Implementation of a smartphone for evaluating gait characteristics of a trans-tibial prosthesis

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Abstract—**Smartphone applications have been demonstrated for their capacity to measure gait in functionally autonomous environments beyond the limitations of a traditional gait laboratory. A software application enables the iPhone to function as a wireless accelerometer platform. The recorded acceleration of gait can be transmitted wirelessly as an email attachment through Internet connectivity. The objective of the research was to demonstrate the capacity of the smartphone to quantify gait features of a trans-tibial prosthesis. The iPhone a standard smartphone was mounted to the carbon fiber blade of the prosthesis through an adapter developed by a 3D printer. The application demonstrated considerable accuracy and reliability for the quantification of gait characteristics.**

Index terms—smartphone, iPhone application, iPhone, wireless accelerometer, gait quantification, trans-tibial prosthesis, 3D printer

I. INTRODUCTION

Wireless and wearable devices enable the capacity to monitor gait status in essentially autonomous scenarios beyond the restrictions of a traditional gait laboratory. The implication of applying wireless and wearable systems is the capacity to ameliorate rampant strain on limited medical economies. Wireless accelerometer applications have demonstrated considerable potential for the domain of gait analysis [1,2].

Smartphones in particular have been established for quantifying gait features through an internal accelerometer system. During 2010 LeMoyne exhibited the capacity of the iPhone, a ubiquitous smartphone, for the evaluating gait. Equipped with a software application, features of the accelerometer waveform of gait were acquired with considerable accuracy and reliability [3].

The application of the smartphone for gait analysis by LeMoyne emphasized the themes of minimizing complexity and minimal use of limited resources. Each gait analysis trial acceleration waveform was conveyed as a file attachment through wireless connectivity to the Internet, with the experimental site and post-processing resources on the scale of over a thousand miles remote. The mounting procedure was simplified by securing the smartphone proximal to the lateral malleolus through the elastic band of a sock [3].

The objective of the research is to apply the smartphone gait analysis strategy developed by LeMoyne to the prosthesis for a person with trans-tibial amputation from an engineering proof of concept perspective. Rather than mounting the smartphone by an elastic band to the prosthesis, a 3D printed adapter was developed to connect the smartphone to the pylon of the trans-tibial prosthesis. The smartphone was secured to the 3D printed adapter and functioned as a wireless accelerometer platform. A Matlab program was implemented to automate the feature extraction of each respective waveform. The smartphone mounted to a trans-tibial prosthesis by a 3D printed adapter revealed considerable accuracy and reliability regarding quantified gait features.

II. BACKGROUND

Currently about one-million people in the United States have amputation about their lower extremity. Forecasts anticipate the number of amputations to double by 2050 [4,5]. The ankle foot complex serves a critical role during gait cycle, as plantar flexor musculature delivers approximately 80% of the mechanical power during the gait cycle [6,7,8,9]. Intuitively, compensatory mechanisms may develop due to the absence of powered plantar flexion as a consequence of trans-tibial amputation.

Ground reaction force and temporal asymmetries can develop during adaptation to trans-tibial amputee gait leading to morbidities as a consequence of degeneration [10]. Osteoporosis can develop with the residual limb [11]. The lack of powered plantarflexion about the prosthetic limb is recognized as a likely cause for the onset of osteoarthritis respective of the intact knee because of amplified loading characteristics [12,13].

Wireless accelerometer systems have been applied to the domain of evaluating gait quality for persons with amputation. Such applications have been incorporated for assessing gait symmetry. The accelerometer signal data was conveyed wireless to a local PC for post processing [14,15]. However the wireless footprint is rather limited, as a local PC is required to be in proximity of the experimental site.

The smartphone applied by LeMoyne has demonstrated the capacity to perform gait experiments thousands of miles remote to a location designated for post-processing resources [3]. The smartphone is essentially ubiquitous as a widely used electronic device. The telecommunications footprint of the smartphone is on the scale of cell phone coverage. Applications for quantifying human movement have even been applied in rural settings [3,16,17].

In order to apply the smartphone as a device for quantifying the features of a trans-tibial prosthesis during

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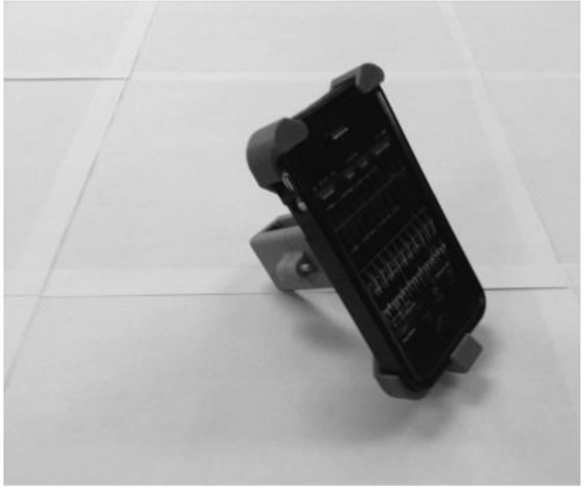


Figure 1. Smartphone (iPhone) mounted to 3D printed adapter.

gait, a novel strategy for mounting the smartphone to the pylon of the prosthesis must be innovated. Previous applications regard smartphones for quantifying gait have incorporated mounting to smartphone to a readily identifiable aspect of the human anatomy through an elastic band [3,18,19]. A viable strategy for mounting the smartphone is enabled through developing a custom adapter that attaches the smartphone to the pylon of the trans-tibial prosthesis.

The custom adapter was developed through SolidWorks for a passive-elastic prosthesis. As illustrated in Figure 1 the adapter secures the smartphone about the four corners of the smartphone. A clip at the base of the adapter enables the smartphone to be easily inserted and removed from the adapter. With the dimensions of the subject's trans-tibial prosthesis known, the adapter can securely grip to the prosthetic pylon by two U-clips that connect by two flat-head screws. Modifications to new prosthetic pylon geometric constraints can be produced on the order of less than an hour.

Once the geometric design constraints for the adapter were defined through a SolidWorks model, the adapter was created through a rapid prototyping 3D printer. The 3D printer incorporated the material acrylonitrile butadiene styrene (ABS). The process time to develop a 3D print of the adapter was on the scale of two hours. The implication of the mounting strategy is that given the geometric dimensions of a trans-tibial prosthesis the mounting adapter can be readily developed within a short time frame. The mass properties of the smartphone consisted of three components: the prosthesis to smartphone adapter, an iPhone, and a protective case to prevent and damage to the iPhone. Overall the total mass of the application was approximately 235 grams.

The smartphone application enabled the recording the acceleration waveform during gait. On activating the application, a ten second countdown occurs prior to the actual ten second recording of the acceleration waveform. The countdown enables the subject to achieve a steady-state gait, while the experimenter can be removed from the subject's proximity. The initiation of the recording and completion were both prompted by a distinct audio tone. Once the gait trial is complete the experimenter can email the gait acceleration waveform through wireless Internet connectivity as an attachment to an email of the experimenter's discretion. The gait acceleration waveform can be downloaded for subsequent post-processing.

The post-processing of the gait acceleration waveform was automated through a Matlab program. Gait is inherently cyclical and rhythmic in nature [6,20,21]. The automation program first identified the cyclical stance initiation features of the gait acceleration waveform. The stance initiation features of the gait acceleration waveform were determined to obtain the temporal duration from stance to stance, and then time averaged acceleration from stance to stance was determined.

III. EXPERIMENT

For engineering proof of concept the smartphone wireless accelerometer application was tested regarding one well adjusted person with trans-tibial amputation. The subject's amputation occurred as a result of trauma, and the amputation event transpired exceeding a threshold of five years. The subject used a conventional passive-elastic prosthesis. The passive-elastic prosthesis enables partial storage and release of energy during gait [22,23].

Previous smartphone experiments incorporated the lateral malleolus proximal to the ankle joint as an anatomical mounting position [3]. In order to emulate the previous smartphone, a linear distance of 11cm from the top of the carbon fiber blade to the top of the fastened U-clips was selected as the mounting position for the 3D printer adapter connected to the smartphone. The experimental process was granted approval from the Northern Arizona University Institutional Review Board (IRB). The subject provided written informed consent prior to the collection of experimental data.

The experiment essentially involved instructing the subject to walk in an indoor environment through a level hallway. The timing of the activation of the wireless accelerometer application and recording of the acceleration waveform of gait was designed such that the subject could achieve a self-selected steady state. Upon activating the application the subject would begin to walk halfway between the ten second countdown at the five second aspect of the countdown, in order to achieve self-selected steady state gait conditions. The subject was also instructed to continue to walk at self-selected steady state after the audio tone termination of the ten second recording. The wireless acceleration application was set to sample at a rate of 100Hz. The following experimental protocol was applied for the acquisition of 30 gait trials:

1. Set the smartphone to 'Do not disturb mode' to prevent any accidental phone calls from disrupting the gait experiment trials.
2. Insert the smartphone to the 3D printed adapter with the clip secured at the base of the smartphone.
3. Secure the 3D printed adapter with smartphone to the carbon fiber blade pylon with two screws by two U-clips, such that the linear displacement

between the top of the pylon blade and top of the fastened U-clips is 11cm.

4. Prepare the subject to walk down a level hallway.
5. Activate the smartphone wireless accelerometer application.
6. When the ten second countdown to the recording of the acceleration waveform reaches five seconds, instruct the subject to walk at a self-selected and comfortable speed.
7. Instruct the subject to walk at a self-selected and comfortable speed beyond the termination audio tone of the ten second acceleration waveform recording.
8. On completion of each gait trial email the gait acceleration waveform as an attachment through wireless connectivity to the Internet.
9. Repeat the experiment from part 4 to part 8 for a collection of 30 trials.
10. On every fifth trial (5, 10, 15, 20, 25, 30), confirm the linear displacement from the top of the carbon fiber blade pylon to the top of the fastened U-clips is 11cm.

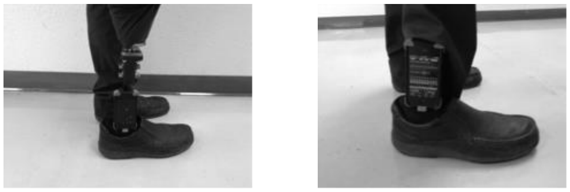
IV. RESULTS AND DISCUSSION

The smartphone with a 3D printed adapter constitutes a gait analysis platform that can readily monitor the subject's gait characteristics. The subject noted no perceptivity of weight encumbrance with the attached device. The linear displacement between the top of the carbon fiber blade pylon and the top of the U-clip adapter was inspected after every fifth trial. The findings revealed that linear displacement was continuously measured at 11cm, implicating the 3D printed adapter can readily secure the spatial position of the smartphone with regards to the prosthesis. The mounting and removal of the 3D printed adapter was even conducted by the subject without any assistance. Figure 2 exhibits the 3D printed adapter with smartphone mounted to the carbon fiber blade pylon of a passive-elastic prosthesis.

Post-processing occurred in a location remote to the gait experimentation site. All 30 gait trials were downloaded for post-processing by accessing the email source where the acceleration waveform attachments through Internet connectivity were emailed. The implication is that the experiment and post-processing resources can be conducted remotely apart anywhere in the world.

Automation of the post-processing was facilitated through a Matlab program. The post-processing time was substantially reduced relative to other more tedious and manual approaches [1,3,18,19,20,24]. The magnitudes of the acceleration waveforms were computed through the three dimensional version of the Pythagorean theorem. As illustrated in Figure 3 the acceleration waveform of the gait cycle exhibits highly rhythmic qualities. The initiation of stance has been previously recognized as the characteristic spike in the acceleration waveform [1,3,18,19,20,24]. The Matlab program first identified the total of stance initiation events. Then the stance to stance temporal disparity and time averaged acceleration from stance to stance were determined, and these parameters have been applied as quantified metrics for evaluating gait quality [1,3,18,19,20,24].

The stance to stance temporal disparity and time averaged acceleration from stance to stance show considerable consistency, which were represented in terms of mean, standard deviation, and coefficient of variation in Table 1. The stance to stance temporal disparity exhibited a mean of 1.10 seconds, a standard deviation of 0.02 seconds, and a coefficient of variation of 0.02. Based on the sample size, the stance to stance temporal disparity was bound with a 96% confidence level with a 4% margin of error about the mean. The time averaged acceleration from stance to stance presented a mean of 1.47 g's, a standard deviation of 0.02 g's, and a coefficient of variation of 0.01. Based on the sample size, the time averaged acceleration from stance to stance was bound with a 96% confidence level with a 4% margin of error about the mean. Both gait parameters demonstrated a considerable degree of accuracy and reliability. With the successful establishment of the smartphone to quantify gait parameters for a prosthesis a clinical trial is warranted.



(a) (b)

Figure 2. (a,b) Smartphone (iPhone) mounted to the carbon fiber blade pylon of a passive-elastic prosthesis.

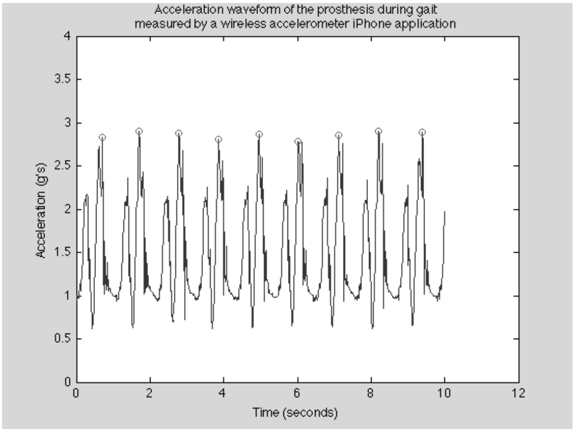


Figure 3. Acceleration waveform of gait with prosthesis based on a sample trial. Each stance initation spike is identifyed by an 'o'.

TABLE I. QUANTIFIED GAIT PARAMETERS OF PROSTHESIS MEASURED BY WIRELESS APPLICATION OF SMARTPHONE

	Stance to stance time disparity	Stance to stance time averaged acceleration
Mean	1.10 seconds	1.47 g's
Standard deviation	0.02 seconds	0.02 g's
Coefficient of variation	0.02	0.01

The preliminary proof of concept of the smartphone application for monitoring gait status of a prosthesis has far reaching implications. The use and activity of the prosthesis can imply whether the subject is comfortably adapted to the prosthesis or whether a prosthesis of a different activity level is more suitable. The derived acceleration waveform can provide feedback for the efficacy of a therapy strategy. Since degenerative patterns can develop over prolonged usage of a prosthesis, the acceleration waveform can infer the onset of such morbidities. The implications of the smartphone application constituting a wireless accelerometer platform with a 3D printed adapter represent the capacity to evaluate and diagnose the health status of a person with amputation from the convenience of a home-bound and autonomous setting.

V. CONCLUSION

Smartphones, such as the iPhone, constitute the capacity to quantify gait features as wireless and wearable devices in autonomous environments. The application of the smartphone for gait analysis accentuates the themes of minimized complexity and minimal use of limited resources. The research objective was to apply the smartphone for the gait analysis of a person with trans-tibial amputation respective of the prosthesis. A 3D printer adapter was incorporated to mount the smartphone about the carbon fiber blade of a passive-elastic prosthesis. The stance to stance temporal disparity and time averaged acceleration from stance to stance was bound with a 96% confidence level with a 4% margin of error about the mean. The two gait parameters demonstrated a considerable degree of accuracy and reliability. Based on the findings a subject may be diagnosed and evaluated at the convenience of a familiar home-bound and autonomous setting.

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