Monitoring Metabolic Energy Expenditure Via the Prostheses of Lower Extremity Amputees
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Introduction
The loss of a lower limb can profoundly increase an individual's metabolic demands (Sagawa et. al, 2011). The significant increase in metabolic cost of ambulation for lower limb amputees has been identified as a major problem in the rehabilitation of these individuals.

Advances in prosthetic technologies have led to the introduction of limb components designed to address some of the biomechanical inefficiencies that arise during ambulation with a prosthesis. Although these advancements offer the potential for reducing metabolic costs during walking, current methods of quantifying energy expenditure (EE) in free-living individuals are cumbersome, expensive, and/or inaccurate. An integrated device that provides accurate EE feedback would enable optimization of prosthetic components to provide improved efficiency during ambulation. Additionally, instantaneous analysis of EE during gait would offer a method for therapists to enhance rehabilitation routines.

The purpose of this research was to develop a prototype system that is integrated into the prosthetic liner and socket and provides accurate, real-time EE feedback to the user and/or clinical personnel.

Methods
A prototype system was developed to incorporate sensors that track key metabolic markers into a prosthetic liner and socket-mounted case. System components included: (1) A gel prosthetic liner with embedded sensors to monitor heart rate (HR) and skin temperature (ST); (2) a small, low-profile data acquisition (DAQ) module that attaches to the prosthetic socket and contains 6 degrees-of-freedom (6-DOF) inertial sensors, a microcontroller, a Bluetooth transceiver, and a rechargeable battery; and (3) a mobile-device software application for real-time display and control capability.

The prosthetic liner with embedded HR and ST sensors was provided by the Ohio Willow Wood Company (OWWC). A liner production methodology was devised with OWWC to embed the sensors into the liner gel material. The prototype DAQ module was fabricated and packaged into a low-profile socket-mounted enclosure. A mobile-device application was developed using JAVA and XTiML to provide a convenient user-interface for data readouts. The functionality of system components was verified by testing each of the sensors separately in conjunction with data readouts from the mobile-device application.

Results
The relevant EE estimation sensors (HR, ST, and 6-DOF kinematics) were successfully incorporated within the prosthetic components. All system sensors were found to be functional. The HR sensors and beat detection algorithm accurately extracted HR. Additionally, communication was established between system components to initiate and cease transmission of sensor data to the handheld mobile-device application.

Discussion
This work demonstrated feasibility of a prototype EE monitor for lower limb prostheses. The system has been designed for unobtrusive collection of sensor data, based on the integration of sensors into gel liners and a low-profile DAQ module that attaches to the socket. Functionality of all sensors has been demonstrated, and communication between the sensors, DAQ module, and handheld device has been demonstrated.
The prototype system has the unique capability of detecting individual heart beats in addition to tracking prosthesis 6-DOF kinematics. The combined monitoring of HR and physical movement is considered to be the best option for generating accurate EE assessments in free-living individuals as an alternative to more sophisticated and expensive methods that can be used for this purpose, such as the doubly-labeled water technique. Measurement of HR is considered to be crucial to obtaining accurate EE estimates, particularly during low activity periods, during which estimates based on inertial information alone tend to deteriorate (Staudenmayer et al., 2009).

Future work on the system will include generation of EE estimates via polynomial neural network (PNN) models. The data obtained from the sensors while the system is worn will be used as PNN model inputs, with indirect calorimetry serving as the criterion measure for model training. Additionally, clinical evaluations of the system will be conducted with lower limb amputees.

**Conclusion**
Functionality has been established for a prototype EE monitor for lower limb prostheses. The availability of reliable EE metrics will contribute significantly to further optimizations in prosthetic technologies and aid in the reintegration of amputees into community activities.

**References**

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