A WIRELESS TELEMETRY SYSTEM TO MONITOR GAIT IN PATIENTS WITH LOWER-LIMB AMPUTATION

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ABSTRACT

Even after rehabilitation, patients with lower-limb amputation may continue to exhibit suboptimal gait. A wireless telemetry system, featuring force sensors, accelerometers, control electronics and a Bluetooth transmission module was developed to measure plantar pressure information and remotely monitor patient mobility. Plantar pressure characterization studies were performed to determine the optimal sensor placement. Finally, the wireless telemetry system was integrated with a previously developed haptic feedback system in order to allow remote monitoring of patient mobility during haptic system validation trials.

Keywords: gait analysis, patient monitoring, lower-limb amputation, prosthesis, rehabilitation

INTRODUCTION

Traditional gait analysis is performed by measuring the motions of the head, upper body, trunk and lower body, along with temporal-spatial parameters (Fig. 1). Commercial software packages are used to collect and process data and calculate kinematic and kinetic parameters for models of subject gait. Critical temporal-spatial parameters (TSP) such as walking velocity, cadence, stride length, step-length, single stance and step-width are collected. The TSPs allow the measurement of gait vital signs for screening, monitoring and as a performance measure. For lower-limb amputees, the TSPs typically deviate from normal gait behavior (Table 1). Three-dimensional gait kinematics and kinetics measurements allow the characterization of joint motion and moments during the gait cycle. Kinematic characteristics include bilateral pelvic obliquity, pelvic tilt, pelvic rotation, hip abduction/adduction, hip flexion/extension, hip rotation, knee varus/valgus, knee flexion/extension, knee rotation, foot rotation, dorsiflexion/plantarflexion, foot progression angle, trunk obliquity, trunk tilt, and trunk rotation. Kinetic variables include bilateral ground reaction forces (vertical force, fore-aft shear and medial lateral shear), lower extremity moments and powers.

The operating costs of gait laboratory use has motivated the development of telemetry system to complement traditional analysis (Kyriazia 2001, Morris 2002 and Bamberg 2008). Several academic and commercially available systems integrate pressure sensors, accelerometers and gyroscopes into standalone wearable devices. These systems aim to perform gait analysis while maintaining portability to achieve remote patient monitoring. For patients with lower-limb amputations, the variations in the loading characteristics and movement of the prosthetic limb may prevent proper monitoring by current telemetry systems. A wireless telemetry system was developed to specifically monitor critical prosthetic gait characteristics.

Table 1. Temporal Spatial Parameters for a subject with transtibial amputation collected using the protocols described.

TSPs	Patient Values	% Deviation from Normal
Velocity	118 cm/sec	-5%
Cadence	103 steps/min	+4%
Stride Length	138 cm	-9%
Step Length, Right	73 cm	+12%
Step Length, Left	64 cm	-2%
Step Width	18 cm	+51%
Single Stance Support, Right	32%	-19%
Single Stance Support, Left	37%	-6%

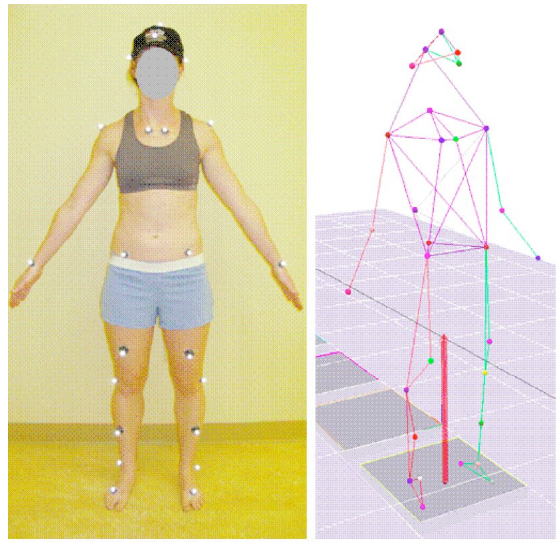

Fig. 1 Example of subject with markers used to acquire motion data (left) and the resultant stick figure in Cortex (MAC, Santa Rosa, CA) from the marker data used to perform gait analysis.

PLANTAR PRESSURE CHARACTERIZATION

In order to properly capture the gait behavior of patients with lower-limb amputation, detailed plantar pressure measurements are required to determine the optimal configuration and implementation of force sensor elements. Although normal gait can be effectively measured using critical pressure points under the hallux, 1^{st} and 5^{th} metatarsal heads and the center heel, those anatomical landmarks may not have analogues on an artificial foot. The F-Scan (Tekscan, Boston MA) system was used to measure reaction forces and the center of pressure vectors during gait (Fig. 2) in an initial test with 1 subject.

Schmid et. al found that, compared to normal gait patterns, the gait patterns of patients with lower-limb amputation contained several asymmetries. Most significantly, it was shown that the center of pressure vectors deviate compared to normal, implying differences in the way a prosthetic foot loads during gait. Due to these variations it is possible that systems designed to capture the movement of normal human feet would not be able to characterize the behavior of prosthetic limbs. Variations in these pressures are also expected throughout rehabilitation, as gait improves. In order to develop a platform to properly measure meaningful data while also allowing for real-time processing, more detailed study will be required.

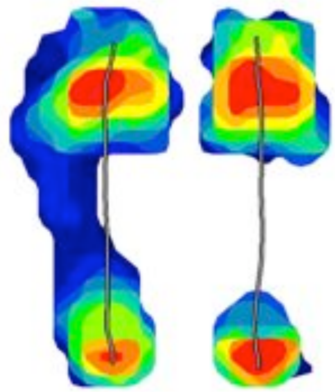

Fig. 2 Detailed plantar pressure distributions and progressions of a patient with a right-side below knee amputation

SYSTEM DESIGN

The wireless telemetry system for gait analysis featured the application of force sensors and accelerometer elements to monitor both plantar pressure and joint moments of the prosthetic limb. System electronics perform data acquisition and a microcontroller unit encodes the data and interfaces with a Bluetooth module. Low power design and the use of a small battery pack allowed the system to be worn outside of the gait lab.

Piezoresistive force sensors were implemented with a biased-inverting amplifier driving circuit to allow data capture over the relevant plantar forces. Sensor placement was governed by the pressure distributions recorded by the F-scan system. A tri-axial accelerometer provided information regarding the movement of the shoe and the prosthetic ankle moment throughout the gait cycle.

Inputs from both the piezoresistive force sensing elements and the accelerometers were captured using an analog-to-digital converter (ADC), and processed by a microcontroller unit (MCU) (Fig. 3). A thresholding algorithm quantized the captured data. Thresholds were calibrated using previously conducted perceptual tests. The MCU interfaced with a Bluetooth module using the RS-232 serial protocol.

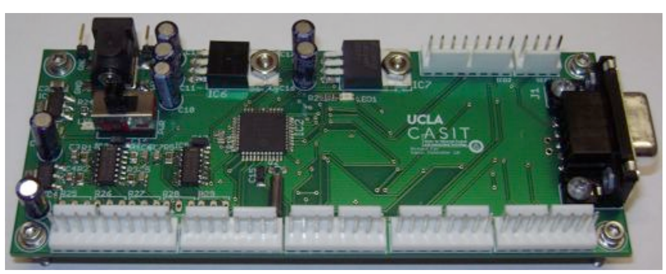

Fig. 3 Electronic control board featuring driving circuitry, ADC, microcontroller and output driver

In this initial work, a commercially available Bluetooth module was used (Fig. 4). This allowed for quick implementation through the use of well-established RS-232 protocols, although future systems will include an internally integrated Bluetooth module. The use of a Bluetooth link allows for instant connectivity to a PC and capture of measured data, without the need for wired tethering. The whole system is shown in (Fig. **5**).

Fig. 4 Commercially available Bluetooth module

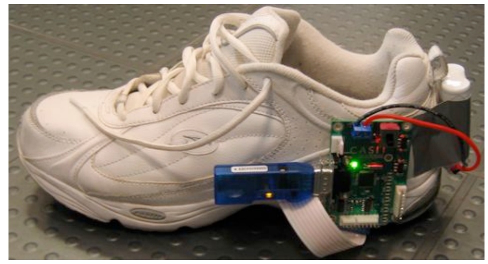

Fig. 5 Integrated gait telemetry system

The wireless telemetry system components were then integrated into our previously developed haptic feedback system. This feedback system worked to translate forces measured on the prosthetic foot into tactile stimuli at the sensate mid-thigh. The tactile stimuli were provided by a haptic feedback cuff typically worn 14 cm above the superior pole of the patella. Each feedback actuator within the cuff consisted of a robust, thin-film silicone membrane placed on a rigid polydimethylsiloxane (PDMS) base to allow for consistent and conformal tactile feedback to the skin surface. The integration between the telemetry and feedback systems allows for the monitoring of patient mobility while also providing augmentative sensory feedback.

CONCLUSIONS

This telemetry system is intended to work in parallel with trials associated with the original haptic feedback work. Planned biomechanical gait analysis will be used to validate both systems. Results from traditional gait analysis regarding the impact of the haptic feedback system will be compared to results recorded by this telemetry platform, and it is intended that the development of both monitoring and interventional technologies will work synergistically.

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