensional MEMS accelerometers (LeMoyne et al., 2008h).
6. Delay evoking the next patellar tendon reflex by one minute (Cozens et al., 2000; LeMoyne et al., 2008h).
7. Repeat the protocol (LeMoyne et al., 2008h).

The test and evaluation experiment was comprised of the unaffected leg of a chronic hemiplegic (subject 1) and a subject without any neurological injuries (subject 2), using the leg on the same side as the preferred arm. Twenty measurements were obtained per subject. The experiment was intended to illustrate engineering proof of concept (LeMoyne et al., 2008h).

Fig. 2. Third generation wireless accelerometer reflex quantification device

Table 1. Quantified reflex parameters

Reflex parameter	Subject 1	Subject 2
Reflex latency mean (msec)	95.5	154.5
Reflex latency standard deviation (msec)	6.863	9.987
Coefficient of variation	0.07186	0.06464
Maximum reflex response mean (g's)	1.024	1.017
Maximum reflex response standard deviation (g's)	0.00446	0.00870
Coefficient of variation	0.00436	0.00855
Minimum reflex response mean (g's)	0.8825	0.9495
Minimum reflex response standard deviation (g's)	0.01243	0.00927
Coefficient of variation	0.01408	0.00976

(LeMoyne et al., 2008h)

The third generation wireless accelerometer reflex quantification system is illustrated in figure 2. The quantified reflex parameters are displayed in table 1. The resultant parameters, such as maximum reflex response, minimum reflex response, and latency, demonstrated consistent accuracy and reliability. The sample size of 20 measurements was bound with a confidence level of 95%, according to a 5% margin of error relative to the mean, respective of both subjects. All reflex parameters were considered for the determination of the bounding confidence level. Based on the quantified measurements, the sample size may be reduced to 10, with a 90% confidence level and a 5% margin of error relative to the mean (LeMoyne et al., 2008h).

The findings of the research implicate the third generation reflex quantification system is capable of ascertaining quantified reflex response, both minimum and maximum, and latency with a considerable accuracy and reliability. Based on the results of the third generation wireless accelerometer reflex quantification system test and evaluation, clinical trials are warranted for the establishment of reproducibility for the device to acquire patellar tendon reflex parameters (LeMoyne et al. 2007b; LeMoyne et al., 2008h). The evaluation of an artificial reflex system could also further validate the reflex quantification system incorporating wireless three dimensional accelerometers.

5.1.4 Wireless accelerometer reflex quantification device using artificial reflex

The tendon reflex is inherently variable, as the functionality is based on the inherently variable neurological system (Kandel et al., 2000; Bickley & Szilagyi, 2003; Seeley et al., 2003). An artificial reflex system, developed and evaluated from 2007 to 2008, was evaluated using the current third generation wireless accelerometer reflex quantification device. The artificial reflex system uses mechanically derived reflex response from stored potential energy of a rubber band and mechanically derived latency from a trigger subsystem incorporating a cam. The third generation reflex system was modified, with the G-Link® Wireless Accelerometer Node configuration set to a wireless activated data-logger mode with a sampling rate of 2048Hz, which provided a more user-convenient methodology for acquiring measurement samples (LeMoyne et al., 2009c). As anticipated, the modified third generation wireless accelerometer reflex quantification system obtained pertinent reflex parameters, such as maximum and minimum reflex response and latency (LeMoyne et al., 2008g; LeMoyne et al., 2009c). Based on a sample of 15 measurements, all significant reflex parameters were sufficient bound with a 96% confidence level using a 4% margin of error about the mean; implicating a considerable degree of accuracy and reliability (LeMoyne et al., 2009c).

5.2 Wireless accelerometer system for quantifying Parkinson’s disease attributes

Parkinson’s disease is classified as a movement disorder affecting about one million people in the United States, while predominantly occurring after an age of 55 years (Kandel et al., 2000; Seeley et al., 2003). A typical attribute of Parkinson’s disease is a four to five per second resting tremor (Kandel et al., 2000; Bickley & Szilagyi, 2003). Two therapy strategies with variable dosage allocations are drug therapy and deep brain stimulation (Kandel et al., 2000; Nolte & Sundsten, 2002; Volkmann et al., 2006). Drug therapy efficacy eventually diminishes over time, and adverse side effects can precipitate (Kandel et al., 2000; Nolte & Sundsten, 2002). Accelerometers have been demonstrated for quantifying the efficacy of drug therapy, deep brain stimulation parameter settings, and classifying temporal oscillations of the disease severity (Schrag et al., 1999; N. L. Keijsers et al., 2000; Obwegeser et al., 2001; Kumru et al., 2004; Gurevich et al., 2006; N. L. Keijsers et al., 2006). A wireless three dimensional accelerometer, serving as an artificial form of proprioception, is the next evolution for the integration of accelerometer technology quantification of Parkinson’s disease tremor.

Wireless accelerometer systems were initially proposed as a feedback modality for deep brain stimulation of Parkinson's disease subjects as of 2007 (LeMoyne, 2007a; LeMoyne et al., 2008b). Subsequent evaluation involved G-Link® Wireless Accelerometer Nodes for quantifying a simulated tremor in contrast to a static control. Both accelerometers were set to a sampling rate of 2048Hz using the data-logging mode with wireless activation (LeMoyne et al., 2009a).

The conceptual evaluation of the G-Link® Wireless Accelerometer Node capacity for quantifying Parkinson's disease tremor involved a simulated hand tremor. One wireless accelerometer was secured to the dorsum of the hand through a flexible strap, and the other wireless accelerometer was placed in a static location. Five trials were conducted during the evaluation, and the data samples were analyzed over one second increments. The time averaged acceleration was calculated using a trapezoid method. The quantified data for both simulated tremor and static control were both sufficiently bound using a 90% confidence level and a 10% margin of error respective of the mean. The Parkinson's disease quantification system involving a wireless accelerometer is illustrated in figure 3. The simulated tremor and static control are characterized in figures 4 and 5 (LeMoyne et al., 2009a).

The fundamental utility of the wireless accelerometer system for evaluating Parkinson's disease is based on the opportunity to characterize disease status and progression in a relatively autonomous environment, such as a home setting. The measurements could provide a database and effective baseline for tracking therapy efficacy and variation over a 24 hour cycle. Advances in data processing techniques may enable the opportunity of possible continuous tracking (LeMoyne et al., 2009a).

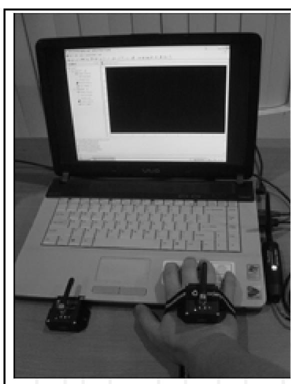

Fig. 3. Wireless accelerometer system for quantifying Parkinson's disease

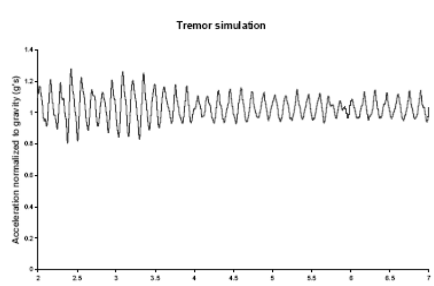

Fig. 4. Simulated tremor acceleration signal

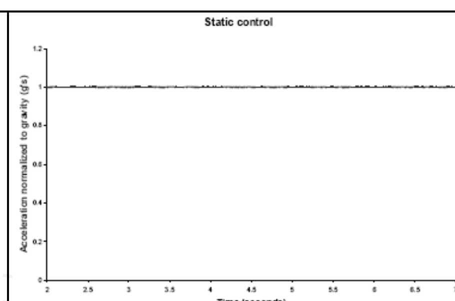

Fig. 5. Static control acceleration signal

(LeMoyne et al., 2009a)

5.3 Wireless three dimensional accelerometer device for quantifying gait

The incorporation of wireless and wearable accelerometer systems enables a considerable expansion for the autonomy of gait analysis, permitting both outdoor and indoor gait analysis and quantification beyond clinical confines (LeMoyne et al., 2009b; LeMoyne et al., 2009d). Standard gait evaluation technologies consist of devices, such as EMG systems, electrogoniometers, metabolic energy expenditure systems, ground reaction force analyzers, foot switch stride analyzers, and optical motion analysis systems (Mayagoitia et al., 2002; Dobkin, 2003; LeMoyne et al., 2008c). Relative to traditional gait analysis technologies, effectively wearable and wireless accelerometers offer advanced utility, such as autonomy of application, portability, minimal intrusion on gait cycle, ease of operation, and operation beyond the setting of a gait analysis laboratory (LeMoyne et al., 2008c; LeMoyne et al., 2009b; LeMoyne et al., 2009d). The evolution of accelerometer devices for analyzing the gait cycle has steadily progressed from uniaxial to biaxial to triaxial accelerometers (Mayagoitia et al., 2002; Kavanagh et al., 2006; Saremi et al., 2006; LeMoyne et al., 2008c). Initial experimentation of novel wireless gait analysis systems integrating three axis accelerometers and multiple two axis accelerometer systems have been conducted (Lee et al., 2007; Bamberg et al. 2008). As previously discussed, the G-Link® Wireless Accelerometer Node offers an advance in utility of wearable and wireless three dimensional accelerometer systems for gait analysis and quantification in contrast to the integrated wireless accelerometers (www.microstrain.com; LeMoyne et al., 2008c).

Fig. 6. Wearable and wireless accelerometer device mounted at lateral epicondyle adjacent to the knee joint

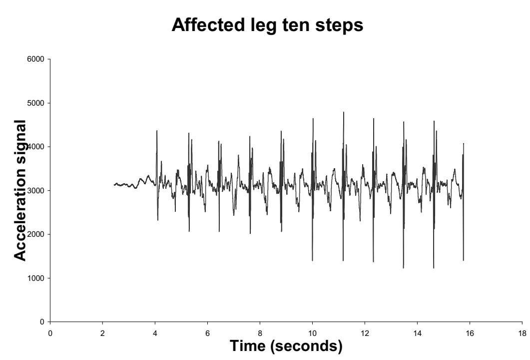

Fig. 7. Acceleration waveform of affected leg during gait cycle

Table 2. Stance to stance time averaged acceleration ratio with 100 milliseconds bound about the stance component removed (affected leg/ unaffected leg)

Trial	Stance to stance time averaged acceleration ratio with 100 milliseconds bound about the stance component removed (affected leg/ unaffected leg)
1	0.79
2	0.94
3	0.73

(LeMoyne et al., 2009d)

The functional utility of the G-Link® Wireless Accelerometer Node was demonstrated with respect to two disparate experiments, both conducted in 2008: a gait evaluation of a chronic hemiparetic while walking on an outdoors sidewalk and a gait evaluation of a chronic hemiparetic while walking through the hallway of a house (LeMoyne et al., 2009b; LeMoyne et al., 2009d). Previous research has established the utility of well defined anatomical mounting points for the accelerometer nodes (Kavanagh et al., 2006; Saremi et al., 2006). With respect to the outdoor gait analysis, the anatomical mounting position was the readily identifiable lateral epicondyle next to the knee joint (LeMoyne et al., 2009d). For the indoor homebound gait analysis the anatomical mounting position was selected as above the lateral malleolus adjacent to the ankle joint (LeMoyne et al., 2009b). For both experiments the G-Link® Wireless Accelerometer Nodes were set to a sampling rate of 2048Hz, while using the wireless activated data-logger mode; acquired gait cycle data was subsequently transmitted wireless to a local PC for post-processing (LeMoyne et al., 2009b; LeMoyne et al., 2009d).

The first experiment was the outdoors application of the wearable and wireless three dimensional accelerometer gait quantification system. The chronic hemiparetic subject was instructed to walk on a sidewalk for three trials with ten steps per leg, with the G-Link® Wireless Accelerometer Nodes activated by wireless transmission, recording in data-logger mode, and subsequently downloading the acquired data by wireless transmission to a local PC for data processing. Figure 6 characterizes the mounting of the wearable and wireless accelerometer device at the lateral epicondyle adjacent to the knee joint; and figure 7 illustrates a characteristic acceleration waveform (LeMoyne et al., 2009d).

Subsequent analysis involved calculating the stance to stance time averaged acceleration ratio (affected leg/ unaffected leg), using a trapezoid method to compute the respective integrals. A 100 millisecond bound about the stance aspect of the gait cycle was removed, in order to focus attention toward the swing aspect of gait. As indicated with table 2 an apparent and quantified affected to unaffected leg disparity was ascertained. Based on the acceleration waveform time averaged acceleration ratio, the unaffected leg was bound with a 95% confidence level using 5% margin of error about the mean with respect to all trials. For the affected leg trial 1 was bound by a 95% confidence level using a 5% margin of error about the mean, but trial 2 and 3 diminished to a 90% confidence level using a 10% margin of error about the mean (LeMoyne et al., 2009d).

The subsequent application of a wearable and wireless three dimensional gait analysis system focused on analyzing and quantifying gait cycle in a homebound setting. The subject, a chronic hemiparetic, was instructed to walk through the hallway of a home environment. Three trials were acquired using four complete step cycles. The application in the home setting involved mounting the wireless accelerometers to the lateral malleolus adjacent to the ankle joint as illustrated in figure 8 (LeMoyne et al., 2009b).

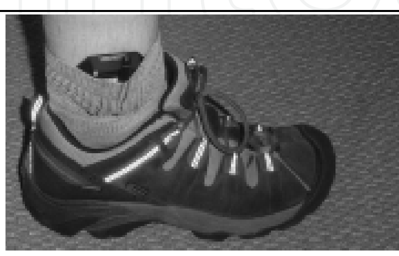

Fig. 8. Wireless accelerometer mounted to the lateral malleolus (LeMoyne et al., 2009b)

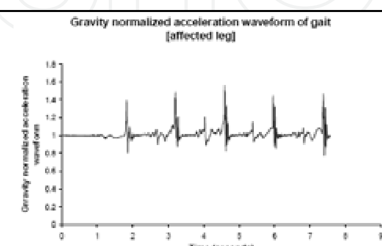

Fig. 9. Acceleration waveform affected leg

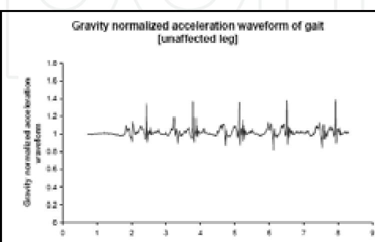

Fig. 10. Acceleration waveform unaffected leg

Figure 9 and 10 characterize the disparate acceleration waveforms respective of the affected and unaffected leg during gait. Visual inspection of the acceleration waveforms for affected and unaffected leg warranted the separation of stance and swing aspects of the gait cycle. The stance cycle component was bound to a 0.20 second duration, with the remaining temporal allocation of the gait cycle allocated to swing. The temporal disparity between stance to stance was highly consistent, with 1.32 seconds for the affected leg with a standard deviation of 0.06 seconds and 1.31 seconds with a standard deviation of 0.06 seconds for the unaffected leg. The stance to stance temporal aspects of gait cycle were bound with a 95% confidence level using a 5% margin of error about the mean. The time averaged acceleration ratio of the affected leg divided by unaffected leg was calculated for the stance aspect of gait cycle yielding 2.23 with a 0.30 standard deviation. The remaining swing aspect of the gait cycle produced a time averaged acceleration ratio of 0.71 with a standard deviation of 0.11 for affect leg per unaffected leg. The respective stance and swing aspect time averaged acceleration ratios were bound with a 90% confidence level incorporating a 10% margin of error about the mean (LeMoyne et al., 2009b).

The previous applications in outdoors and homebound environments for wireless accelerometer gait analysis and quantification underscore the flexible and autonomous nature of the device. Essentially a patient could be evaluated by a therapist from a remote distance. The gait cycle acceleration waveforms could be stored in a database for monitoring the status of therapy, while augmenting the acuity of the therapy strategy and respective efficacy (LeMoyne et al., 2009b; LeMoyne et al., 2009d).

5.4 Virtual proprioception real-time artificial proprioception biofeedback for gait rehabilitation

Virtual proprioception is envisioned to provide an alternative modality for the progressively strained resources encompassing neurorehabilitation, with the attributes to evolve to an autonomous gait rehabilitation system. The concept of virtual proprioception is envisioned to provide real-time biofeedback respective of gait disparity characteristics. The device is particularly envisioned for hemiparetic gait rehabilitation. Two systems incorporating virtual proprioception are currently presented. The first version of virtual proprioception conceptualized as of 2005 and developed in 2007, which focuses on real-time acceleration waveform disparity while incorporating G-Link® Wireless Accelerometer Nodes, is presented (LeMoyne, 2005a; LeMoyne et al., 2008f). The second version of virtual proprioception developed in 2008, which provides auditory feedback based on the quantified disparity of stance to stance time averaged acceleration ratio of affected per unaffected leg using wireless three dimensional accelerometers from a system termed the Wireless Health package, is addressed (LeMoyne et al., 2008e). Virtual proprioception especially offers the capacity to advance gait-related neurorehabilitation for patients with traumatic brain injury.

Locomotion is inherently regulated through the influence of subcortical, cortical, and interneuronal networks. Traumatic brain injury can impair the quality of locomotion, resulting in diminished muscle activation, hypertonicity, muscle coactivation, and leg length disparity. With these features, compensatory strategies can develop, such as circumduction and vaulting from the foot of the stance leg, given the inherent attributes hemiparetic gait

(Dobkin, 2003). Trauma to the central nervous system can lead to decrements in proprioceptive feedback acuity (Dietz, 2002). Virtual proprioception provides a wearable form of artificial proprioception, which as demonstrated through preliminary test and evaluation may circumvent decrements to gait caused by traumatic brain injury (LeMoyne et al., 2008e; LeMoyne et al., 2008f).

Biofeedback applications for rehabilitation, such as the rehabilitation of gait, have been soundly established (Huang et al., 2006). EMG biofeedback has been demonstrated for rehabilitation of hemiparetic gait (Aiello et al., 2005). The accelerometer system of the MiniSun IDEEA device has illustrated that acceleration waveforms are temporally representative of EMG waveforms (Saremi et al., 2006).

The first version of virtual proprioception emphasizes the real-time modification of the affected leg acceleration waveform to acquire near parity with the unaffected leg acceleration waveform. Virtual proprioception emphasized the following system-level parameters: minimization of accelerometers, an easily wearable application, and real-time feedback with minimal distraction to the subject. As illustrated in figure 11, the anatomical mounting point for the first evolution of virtual proprioception was the lateral epicondyle of the femur adjacent to the knee joint (LeMoyne et al., 2008f). The second version of virtual proprioception also selected the lateral epicondyle of the femur adjacent to the knee joint as the mounting position (LeMoyne et al., 2008e).

The operation of the first version of virtual proprioception involved an assistant walking in tandem while holding the laptop PC receiving real-time acceleration waveform graphic data with a sampling rate of 100Hz. The user of virtual proprioception, a chronic hemiplegic subject, would follow the assistant while observing the laptop PC monitor screen. During the 'off' status, the subject would observe the screen without any modification of gait. During the 'on' status for virtual proprioception, the subject would attempt to modify the gait pattern of the affected leg acceleration waveform to relative parity of the real-time acceleration waveform for the unaffected leg (LeMoyne et al., 2008f).

The following experimental protocol, involving three trials, was applied to the first evolution of virtual proprioception:

1. Secure the wireless accelerometers to the lateral epicondyle of each leg with an elastic band.
2. Initiate the real-time data stream of the wireless accelerometers to the laptop PC.
3. Walk 10 steps per leg while observing the affected and unaffected leg acceleration waveform disparity ('off' mode).
4. For next 10 steps per leg focus on the disparity of the acceleration waveforms. Adjust the affected leg acceleration waveform to correspond in parity with the unaffected leg acceleration waveform ('on' mode).
   (LeMoyne et al., 2008f)

The first generation prototype version of virtual proprioception consisted of two G-Link® Wireless Accelerometer Nodes mounted with elastic knee bands to each leg. The laptop PC was equipped with wireless connectivity to the wireless accelerometers, while visually conveying real-time wireless accelerometer signals. The portable and autonomous attributes of the first generation virtual proprioception system enabled effectively natural gait cycle, with minimal intrusion. The objective of the first generation virtual proprioception system was to provide the capacity for real-time modification of hemiparetic gait, using real-time biofeedback of acceleration waveforms from wireless accelerometers (LeMoyne et al., 2008f).

The waveforms of the wireless accelerometer signals were analyzed after completion of the experimental protocol. The stance to stance time averaged acceleration ratio of the affected leg divided by unaffected leg was calculated. The trapezoid method was incorporated to calculate the integral of the time averaged acceleration. The gravity aspect of the signal was removed from the time averaged integrated acceleration signal. Transient aspects of the gait cycle measurements were removed, and measurements which involved discontinuity of the wireless signal were removed (LeMoyne et al., 2008f).

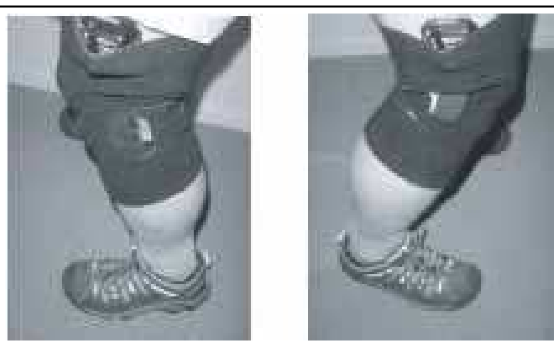

Fig. 11. The wireless three dimensional accelerometers secured to the lateral epicondyle with an elastic band

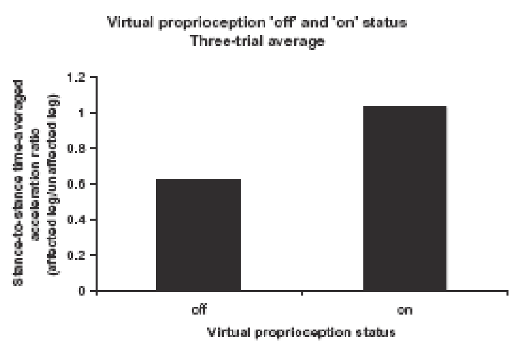

Fig. 12. Three-trial average of chronic hemiplegic, during gait cycle with ‘off’ and ‘on’ status of virtual proprioception

(LeMoyne et al., 2008f)

All three trials were characterized by a notable and quantified improvement in the gait, which is summarized in the three trial global averaging of figure 12. The global averaging of all three trials resulted in a stance to stance time averaged acceleration ratio of 0.615 during the ‘off’ mode and 1.029 during the ‘on’ mode. The relative variation of the stance to stance time averaged acceleration ratios were bound by a 15% relative variation respective of the mean, implicating the accuracy of the system even while adjusting to the device and incorporating a new real-time biofeedback induced gait strategy. The ‘off’ mode consists of walking without using the first generation virtual proprioception system for biofeedback modification of gait cycle disparity. During the ‘on’ mode the first generation virtual proprioception system is used as a biofeedback method for adjusting gait cycle to near parity during real-time operation. In consideration of the initial results for the first generation virtual proprioception device, further research and evolution of this highly novel real-time biofeedback system for modifying gait is warranted. Further research should be extended into evaluating the virtual proprioception concept using other learning modalities, such as auditory feedback (LeMoyne et al., 2008f).

The second generation virtual proprioception system incorporated auditory feedback to inform the subject of the quantified comparison of affected to unaffected leg and efficacy of real-time gait modification strategies. As an alternative to the G-Link® Wireless Accelerometer Nodes, comparable wireless three dimensional accelerometers that support the Wireless Health package affiliated with the research laboratory of Dr. Kaiser of the UCLA Electrical Engineering Department were incorporated. The selected accelerometer package resembles the inherent features of the G-Link® Wireless Accelerometer Node, in consideration of data sampling capacity, portability, and minimal intrusion respective of the gait cycle (LeMoyne et al., 2008e).

The second generation virtual proprioception system utilizing wireless accelerometers incorporating the Wireless Health package is uniquely equipped with a software analysis program enabling a real-time step detection algorithm. The step detection algorithm employs peak detection to ascertain the status of stance initiation. Peak initiation and termination are acquired upon the acceleration signal exceeding a prescribed threshold bound and subsequent threshold bound respectively. The algorithm implements a temporal threshold to prevent a single step from being counted multiple times. A Riemann summation numerical method is applied to calculate the time averaged acceleration integral (LeMoyne et al., 2008e). The offset is removed from the acceleration signal, which is obtained through a three dimensional application of Pythagorean's theorem (LeMoyne et al., 2008e; LeMoyne et al., 2008f). The Riemann sum numerical technique has been contrasted as accurate in comparison to the trapezoid method for the virtual proprioception application (LeMoyne et al., 2008d). The moving average of the time averaged acceleration integrals for ten steps was obtained for both affected and unaffected leg. The ratio of affected divided by unaffected leg, based on time averaged acceleration integrals, was calculated. The Wireless Health package enables all computations to be determined in real-time. The second generation virtual proprioception system was amenable for an assistant to provide auditory biofeedback respective of the affected per unaffected leg ratio of the time averaged acceleration waveform integrals. The assistant could provide the subject with quantified information of the real-time status comparison of affected and unaffected leg during gait cycle (LeMoyne et al., 2008e).

Preliminary testing and evaluation of the second generation virtual proprioception system was applied to one chronic hemiparetic subject. During gait cycle the subject was provided with verbal auditory feedback from the assistant operating the second generation virtual proprioception system, pertaining to the real-time computed time averaged acceleration signal integral ratio of affected divided by unaffected leg. With the auditory biofeedback of gait status, the subject would modify gait pattern with the objective of achieving an effectively parity ratio (LeMoyne et al., 2008e). The experimental protocol of the second generation system was similar to the first generation virtual proprioception experimental protocol. The predominant disparity was the incorporation of real-time quantified auditory feedback, as opposed to real-time visual evaluation of the respective acceleration waveforms (LeMoyne et al., 2008e; LeMoyne et al., 2008f). Five trials were conducted. The wireless accelerometers were mounted above the lateral epicondyle of the femur using an elastic band, as illustrated in figure 13. With the Wireless Health package active, the subject would walk approximately 75 feet during 'off' mode without biofeedback from virtual proprioception. Subsequently, for the next 75 feet the subject would walk using the ‘on’ mode of virtual proprioception, while adjusting gait in real-time according to the verbal feedback respective of the affected per unaffected leg ten step moving averaged time averaged acceleration integral ratio. The goal of the subject was to modify gait in real-time to achieve a near parity ratio (LeMoyne et al., 2008e).

As illustrated in trial 5 according to figure 14, the chronic hemiparetic subject while using virtual proprioception demonstrated the capacity to modify gait cycle to a near parity ratio of affected per unaffected leg. Figure 15 summarizes the comprehensive efficacy of virtual proprioception with a global averaging of all five trials, respective of the ‘off’ and ‘on’ status for the second generation of virtual proprioception. Statistical analysis of the test and evaluation was considered. During the ‘off’ status for virtual proprioception, the global mean for the affected per unaffected leg ratio was 79.38 with a standard deviation of 3.83. By contrast, during the ‘on’ status using virtual proprioception, the ratio of affected per unaffected leg achieved near parity status with a global mean of 103.75 and a standard deviation of 10.65. Full parity of the ratio would be achieved with a value of 100.00. The ‘off’ status affected per unaffected leg ratio for the virtual proprioception device application was bound with a 95% confidence level using a 5% margin of error about the mean. During ‘on’ status for virtual proprioception the affected per unaffected leg ratio was bound with a 90% confidence level using a 10% margin or error about the mean. The disparity in confidence level implicates the intrinsic variability while adapting to a new gait strategy during the real-time application of the second generation of virtual proprioception (LeMoyne et al., 2008e).

Fig. 13. Wireless accelerometer for virtual proprioception (LeMoyne et al., 2008e)

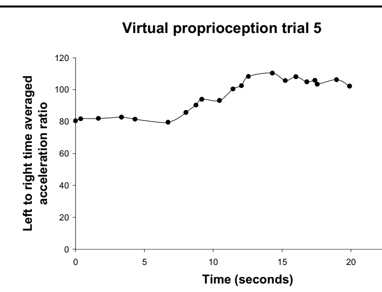

Fig. 14. Virtual proprioception trial 5 results for affected (left) leg relative to unaffected (right) leg

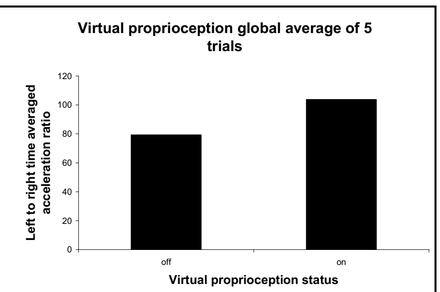

Fig. 15. Virtual proprioception five trial global average for affected (left) leg relative to unaffected (right) leg

6. Conclusion

As demonstrated throughout the chapter the merits of artificial proprioception have been advocated in consideration of the progressive advance of wireless accelerometer technology. Current wireless accelerometer technology has provided the foundation for the biomedical/ neuroengineering artificial equivalent of proprioception. The application of wireless accelerometers representing artificial proprioception has enabled the quantification of movement attributes, such as reflex, Parkinson's disease tremor, and gait. Artificial proprioception has also been demonstrated as a biofeedback application for real-time gait rehabilitation termed virtual proprioception.

The virtual proprioception system has been evolved over the course of two generations. The first generation incorporating visualization of the real-time status of both affected and unaffected leg acceleration waveforms for biofeedback; and the second generation utilizing auditory feedback of the real-time ten step moving average affected per unaffected leg time averaged acceleration integral ratio (LeMoyne et al., 2008e; LeMoyne et al., 2008f). Gait quantification and analysis has been demonstrated in autonomous settings, such as outdoors on a sidewalk and the hallway of a home setting, while selecting anatomical mounting positions such as the lateral epicondyle of the femur and the lateral malleolus (LeMoyne et al., 2009b; LeMoyne et al., 2009d). By mounting a wireless accelerometer to the dorsum of the hand for evaluating hand tremor, a concept intended for quantifying and classifying Parkinson's disease status has been developed (LeMoyne et al., 2009a). The quantification of reflex parameters, such as response and latency, has been demonstrated through a third generation device and novel artificial reflex system (LeMoyne et al., 2008h; LeMoyne et al., 2009c).

With the progressive development of foundational technologies for artificial proprioception, represented by wireless accelerometers, there is the potential for considerable evolution for future applications. Future generational systems incorporating artificial proprioception are anticipated to alleviate strain on medical resources, while also potentially advancing therapy and treatment strategies. Progress in fields, such as the software and robotics industry, will likely augment the implementation of artificial proprioception applications.

7. Future concepts

In tandem with multiple technology applications, the wireless accelerometer is anticipated to likewise evolve, in consideration of miniaturization, data storage capacity, wireless transmission strength, and robust software development. Virtual proprioception has the potential to expand to multiple biofeedback modalities, such as advances in visual, auditory, and eventually haptic/tactile sensation biofeedback. Refinements in software should enable improvements in step detection algorithms and improved strategies for learning alternative gait strategies. Another tangent application would be for improved proprioceptive feedback, monitoring, and learning techniques for prosthetic limbs. Future evolutions of virtual proprioception may significantly advance gait rehabilitation and ameliorate strain on medical resources.

A similar application is gait monitoring through wireless accelerometers functioning as artificial proprioception. Essentially the gait status of a patient may be recorded and analyzed for recovery status or disease progression in an effectively autonomous environment. Wireless accelerometer monitoring of gait status can be conducted with the therapist at a location remote to the patient. The incorporation of wireless accelerometer systems for quantifying locomotion enables advanced post-processing numerical techniques, such as spectral analysis; potentially initiating novel approaches for therapy strategies. Incorporating the progressive status of gait quality in a database could advance the evaluation of therapy strategy efficacy.

Database status tracking may be especially useful for a progressive neurodegenerative disease, such as Parkinson's disease. The status of a Parkinson's disease patient could be monitored through wireless accelerometers over durations in excess of 24 hours. Continual monitoring could augment drug therapy dose allocation and efficacy assessment. Improvements in wireless transmission strength, such as conveying the accelerometer signal to a wireless phone for subsequent transmission to a database, could provide significant advances in application autonomy. Similar to wireless accelerometers providing the basis for biofeedback with virtual proprioception, wireless accelerometers could provide feedback insight for deep brain stimulation parameter settings. Wireless accelerometer feedback could provide the basis for temporally optimal deep brain stimulation parameters with the integration of multi-disciplinary design optimization algorithms.

Wireless accelerometer systems for reflex quantification could advance the evaluation of central and peripheral nervous system trauma. The application has been developed with the intent to alleviate the growing strain on medical resources. Advances in machine learning classification techniques may further augment the impact of the wireless accelerometer reflex quantification system. Future advances envision the integration of machine learning and wireless accelerometer applications, such as reflex quantification for trauma and disease status classification.

Machine learning incorporates development of software programs, which improve with experience at a specific task, such as the classification of a phenomenon. Machine learning has been envisioned for optimizing treatment efficacy for medical issues (Mitchell, 1997). For example, machine learning algorithms have been applied for predicting pneumonia attributed mortality of hospital patients (Cooper et al. 1997). Machine learning intrinsically utilizes multiple disciplines, such as artificial intelligence, neurobiology, and control theory. Speech recognition software can be derived from machine learning, while incorporating learning methods such as neural networks (Mitchell, 1997).

Speech recognition has been successfully tested and evaluated in robust applications. Effectively speech recognition techniques incorporate analysis of acoustic waveforms (Englund, 2004). Similar to the attributes of an acoustic waveform, human movement may be recognized through the use of a wireless accelerometer representing artificial proprioception to derive an acceleration waveform. The testing and evaluation of activity classification using the frequency domain of the acceleration waveform has been demonstrated (Chung et al., 2008). Machine learning classification techniques in consideration of the derived acceleration waveform may augment the status evaluation of reflexes; Parkinson's disease; and gait diagnostic and treatment methods. Machine learning applications respective of virtual proprioception may advance and optimize near autonomous rehabilitation strategies.

The concept of artificial proprioception utilizing wireless accelerometers emphasizes a non-invasive approach for acquiring movement status characteristics. A machine learning algorithm with a tandem philosophy would be advantageous. During 2003 at Carnegie Mellon University a machine learning software program called HiLoClient demonstrated the ability to ascertain classification status while incorporating non-invasive methods. The HiLoClient software actually enabled researchers to detect, classify, and extrapolate the data statistically turning patterns into predictions from seemingly random generated data (Mastroianni, 2003).

Progress relevant to technology applications incorporating artificial proprioception will likely be augmented through tandem advances in the fields of the robotics industry and feedback control theory. The field of robotics incorporates a hierarchical control architecture, generally consisting of high, intermediate, and low level control. In general biological control systems and robotic control systems are representative of similar control system structures. The hierarchical nature of human locomotion provides a relevant example, with the high level representing descending commands from the brain. The central pattern generator may be applied to represent the intermediate level of control; and the lower level of control could encompass proprioceptors, such as muscle spindles and Golgi tendon organs. Respective of this control architecture, reflexes provide an important feedback control system (Bekey, 2005).

Progress in the fields of robotics and feedback control theory will likely advance biomedical applications of artificial proprioception, such as the characterization of reflexes and gait. The tandem technology evolutions are envisioned to provide substantial improvement in prosthetic applications. Alternative strategies and concepts incorporating robotics and feedback control theory should advance virtual proprioception biofeedback applications for augmented rehabilitation methods.

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Biomedical Engineering can be seen as a mix of Medicine, Engineering and Science. In fact, this is a natural connection, as the most complicated engineering masterpiece is the human body. And it is exactly to help our "body machine" that Biomedical Engineering has its niche. This book brings the state-of-the-art of some of the most important current research related to Biomedical Engineering. I am very honored to be editing such a valuable book, which has contributions of a selected group of researchers describing the best of their work. Through its 36 chapters, the reader will have access to works related to ECG, image processing, sensors, artificial intelligence, and several other exciting fields.

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