Wheelchair Exercise Monitor Development Platform
An Application for Wireless EMG Sensors

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Abstract: We present here a novel application for wireless EMG sensors. To combat the physical inactivity which has tended toward cardiovascular disease in individuals who use wheelchairs, we have developed a monitoring system to encourage these individuals to exercise. Wireless sensors are used to monitor kinematic or physiological metrics, which inform the user of their activity levels during exercise and to track progress of their fitness levels over time. In particular, a new completely wireless, wearable EMG sensor (Dynofit, Inc., TX) is integrated with accelerometer and heart rate sensor data to monitor energy expenditure. The sensors communicate with a custom designed mobile app which facilitates exercise at home, with the aim of helping individuals who use a wheelchair to overcome what are commonly hindrances to exercising.

1 CARDIOVASCULAR FITNESS IN WHEELCHAIR USERS

Individuals who use wheelchairs have an increased risk of cardiovascular disease (Selassie et al., 2013; Garshick, 2005). To address this growing health issue, and to support preventative measures for cardiovascular co-morbidity, we are developing a system which would promote and facilitate exercise for wheelchair users. (Abel et al., 2008; Blair, 1999). A widely accepted recommendation for reducing cardiovascular disease risk has been to increase average daily energy expenditure by 300-350 kilocalories (RS et al., 1993).

Thus, it has been important to the research community to determine what forms and amounts of exercise should be prescribed to reach this fitness goal. However, those who use wheelchairs face many barriers to exercising the right way and right amount, many tied to the challenge of getting to specialized gyms or wellness centers.

To encourage and support wheelchair-dependent persons in meeting these recommendations for caloric expenditure, we are developing an in-home exercise program, so that their workouts do not depend on having access to expensive and/or large equipment, and/or to therapists with whom scheduling or transportation also disincentivizes exercising. In keeping with the current trend of fitness trackers, we are developing a system to track a measure of fitness to motivate individuals to exercise and be encouraged by progress in fitness and/or activity levels. As energy expenditure has been agreed upon as the most informative metric of cardiovascular fitness (Abel et al., 2003; Ainsworth et al., 1993), at the crux of this in-home exercise monitoring system is the ability to monitor energy expenditure continuously at home, during exercise.

2 MEASURING ENERGY CONSUMPTION

Currently available or researched activity monitors and fitness trackers for mobility impaired individuals predominantly rely on acceleration, heart rate, or a

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combination of the two. Clinically relevant outcomes for wheelchair users, such as amount of movement, distance travelled, strength of maximum voluntary contractions, and wheelchair propulsion have been effectively quantified with various sensing mechanisms, the most common being the accelerometer or a reed switch-based data logger(1). Accelerometry and the data logger provide a reasonable measure of movement and wheelchair propulsion (2), but motion detectors are prone to false positives, as in the case of an accelerometer-based step counter, which would detect shaking of the device up and down and mistake such motion as exercise. EMG is also better suited to tracking compliance with prescribed exercises, since the pattern of activation across multiple muscles can be monitored. Furthermore, in contrast to accelerometers, EMG may not only be used to monitor the contractions of individual muscles, but also to capture muscle activations during isometric contractions.

Energy expenditure is consistently relied upon to measure and predict cardiovascular disease risk (Sawka et al., 1980). However, measuring energy expenditure directly through whole body calorimetry or through oxygen uptake (VO_2) measurements requires expensive and/or impractical equipment and facilities. Heart rate can be used to fairly accurately compute energy expenditure (**?**). However, heart rate is difficult to obtain accurately during exercise, and in particular, for spinal cord injury patients. Autonomic dysfunction is common in spinal cord injured patients (Krassioukov et al., 2008), and we have observed anomolous heart rate recordings in spinal cord injury subjects during exercise.

3 DREAM EXERCISE MONITORING SYSTEM DESIGN

The DREAM (Disability, Rehabilitation, and Engineering Access for Minorities) exercise monitoring system is designed to provide feedback which motivates the user to improve his/her cardiovascular fitness through exercise. The main system components are shown in Fig. 1.

Muscle activation, heart rate, and endpoint acceleration are measured in real-time from wireless sensors, which include Flexdot EMG sensors (Dynofit, Carrollton, TX), a Wahoo Tikr heart rate monitor (Wahoo Fitness, Atlanta, GA), and a custom-packaged inertial monitoring unit. The DREAM app allows users to set HR and activity target zones, continuously monitor their activity levels, and track the monitored metrics over time. The performance specifications for the DREAM monitoring device are given in Table 1

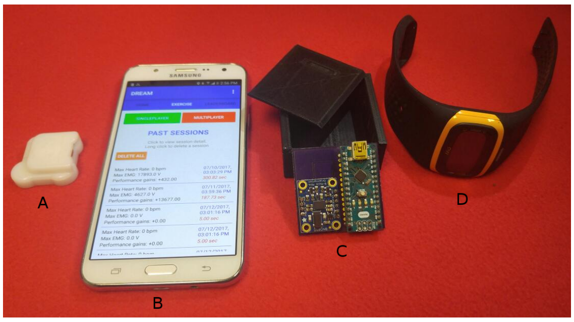

Figure 1: System components of the DREAM exercise monitor: A) Dynofit's Flexdot wireless EMG sensor; B) the DREAM mobile app; C) the custom packaged wireless IMU board; D) Mio Global's Alpha 2 heart rate monitor (Mio Global, Vancouver, British Columbia).

Table 1: Performance specifications.

	EMG	HR	IMU
output metric	integrated envelope	heart rate	wrist acceleration
units	% of max. isometric	beats per minute	m/s^2
sampling rate (samples/sec)	60	1	4
input range	$\pm300\mu V$	0-200bpm	$\pm8g$
resolution	$440\mu V$ (12-bit)	1bpm	$940\mu g$ (14-bit)
current consumption (active mode)	3mA	<1mA	12.5mA
battery life (hrs of active use)	73hrs	300hrs	41 hrs

The fitness-relevant physiolgical metrics are monitored and wirelessly transmitted to a smart phone app which depicts the metrics in an easy-to-read and motivating way. Fig. 3 illustrates the screen users will see when exercising.

This cloud-based multi-user functionality and web portal have yet to be implemented.

Here we describe the unique sensing components of our design in greater detail.

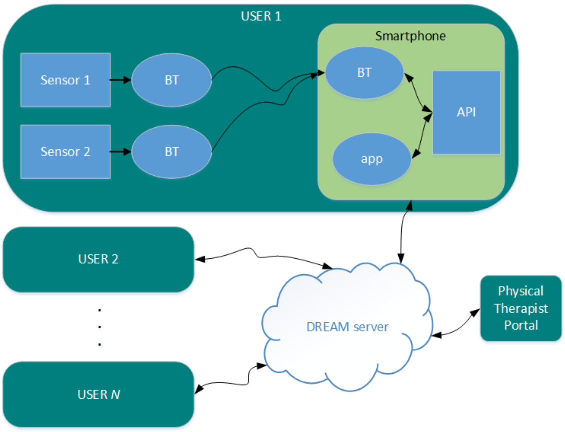

Figure 2: Schematic system diagram of a next generation DREAM exercise monitor.

3.1 EMG Sensors

EMG is acquired by commercial sensors developed by Dynofit to allow for completely wireless EMG acquisition tailored for mobile applications. Other vendors manufacture wireless EMG sensors, but these sensors are more well suited for research applications, as they require proprietary hardware (a base station) and software. In contrast, the Dynofit Flexdots communicate via Bluetooth Low Energy (BLE), and all the hardware needed to perform wireless communication with a smartphone is contained within the wearable sensing unit. The sole requirement to acquire data from the Flexdot is the capability of the receiver to communicate via BLE.

The Flexdot module is fully packaged into a plastic housing with snap female connectors for the electrodes. Disposable electrolyte gel-filled electrodes are snapped into the electrode contact terminals. Inside the plastic housing is a custom board which provides signal conditioning and A/D conversion, a BLE transmitter, and a lithium coin cell battery.

3.2 Wearable IMU Module

During this development phase of the wheelchair exercise monitoring system, in order to determine the most suitable fitness metric, commonly used metrics of activity will be acquired and compared to novel metrics which incorporate or even rely centrally on EMG measurements. Activity monitors most commonly measure heart rate and acceleration. An off-the-shelf popular heart rate monitor, the Wahoo Tikr is able to be used in the DREAM development platform because the Tikr transmits data via the ANT+ wireless protocol. Thus, the DREAM app can communicate directly with the Tikr without need for any

Figure 3: Screenshots of two of the main DREAM app screens: 1) activity metrics page displayed in real-time during an exercise session; 2) the “Leaderboard” showing the ranking of DREAM app users, ranked according to a fitness metric; 3) a log of stored data from past exercise sessions, all accessible from the DREAM cloud server.

proprietary information. However, the top-of-the-line accelerometers that are most often used in activity monitoring in the literature pose the same issues that the wireless EMG did; namely, they require connection to a PC and proprietary software. From preliminary data, we had already seen that accelerometry alone would not provide sufficiently accurate feedback about energy consumption. Therefore, we custom built a wearable BLE-based wireless inertial monitoring unit module.

The system components and IMU module design are provided in the board schematic in Fig. 5. This custom PCB board consists of an IMU IC, BLE-

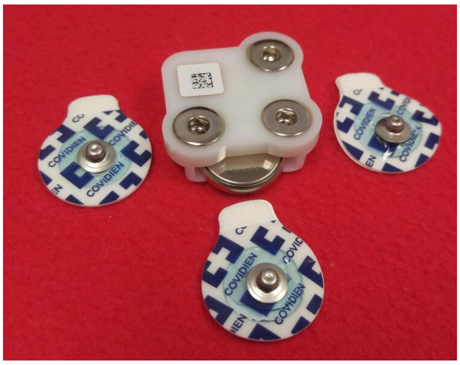

Figure 4: Flexdot components: the plastic housing for the signal processing circuitry, with 3 female snap connections, a 3V-coin cell battery, and the disposable snap electrodes (Medtronic Covidien PLC, Minneapolis, MN).

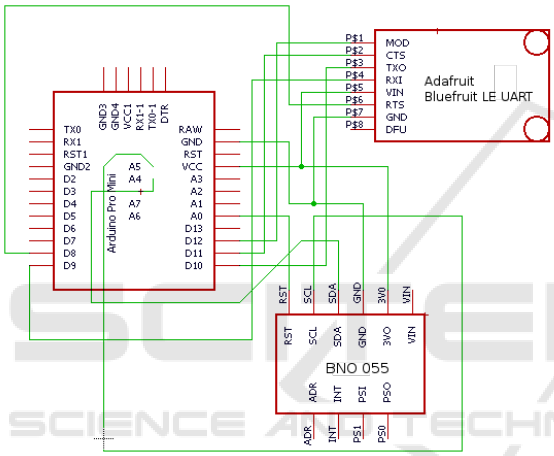

Figure 5: Circuit schematic of IMU module.

UART wireless adapter, and Arduino microcontroller board. The BNO055 is an intelligent 9-axis orientation MEMS sensor with a UART interface. We use only the accelerometry measurements. In order for our mobile app to acquire acceleration data wirelessly from the BNO055, we interface the BNO055 with a BLE transmitter on board the Bluefruit LE-UART Friend (Adafruit Industries). The Bluefruit board is a UART wireless adapter that establishes serial communication with the BNO055 and then transmits this data through the BLE transmitter to the mobile smart phone. The ATMega 328P microcontroller, on board an Arduino Pro Mini, controls the UART communication between the BNO055 and Bluefruit board.

This IMU module is powered by two 3.7V Li-ion Polymer batteries in series, and fits in a custom housing unit that can be worn via velcro strap around the wrist. The Solid Works CAD drawing for the housing unit is provided in Fig. 6. The package has slots for the velcro strap and space for a power switch. The housing is approximately 4cm x 4cm x 2cm.

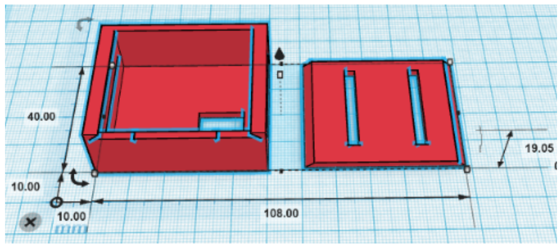

Figure 6: CAD design for the IMU module housing unit, 3d-printed in ABS plastic. Dimensions are provided in mm.

Magnitude of 3D acceleration recorded during wheelchair pushes, tricep extensions, and lat rows for approximately 30 second bouts, with 30-second rest intervals, is shown in Fig. 7. The DREAM IMU module appears to record similar magnitude as Actigraph, but the Actigraph shows less high frequency noise. We plan to implement low-pass filtering in the DREAM IMU module to obtain acceleration waveforms which even more closely match Actigraph's.

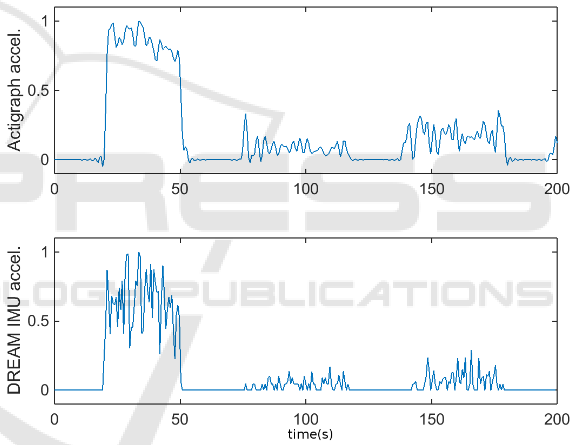

Figure 7: Endpoint acceleration magnitude acquired by Actigraph sensor vs. DREAM IMU module.

4 PERFORMANCE OF EMG SENSOR

Before Dynofit's existence, a number of commercial wireless EMG sensors existed on the market. These are generally high performance sensors with excellent noise cancellation, motion artifact suppression, and overall signal to noise ratio. However, to the authors' knowledge, all of these wireless EMG sensors require a receiver base station and a PC workstation with proprietary software for data acquisition. We selected the Dynofit Flexdot for EMG sensing because of its standalone capability; i.e., the Flexdot requires no base station but transmits data wirelessly through

Bluetooth Low Energy (BLE) without requiring any proprietary software. These features make it well suited for our in-home exercise application, whereas the other high performance EMG systems are better suited for research applications or patient assessment in a clinical setting but not practical for our application of in-home exercise monitoring.

While the Dynofit Flexdot sensors were more practical and were the only sufficiently practical EMG wireless sensors of which we were aware, we also wanted to test the performance of the EMG sensors relative to one of the top-of-the-line wireless EMG commercial systems. We selected the Delsys Trigno to which to compare the Flexdot.

A Flexdot was adhered to the muscle belly of the right bicep; a Trigno sensor was adhered to the muscle belly as well, adjacent to the Flexdot. EMG was acquired from both systems for 60 seconds during bicep curl exercises and isometric contractions. The EMG envelope was obtained by full-wave rectifying the raw EMG, and then applying a moving average filter with a rectangular window of 100ms. Figure 8 illustrates that the envelope was appropriately obtained from the raw EMG. Both envelope amplitudes were normalized to range between 0 and 1.

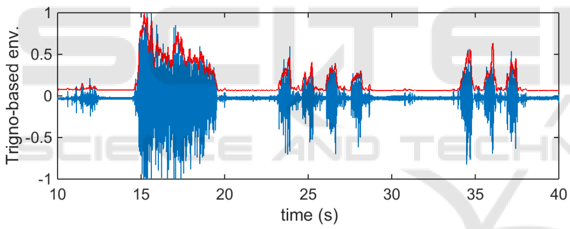

Figure 8: EMG envelope superimposed on the raw EMG acquired from the Trigno sensor.

The envelope obtained from each of the sensors were compared, as shown in Fig. 4. While the Flexdot captured each muscle activation and showed temporal accuracy, the amplitude of muscle activation sometimes exceeded that of the Delsys Trigno in this application. Factors contributing to the amplitude differences may include the differences in the location of the sensors on a single muscle, spacing of electrodes on the devices, size and the conductivity of the pads used to adhere the device to the skin above the muscle. These factors were not likely to explain the differences, however, given that these amplitude changes were observed for a given subject within the same recording session. What appeared to be more likely the case is that adaptive filtering is being applied to maximize use of the dynamic range on the amplitude scale, such that the normalization of relative amplitude is adjusted over time. Switching to non-adaptive normalization is simply a matter of adjusting the post-processing in firmware.

In order to quantify a direct comparison between the Flexdot-based and Trigno-based EMG activity, the Flexdot data was first upsampled, since the former was acquired at 64Hz , and the latter at 2000Hz. We then computed the RMS difference between the two normalized envelopes, and obtained an RMS error of 0.27. Since the amplitudes are normalized, we represent the RMS difference as 27% of the amplitude range. As indicated above, this difference can be attributed to the post-processing methods implemented in firmware.

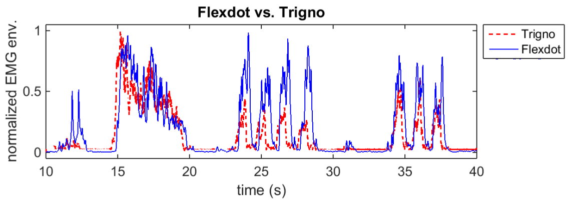

Figure 9: Comparison of EMG envelope acquired from the Dynofit Flexdot by the DREAM app and the EMG envelope obtained from Delsys Trigno.

To help confirm that the differences were more likely due to differences in post-processing schema than to physical characteristics, such as size and location of the electrodes, we conducted another test. This time, the subject performed bicep curls with elastic arm bands (TheraBand, Akron, OH) at 3 levels of increasing resistance. Recordings were taken from a Trigno sensor placed on the left arm slightly proximal to the center of the muscle belly, and a Flexdot sensor placed just distal to the Trigno sensor, such that they both overlapped with the center of the muscle belly. On the right arm, we had the converse placement of sensors, as seen in Fig. 10.

Figure 10: Placement of wireless EMG sensors. Left arm: Trigno sensor placed more proximally, Flexdot sensor more distally. Right arm: Flexdot sensor placed more proximally, Trigno more distally.

Five bicep curls were conducted at each resistance level. To increase the resistance level, we merely shortened the theraband to fixed lengths (of 80, 60, and 40 cm). The resulting EMG envelopes are shown in Fig. 11 for the left arm, and Fig. 12 for the right arm.

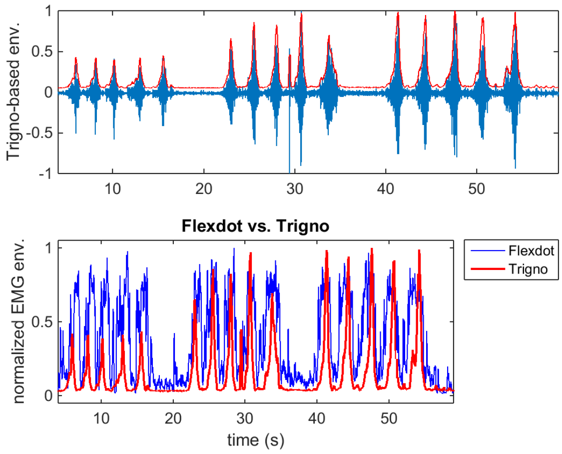

Figure 11: Comparison of Trigno-derived vs. Flexdot-derived EMG envelopes (from left arm) with Trigno sensor more proximal, Flexdot more distal.

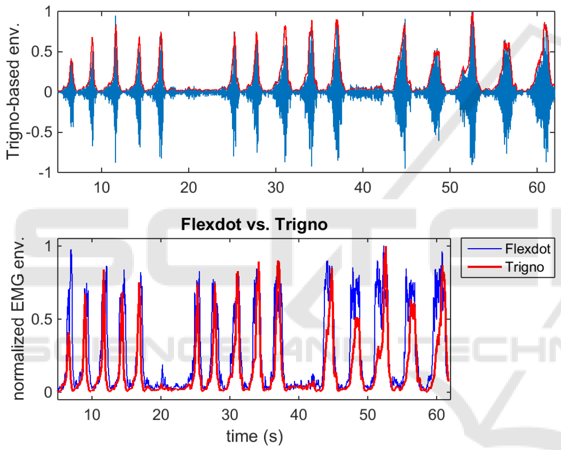

Figure 12: Comparison of Trigno-derived vs. Flexdot-derived EMG envelopes (from right arm) with Trigno sensor more distal, Flexdot more proximal.

The increasing amplitude of the Trigno envelope corresponds with the increasing resistance of the arm bands. It is possible that the Flexdot envelope has an adaptive gain that was designed to maximize use of the dynamic range at all times. The Flexdot performs very well in terms of temporal resolution, which in our application is critical. The location of the sensor does have some influence on the EMG amplitudes, but the main cause of the difference in amplitudes appears to lie within the post-processing in the sensors' firmware.

How accurate the amplitude needs to be in order to provide a motivating, reliable fitness metric to potential DREAM app users has yet to be researched. Adjustment of the EMG envelope amplitude is expected to require a straightforward adjustment of low-pass filtering parameters applied to compute the envelope.

5 CONCLUSIONS

Wireless sensing capabilities of EMG, heart rate, and accelerometry have been integrated into a single mobile app-based exercise monitoring system. The DREAM system is being designed to help motivate individuals who use wheelchairs to improve their cardiovascular fitness through exercise. We have presented the design and implementation of a first prototype which will enable us to research the most appropriate fitness metric on which to provide motivating feedback to the users. In particular, we highlight the selection and use of a new standalone wireless EMG sensor which performs with signal quality comparable to high-end wireless EMG sensors on the market, with the added benefits of low cost and practicality in an in-home exercise application that is predicted to help advance rehabilitation therapy.

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