33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Wireless accelerometer iPod application for quantifying gait characteristics

Robert LeMoyne, *Member*, *IEEE*, Timothy Mastroianni, and Warren Grundfest, *Member*, *IEEE*

Abstract— **The capability to quantify gait characteristics through a wireless accelerometer iPod application in an effectively autonomous environment may alleviate the progressive strain on highly specific medical resources. The iPod consists of the inherent attributes imperative for robust gait quantification, such as a three dimensional accelerometer, data storage, flexible software, and the capacity for wireless transmission of the gait data through email. Based on the synthesis of the integral components of the iPod, a wireless accelerometer iPod application for quantifying gait characteristics has been tested and evaluated in an essentially autonomous environment. The quantified gait acceleration waveforms were wirelessly transmitted using email for post-processing. The site for the gait experiment occurred in a remote location relative to the location where the post-processing was conducted. The wireless accelerometer iPod application for quantifying gait characteristics demonstrated sufficient accuracy and consistency.**

Index Terms—**gait, locomotion, iPod application, iPod, wireless accelerometer, gait quantification**

I. Introduction

Wireless accelerometer applications have demonstrated the capacity to quantify features inherent with locomotion [1]. The evolution of such wireless applications for gait quantification may alleviate the progressive strain on limited medical resources. Wireless gait quantification applications have demonstrated the capacity to evaluate gait experiments with the evaluator at a position remote to the actual subject [1, 2, 3]. LeMoyne advocated the integration of wireless accelerometers as a representative form of artificial proprioception. The implementation of artificial proprioception through wireless accelerometers has demonstrated the capacity to quantify movement characteristics of a subject in essentially autonomous environments [1].

Previous applications for wireless accelerometer strategies have been successfully implemented in both indoor and outdoor environments, underscoring the autonomy of the application [2, 3, 4, 5]. The concept of a wireless accelerometer system for quantifying the attributes of gait have been illustrated through the G-Link® Wireless Accelerometer Node and iPhone [2, 3, 4, 5]. The supporting foundation for the wireless accelerometer system technology space is rapidly evolving [1, 6].

For example the iPod developed by Apple is comprised of a three dimensional accelerometer. The iPod has the capacity to store gait quantification data samples, which can be conveyed wireless through email to a remote location for post-processing. The iPod is enabled with flexible software that facilitated the objective of characterizing quantitative gait features in an essentially autonomous environment [7].

The iPod application for quantifying gait attributes is demonstrated from a biomedical engineering perspective. The strategy of utilizing an iPod for gait quantification involves the application of software that can record the gait acceleration waveform using the iPod three dimensional accelerometer. The stored acceleration waveform representing gait is subsequently conveyed wirelessly though email to a location for post-processing over one thousand miles remote to the site of the gait experiment. The iPod application exhibits the ability to represent the functionality of a wireless accelerometer node for quantifying the acceleration waveform of gait with a sufficient degree of accuracy and reliability.

II. Background

A. Neurological foundation for gait

Locomotion is inherently derived from the central nervous system, while inherently influenced through interneuronal, subcortical, and cortical representation [8, 9]. Proprioception constitutes the afferent perception of motion, which inherently contributes to the rhythmic attributes of gait [9]. Traumatic brain injury generally disrupts the high degree of synchronicity and integration inherent with healthy gait. Efficacious gait quantification methodologies have been demonstrated to evaluate the quality of a therapy strategy [8]. In essence, the acceleration waveforms derived from a wireless accelerometer device enable an exteroreceptive representation of gait and the inherent neural signals that represent gait [1].

Manuscript received April 1, 2010.
R. LeMoyne, Dr., is with Sandia National Laboratories, Albuquerque, NM 87185 USA (e-mail: rlemoyn@sandia.gov).
T. Mastroianni is Independent, Pittsburgh, PA 15243 USA (e-mail: cognitionengineering@gmail.com).
W. Grundfest, Dr., is a Professor of the Biomedical Engineering IDP, UCLA, Los Angeles, CA 90095-1600 USA (e-mail: warrenbe@seas.ucla.edu).

B. Traditional devices for quantifying gait

There are six general devices that are currently applied for gait analysis: footswitch stride analyzers, ground reaction force analyzers, electrogoniometers, electromyography (EMG), metabolic energy expenditure, and optic sensors [8, 10]. In general these six standard devices are restricted to the confines of a clinical environment [1]. Wireless three dimension accelerometer applications have been demonstrated in effectively autonomous scenarios, while demonstrating the capacity for inherently progressive evolution [1, 2, 4, 5, 6].

C. Gait quantification through accelerometer systems

Saremi and Kavanagh have provided essential preliminary testing and evaluation for gait quantification using accelerometer systems [11, 12]. Saremi evaluated the Intelligent Device for Energy Expenditure and Activity (IDEEA) as an accelerometer application for quantifying gait. The device incorporated five biaxial accelerometers positioned at discrete anatomical positions on both legs and the trunk, which enabled the definition for the spatial characteristics of gait, respective of the sagittal plane. The gait quantification accelerometer device evaluated by Saremi was successfully contrasted to standard gait quantification devices [11]. Kavanagh also investigated the strategy of precisely defined anatomical mounting positions for an accelerometer derived gait quantification application. The strategy involved applying four accelerometer nodes located at the head, neck, lower leg, and trunk. Kavanagh demonstrated the strategy of mounting the nodes of the accelerometer system at precise mounting positions could reliably acquire quantitative gait parameters [12].

The evolution of technology supporting the development of accelerometers has led to the incorporation of wireless accelerometer systems for gait quantification [1]. The strategy of well-defined anatomical mounting positions advocated by Saremi and Kavanagh provide the basis for the mounting point for the iPod application experiment, which is the lateral malleolus. The lateral malleolus mounting strategy has been successfully applied to gait quantification experiments using the G-Link® Wireless Accelerometer Node and iPhone application [2, 4].

D. Wireless accelerometer gait quantification systems

Subsequently wireless accelerometer applications for quantifying gait attributes were conducted, leading from integrated systems to eventually a fully wireless accelerometer device. Lee successfully tested an integrated wireless accelerometer, demonstrating the capability to obtain temporal parameters derived from the acceleration waveform relative to a footswitch device [13]. Another integrated application consisting of an accelerometer component with the integrated capacity to convey data wirelessly is the GaitShoe, which integrates many gait analysis systems, such as accelerometers, gyroscopes, force sensors, bend sensors, electric field height sensors, and pressure sensors [14]. Given the attributes of the GaitShoe, potential limitations are the packaging, power, and mass requirements based on the multitude of sensors.

The G-Link® Wireless Accelerometer Node enables a single compact and efficient system for acquiring the acceleration waveform of gait, while wirelessly transmitting the data sample. The wireless accelerometer was tested and evaluated in both indoor and outdoor environments under essentially autonomous scenarios. The anatomical mounting strategies involved the lateral malleolus representing the ankle joint and the lateral epicondyle representing the knee joint, respectively. The G-Link® Wireless Accelerometer Node successfully demonstrated the ability to quantify gait attributes [4, 5].

The next evolutionary step in wireless accelerometer technology for gait quantification involved the implementation of the iPhone 3G. The iPhone 3G represented advancement in wireless transmission, data storage, and software flexibility. Multiple test and evaluation cycles were conducted using the precisely defined mounting strategy, such as the lateral malleolus, lateral epicondyle, and lower lumbar vertebrae. The results successfully demonstrated the ability to quantify gait based on the derived acceleration waveform [2, 3, 15]. The next logical evolution in characterizing gait through the use of a wireless accelerometer involves the implementation of the iPod.

E. iPod for gait quantification

The current iPod application is uniquely situated for characterizing the attributes of gait. The iPhone is essentially a wireless telephone, effectively requiring a wireless phone service. Generally acquiring multiple iPhones for characterizing tandem aspects of gait, such as affected and unaffected legs during hemiplegic gait, may be excessively costly. The iPod has the same essential functionalities necessary for gait quantification, without the cost encumbrance of an associated wireless phone service. Multiple iPod applications could be mounted to a single subject for a more sophisticated gait analysis, relative to a more costly iPhone wireless accelerometer scenario [7, 16].

The iPod imparts a lower mass encumbrance on the subject in comparison to the iPhone. The mass of the iPod is 101 grams, which is 26 % less than the iPhone mass of 137 grams. The iPod consists of an 8 GB storage capacity and a robust software package. Rather than using wireless cell phone coverage to convey the gait data, the iPod is capable of storing a series of gait samples and conveying the gait data using a wireless coverage zone through email [7, 16].

In the case of the test and evaluation of the iPod application for gait quantification from an engineering proof of concept perspective, the gait experiment was conducted on a scale of over one thousand miles remote from the location of the gait data post-processing resources. The iPod software incorporates multiple efficiencies for gait quantification. The iPod software utilizes an initial calibration protocol, which simplifies the post-processing of the data. Also the software uses a temporal delay methodology, which better prepares the subject for the respective gait experiment. For proof of concept from an engineering perspective, the subject with healthy gait was

Fig. 1. iPod wireless accelerometer gait quantification system.

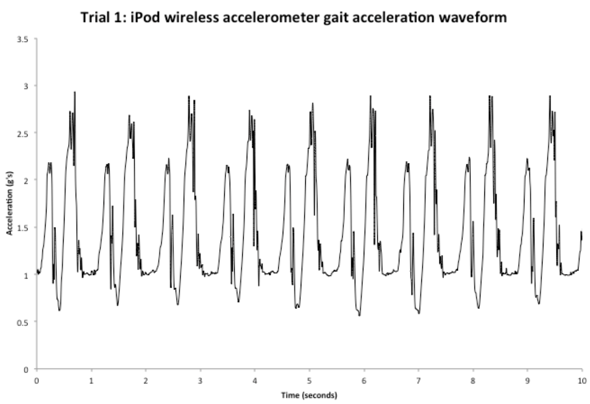

Fig. 2. iPod wireless accelerometer application gait acceleration waveform.

Table 1
iPod quantified gait parameters

	time averaged acceleration (g's)		step cycle time (seconds)	
trial number	mean	standard deviation	mean	standard deviation
1	1.42	0.03	1.09	0.05
2	1.42	0.03	1.10	0.03
3	1.41	0.02	1.11	0.02
4	1.44	0.05	1.10	0.04
5	1.41	0.04	1.13	0.04
6	1.41	0.03	1.09	0.05
7	1.41	0.07	1.13	0.08
8	1.41	0.03	1.11	0.05
9	1.42	0.04	1.11	0.05
10	1.43	0.04	1.08	0.03
global (all 10 trials)	1.42	0.04	1.10	0.05

instructed to walk through a hallway, while the iPod application was recording the gait acceleration waveform with the iPod three dimensional accelerometer. The stored gait data was conveyed through email using a localized wireless connectivity zone. The iPod application demonstrates the potential for the subject and post-processing resources to exist remotely based on the wireless transmission of gait data through email.

III. EXPERIMENTATION

The iPod was tested and evaluated, using a wireless accelerometer application for gait analysis, respective of one subject with healthy gait features. The subject was instructed to walk through the level hallway of an indoor environment. A data sampling rate of 100 Hz characterized the gait acceleration waveform. The subsequent experimental protocol acquired quantified gait data for 10 trials:

1. Calibrate the iPod device by static orientation for all three orthogonal vectors in alignment with gravity.
2. Mount the iPod above and adjacent to the lateral malleolus of the leg on the same side as the preferred arm secured with and elastic band. Orient the iPod parallel to the tibia of the leg and superior (top pointing up).
3. Activate the iPod wireless accelerometer system for the acquisition of quantified gait data.
4. Instruct the subject to walk 10 seconds at a comfortable and consistent pace.
5. Continue the protocol to acquire 10 trials.

IV. RESULTS AND DISCUSSION

The iPod wireless accelerometer gait quantification application represents a portable and comfortably wearable device, as illustrated in Figure 1. An acceleration waveform representing the rhythmic patterns of gait is illustrated in Figure 2. Table 1 presents two pertinent gait parameters: the stance to stance time averaged acceleration of the gait cycle and step cycle time from stance to stance.

The functional autonomy of the application is demonstrated by the distant and remote positioning respective of the gait experiment and the location of the post-processing resources. The gait experiment data was obtained in the region of Pittsburgh, Pennsylvania. The data was conveyed by wireless transmission through email to a local area of Albuquerque, New Mexico for post-processing. The remote positioning of gait quantification resources demonstrates the application autonomy.

The gait parameters demonstrate considerable accuracy and consistency. The stance to stance time averaged acceleration of the gait cycle and step cycle time from stance to stance are bound with a 96% confidence level with a 4% margin of error about the mean. The global mean for the gait cycle time averaged acceleration was 1.42 g's with a standard deviation of 0.04 g's. The step duration cycle global mean was 1.10 seconds with a standard deviation of 0.05 seconds. The iPod wireless accelerometer application demonstrates considerable potential for use as a wearable application for the quantification and evaluation of gait status.

V. Conclusion

The iPod wireless accelerometer demonstrates the capacity to acquire quantified gait parameters with a high level of accuracy and consistency. The gait parameters of time averaged acceleration of the gait cycle and step duration cycle are bound with a 96% confidence level with a 4% margin of error about the mean. The successful initial proof of concept from an engineering perspective warrants greater testing and evaluation for the iPod wireless accelerometer application for gait quantification.

The attributes of the iPod are envisioned to progressively advance, which should augment the capacity to quantify gait characteristics, such as duration of operation, data storage, mass properties, and software. Improvements in software are especially of interest. The capacity to automate the acquisition of gait quantification attributes could reduce processing time. Machine learning could be instilled to augment the classification of recovery status for gait rehabilitation and facilitate diagnostics techniques. Clinicians could evaluate patients remotely. With the advance of software techniques, real-time gait biofeedback applications can be developed, such as the successfully demonstrated application 'Virtual Proprioception' [1, 17, 18].

References

[1] R. LeMoyne, C. Coroian, T. Mastroianni, P. Opalinski, M. Cozza, and W. Grundfest, "The merits of artificial proprioception, with applications in biofeedback gait rehabilitation concepts and movement disorder characterization," C. A. Barros de Mello, *Biomedical Engineering*. Vienna, Austria: Intech, 2009, Ch 10.

[2] R. LeMoyne, T. Mastroianni, M. Cozza, C. Coroian, and W. Grundfest, "Implementation of an iPhone as a wireless accelerometer for quantifying gait characteristics," *in Proc. 32nd Int. Conf. IEEE EMBS*, Buenos Aires, Argentina, 2010, pp. 3847-3851.

[3] R. LeMoyne, T. Mastroianni, M. Cozza, and C. Coroian, "iPhone wireless accelerometer application for acquiring quantified gait attributes," *in Proc. ASME 2010 5th Frontiers in Biomedical Devices Conference (BioMed2010)*, Newport Beach, CA, 2010, pp. 1-2.

[4] R. LeMoyne, C. Coroian, and T. Mastroianni, "Wireless accelerometer system for quantifying gait," *in Proc. IEEE/ICME International Conference on Complex Medical Engineering (CME2009)*, Tempe, AZ, 2009, pp. 1-4.

[5] R. LeMoyne, C. Coroian, T. Mastroianni, and W. Grundfest, "Wireless accelerometer assessment of gait for quantified disparity of hemiparetic locomotion," *J. Mech. Med. Biol.*, vol. 9, no. 3, pp. 329-343, Sep. 2009.

[6] R. LeMoyne, C. Coroian, T. Mastroianni, and W. Grundfest, "Accelerometers for quantification of gait and movement disorders: a perspective review," *J. Mech. Med. Biol.*, vol. 8, no. 2, pp. 137–152, Jun. 2008.

[7] http://www.apple.com/ipodtouch/specs.html

[8] B. H. Dobkin, *The Clinical Science of Neurologic Rehabilitation*. New York: Oxford University Press, 2003, Ch 6.

[9] V. Dietz, "Proprioception and locomotor disorders," *Nat. Rev. Neurosci.*, vol. 3, no. 10, pp. 781-790, Oct. 2002.

[10] R. E. Mayagoitia, A. V. Nene, and P. H. Veltink, "Accelerometer and rate gyroscope measurement of kinematics: an inexpensive alternative to optical motion analysis systems," *J. Biomech.*, vol. 35, no. 4, pp. 537-542, Apr. 2002.

[11] K. Saremi, J. Marehbian, X. Yan, J. P. Regnaux, R. Elashoff, B. Bussel, and B. H. Dobkin, "Reliability and validity of bilateral thigh and foot accelerometry measures of walking in healthy and hemiparetic subjects," *Neurorehabil. Neural Repair*, vol. 20, no. 2, pp. 297-305, 2006.

[12] J. J. Kavanagh, S. Morrison, D. A. James, and R. Barrett, "Reliability of segmental accelerations measured using a new wireless gait analysis system," *J. Biomech.*, vol. 39, no. 15, pp. 2863–2872, 2006.

[13] J. A. Lee, S. H. Cho, J. W. Lee, K. H. Lee, and H. K. Yang, "Wearable accelerometer system for measuring the temporal parameters of gait," *in Proc. 29th Int. Conf. IEEE EMBS*, Lyon, France, 2007, pp. 483-486.

[14] S. J. Bamberg, A. Y. Benbasat, D. M. Scarborough, D. E. Krebs, and J. A. Paradiso, "Gait analysis using a shoe-integrated wireless sensor system," *IEEE Trans. Inf. Technol. Biomed.*, vol. 12, no. 4, pp. 413-423, Jul. 2008.

[15] R. LeMoyne, T. Mastroianni, M. Cozza, and C. Coroian, "Quantification of gait characteristics through a functional iPhone wireless accelerometer application mounted to the spine," *in Proc. ASME 2010 5th Frontiers in Biomedical Devices Conference (BioMed2010)*, Newport Beach, CA, 2010, pp. 1-2.

[16] http://www.apple.com/iphone/specs.html

[17] R. LeMoyne, C. Coroian, T. Mastroianni, W. Wu, W. Grundfest, and W. Kaiser, "Virtual proprioception with real-time step detection and processing," *in Proc. 30th. Int. Conf. IEEE EMBS*, Vancouver, Canada, 2008, pp. 4238-4241.

[18] R. LeMoyne, C. Coroian, T. Mastroianni, and W. Grundfest, "Virtual proprioception," *J. Mech. Med. Biol.*, vol. 8, no. 3, pp. 317–338, Sep. 2008.