DFT: Digital Fitness Trainer

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***Abstract*—DFT is a piece of exercise equipment combined with wearable technology that will allow users to do strength training with a reduced risk of injury. We will provide users with a Microsoft Kinect that will use our software to look for signs of improper form, as well as a pair of compression shorts with surface electromyography (sEMG) probes and an embedded system. The Kinect will allow our software to warn the user when they are exercising incorrectly, and the shorts will allow the software to warn the user when their muscles are approaching the fatigue threshold. The combination of these sources of information will allow the DFT software to help users work out properly and avoid overexertion.**

I. Introduction

It is common knowledge that exercise has many health benefits. People who are more physically active tend to have lower annual healthcare costs [1]. According to the 2008 Physical Activity Guidelines for Americans, exercise's positive effects include reducing the risk of diabetes, certain types of cancers, weight gain, and osteoporosis [2].

These health benefits are certainly a good reason for people to exercise, but exercise also has its risk. People who work out risk injuring themselves, especially when they work out improperly. A New York Times study found that 970,000 Americans were treated for weight-training injuries from 1990 to 2007. Of these, 14 percent were injured because of overexertion, muscle pulls, and loss of balance, which could have been corrected by using proper form and stopping before exertion hit [3].

There have been a number of attempted solutions to this problem in the past. Two companies have recently come up with wearable technology solutions to common exercise problems. One of these, Sensoria, released a pair of socks that senses pressure to give feedback about users' running form, as well as a comfortable heart rate monitor in a shirt [4]. These solutions probably work well for running, but not for weight training. Another company, Athos, is developing a suit containing EMG sensors that can reportedly track muscle fatigue in users via a smartphone app [5]. This product is more weight training oriented, but it does not seem to give real-time feedback that could help users to prevent injuries as they are working out. Another product on the market that purports to help users track their weight training is PUSH. PUSH takes the form of an armband with an accelerometer in it which it uses to track a user's velocity throughout a workout [6]. Again, it does not provide real-time feedback, and is most useful for professional athletes who want to know how powerful their lifts are.

There are also a number of Kinect-based fitness solutions on the market. Among these, the most popular is Your Shape Fitness Evolved. It does a good job of providing visual feedback to the user during workouts, but it mainly consists of timed aerobic workouts such as those found in exercise videos [7]. There is still space in the market for a product that both tracks muscle use and provides visual feedback, which would be helpful for people who want to start weight training and don't want to injure themselves.

TABLE I
SPECIFICATIONS

Specification	Value
Sensors (EMG probes)	
Height	<1cm
Length	<3cm
Width	<3cm
Embedded System	
Weight	<2lbs
Height	<4cm
Length	<10cm
Width	<10cm
Battery Life	>4 hours
Detachable	Must be able to wash shorts
Kinect	
False Positive Rate	<1 per workout
Supported Exercises	Squats, Deadlifts, Lunges
Bluetooth	
Maximum Distance	>10 feet

With our solution, the Digital Fitness Trainer, we hope to give real-time feedback on weightlifting form and muscle fatigue, so users can make corrections to their workout that will help them to prevent injuries. Since it is intended to be used during workouts, the system has to be portable and the wearable portion has to be comfortable. It has to be able to process data in real-time. The wearable's battery should last at least four hours, so the batteries do not have to be changed or charged after every workout. It should not weigh more than two pounds, so it does not affect the amount of weight lifted or the user's center of balance. Users should be able to select a workout on a graphical user interface (GUI) and see themselves on their laptop screens as they are working out.

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II. Design

A. Overview

To solve the problem of workout-related injuries, we will combine two sources of information about the user using a total of four blocks. One source of information is the Kinect, which is attached to the laptop and has all of its data processed in the Kinect processing block. The other source of information is the sensors, which are attached to a pair of compression shorts and are in contact with the user's skin. These sensors are wired to a microcontroller, which is attached to a Bluetooth module. The Bluetooth module connects to the laptop, where the sensor data processing software block handles all the processing of the sensor data. A GUI displays the information from these two systems to the user.

The Kinect processing portion of DFT takes live video of the user's workout and uses that to create a virtual skeleton. Using this virtual skeleton and the Kinect API, it is possible to measure distances and angles between limbs. With this information, DFT can compare the user's position to the ideal form for the selected workout. It then warns the user when they stray too far from perfect form. It must be accurate, with less than one false positive per workout session. If users get multiple false positives, it may lead them to believe they are working out improperly, while no false positives is an unrealistic goal. The Kinect should also be able to isolate the user from the environment and from other people in the background.

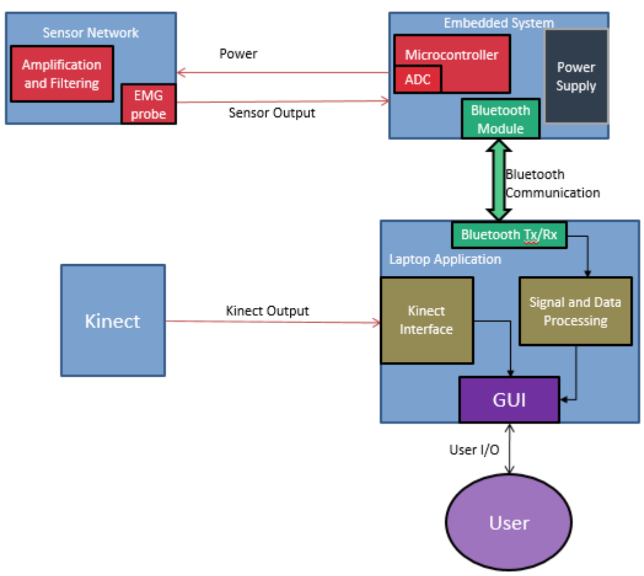

Fig. 1. Block Diagram of the System

The NIRS sensors will send light into the skin and measure the amount returned, using two wavelengths to measure both oxygenated and deoxygenated hemoglobin. The sensors will output voltages that will be read by the microprocessor's ADC, stored in memory, and then transmitted to the laptop once per second, allowing the laptop to check for fatigue on a second-by-second basis. The sensors must be small enough to be unobtrusive, and the microcontroller should have multiple ADC channels and at least one UART channel. The Bluetooth communications must be consistent, with 99% accuracy in transmission. It should be able to work from at least 10 feet away.

The Kinect was chosen because it was the most reasonable solution we could find for tracking motion and providing visual feedback. Bluetooth was chosen over WIFI because it does not require network access. We originally chose NIRS sensors because they have a few advantages over Electromyography (EMG) sensors. EMG sensors require a conducting medium, usually liquid, be applied between them and the skin. NIRS sensors have no such limitation. EMG sensors also tend to have a lower signal-to-noise ratio than NIRS sensors.

B. Visual Sensor (Kinect v2.0 for Windows)

This block encompasses the data processing and GUI that make up the software application for our solution. The windows-based application will display a useful and visually appealing showing of the exercise data. We are using the Kinect v2.0 for Windows sensor, a premade piece of hardware that contains the necessary color and depth sensors for our use. The user is able to stand in front of the camera and perform a selected exercise movement while our system collects visual data to generate useful feedback through the GUI.

The Kinect utilizes a "time-of-flight" camera system that emits light signals and measures the time to return for each pixel in order to generate a depth-mapped image of the user and their surroundings [8]. Based on software algorithms that use machine learning and inferences about the human body, it is able to use the depth data to recreate a full 3D model of the person in real-time. Further, it is able to make accurate inferences about the 3D coordinate locations of the user's joints, and subsequently their limbs. These algorithms are proprietary, but available for use by third parties through Microsoft's developer API [8].

Our software application will be able to use the skeletal tracking of the human body, along with known quantitative markers of correct and incorrect form for various exercise motions to give feedback to the user. One specific example is the measurement of the user's joint angles throughout the exercise motion. Maintaining bad angles in certain places such, as the knees, neck, and hips can put undue stress on joints [9,10]. Our application will warn the user if one of these angles is outside of the proper range. Another example is measuring relative limb action throughout the exercise motion. The application will detect whether the user is maintaining a fluid motion with all limbs moving in a proper orchestra. For instance, in a full-body motion, such as the squat, it is ideal to have the knees and back bend into the squat and push back up to standing position in a relatively synchronous fashion. This minimizes the risk of overstressing the lower back.

C. NIRS Sensors

The function of this block is to continuously monitor muscle fatigue during a workout. Two technologies were originally determined to be viable for this task, Near Infrared Spectroscopy (NIRS) and surface Electromyography (sEMG). After extensive research we decided to proceed with the development of a NIRS sensor to monitor blood oxygen content in the muscle. Typical design of such a sensor utilizes transmission multiple wavelengths of light through muscle tissue and a photodiode to determine absorption in the body.

Our design of the NIRS sensor was originally to be implemented using a bi-wavelength LED manufactured by Epitex, part name SMT 735,850. This part has been used in multiple previous designs of NIRS sensors, which were summarized in [11]. Previous success in designing this type sensor provided confidence in our ability to use this LED. After inquiring Epitex about purchasing them, we learned it would be a 12 week turn around after ordering and that there was a minimum order of 100 at four dollars per LED. These requirements made the use of this device impossible for our project. To replace this LED we incorporated the use of two LEDs commonly used in Pulse Oximetry. The Kingbright 660 nm wavelength red LED and Fairchild T-3/4 I/R EMITTER dominant 940 nm wavelength LED were chosen. They were chosen because of their successful use in blood oxygen sensing content in human tissue and consistent output wavelengths. To determine the absorption of light in the tissue our research produced a commonly used device, TI OPT101 photodiode [11]. This device was chosen because it provided a high linear sensitivity to irradiant light intensity and a low quiescent current. The sensor design utilizes two input lines, one output line, power and ground. Each input line connects to the base of a BJT illuminating each LED.

After completing the sensor prototype multiple issues were discovered during preliminary testing. The sensor was strapped to the skin above the quadricep muscle and each LED was turned on individually and the output read on the oscilloscope. The IR wavelength LED transmitted through the muscle with ease; however, the red LED did not radiate enough power that adequate power was reflected to the OPT101. To solve this issue a second LED was added in parallel. The second issue proved to be insurmountable, the sensor was extremely sensitive to pressure. Since the sensor network is intended to be adaptable for multiple users this issue makes the NIRS sensor unusable. This prompted us to delve into the idea of sEMG sensors as it was our alternative to NIRS. We have been in contact with Dr. Jane Kent in the Kinesiology department at the University of Massachusetts about the use of sEMG to monitor muscle fatigue.

D. Embedded System

This block is responsible for recording the voltage data that the sensors pick up and sending it to the laptop. Using techniques from Computer Systems Lab I, ECE 353, we are programming a microcontroller to do several operations. Among these operations are a time delay using the microcontroller's timers, analog-to-digital conversion using its 10-channel multiplexed ADC, and reception and transmission of character arrays using the UART. The UART is connected to a Bluetooth module with a PCB antenna, which adds Bluetooth headers to the UART messages before transmitting them to the laptop.

The heart of this block is the PIC32MX110F016B microcontroller, a 32-bit microcontroller from Microchip Technology, Inc. It has three timers, 10 ADC channels, an internal oscillator that is stable up to 40 MHz, and two UARTs [12]. These characteristics make it a good choice for the microcontroller in our system. The software that is running on the microprocessor is fairly simple. It waits to receive a message from the UART. It then checks the first byte of the message, and depending on the character received, it turns on one LED, waits, and reads from a certain ADC channel. It then stores the value in a buffer which it transmits to the laptop via the UART and the Bluetooth module.

The Bluetooth module we selected is the Microchip/Roving Networks RN-42. It is a surface-mounted device that can be purchased with or without a PCB trace antenna. The device is low-power, with 3mA draw when connected and 30 mA draw when transmitting [13]. It allows for transmission and reception of data over Bluetooth, and converts Bluetooth messages to UART or I2C and vice-versa. We are using its UART/Bluetooth conversion abilities to make the software on the microcontroller side as simple as possible.

To set up the RN-42, we had to do a few things by attaching the module to a computer's USB port and communicating with it via a terminal. First, we changed the name of the module to DFT-Bluetooth to make it easier for users to find and connect to. Then we changed the security setting so it did not require a password for pairing, which also served to make it easier to connect to. We also set the baud rate to 9600, and made sure there were 8 data bits, no parity bit, and one stop bit.

To test this block, we had the laptop send a series of strings to the microcontroller and wait to receive responses, which it printed in the console. This allowed us to ensure that Bluetooth communications were working, and that the microcontroller could differentiate between different input strings. We then had it sample voltages from a function generator and send them to the laptop. The numbers received by the laptop varied with the voltages on the function generator, indicating that the ADC was working.

E. Data Processing, Bluetooth Communications, and GUI

This block includes the building of a windows socket application using Bluetooth technology to transmit and receive data from the laptop to a PIC32 microcontroller. The windows application begins by creating a Bluetooth socket and querying for nearby Bluetooth devices. The windows application then connects to the Bluetooth device with the matching MAC address of the RN-42 Bluetooth module. Once connected to the Bluetooth module, we can send and receive data to and from the PIC32 microcontroller. Data sent to the microcontroller from the laptop will include data to represent which sensor and which LED to use and receive data from. The data received will be a measure of change in light intensity, which can be related to the change in concentrations of hemoglobin and oxygenated hemoglobin through the modified beer – lambert law. Using a dual wavelength system, measurements for HbO2 and Hb can be solved from the matrix equation:

$$\begin{vmatrix} \Delta OD_{\lambda 1} \\ \Delta OD_{\lambda 2} \end{vmatrix} = \begin{vmatrix} \epsilon_{\lambda 1}^{Hb} d & \epsilon_{\lambda 1}^{HbO_2} d \\ \epsilon_{\lambda 2}^{Hb} d & \epsilon_{\lambda 2}^{HbO_2} d \end{vmatrix} \begin{vmatrix} \Delta [X]^{Hb} \\ \Delta [X]^{HbO_2} \end{vmatrix}$$

[14].

At the 640 nm wavelength the value of ε, the attenuation coefficient, is 442 cm-1/M for HbO2 and the value for Hb is 4345.2 cm-1/M [15]. At the 940 nm wavelength the value for HbO2 is 1214 cm-1/M and the value for Hb is 693.44 cm-1/M [15]. We estimated that d, the photon path length from emitter to detector, is approximately 15.5 cm for our configuration. Using this information, we can calculate the concentration of Hb and HbO2. Using the concentrations of Hb and HbO2 combined with the fact that when the muscle is 60 percent contracted there will be no blood flow to the muscle. Using this information as well as the data from the Kinect which provides a rep count, you can provide the user with an accurate estimate of fatigue.

III. Project Management

TABLE II
MDR Goals

Subsystem	Status
Sensor Network	Demonstration of sensor able to output varying voltages for different incident light intensities.
Bluetooth Communication and Data Processing	Receive test data from microcontroller and run modified Beer-Lambert Law algorithm
Kinect Sensor	Demonstration of accurate identification of several markers of incorrect technique and corrective feedback
Embedded System	Able to send out LED pulse signals and transmit sampled test voltage from function generator to laptop via Bluetooth.

Many of the original tasks listed in Table II have been completed and some exceeded. We have been able to measure different light intensities incident on the photodiode by placing the sensor in different environments and comparing the outputs. The microcontroller has been able to turn on the LEDs and read from the output of the photodiode to its ADC. The laptop and microcontroller have been able to communicate via Bluetooth using data interpreted from the sensor. From there, the laptop has been able to process this data and determine and display the concentrations of oxygenated and deoxygenated Hemoglobin. The Kinect sensor has been able to accurately detect three major faults in a user's form and provide unique feedback for each one. Each block still has much work to be done; however, the sensor presents the biggest challenge. At this point we are exploring the option of sEMG sensors to replace the NIRS sensor.

As a team we have done extremely well collaborating with each other as well as our advisor, Professor Duarte. We have weekly meetings with Professor Duarte and meet at least once as a group per week, often more, to discuss the state of our project and the necessary steps to proceed. Our team has supported one to overcome challenges in each of our individual blocks. Nathan Reynolds and Justin Gardner are the hardware focused members of our group while Ben Sherman and Chris Corbo are the software people. We generally coordinate with one another through email and group text messages, and we meet up to communicate verbally at least once a week.

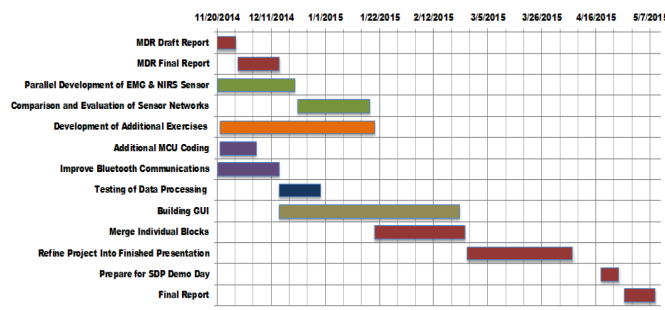

Fig. 2. Gantt Chart of Anticipated Progress

IV. Conclusion

Currently, the three sensor-side blocks of DFT are communicating with one another. The PIC32 microcontroller is receiving data from the NIRS sensor and is then sending data via Bluetooth to a windows application on the laptop. Once the data is received at the laptop, the data is processed and hypothetical concentrations of hemoglobin and oxygenated hemoglobin are displayed to the user. The current system also includes a working Kinect portion that monitors the user's forms and provides feedback to the user on how to correct their form if it is not ideal. This portion does not yet have the necessary false-positive rate, and we have come up with some ideas about how to improve the form-tracking. We plan to fix the issues with the Kinect, and to combine the Kinect application and the windows application into one, and create a GUI for the user to choose and view his or her workout.

Future plans include attempting to use the system with EMG sensors as opposed to NIRS sensors, as we found NIRS sensors provided inaccurate data due to the changing pressure on the skin when working out. Once settled on a sensor design that is accurate, a wearable must be made in order to monitor the user's workout. We expect to face difficulties in achieving accurate form detection for different types of users; therefore the variability of users must be kept to a minimum when testing this product to overcome this obstacle.

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