SQUID: Sensorized Shirt with Smartphone Interface for Exercise Monitoring and Home Rehabilitation

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***Abstract*— Stroke is a leading cause of serious long-term disability in the United States. There is a need for new technological adjuncts to expedite patients' scheduled discharge from hospital and pursue rehabilitation procedure at home. SQUID is a low-cost, smart shirt that incorporates a six-channel electromyography (EMG) and heart rate data acquisition module to deliver objective audiovisual and haptic biofeedback to the patient. The sensorized shirt is interfaced with a smartphone application, for the subject's usage at home, as well as the online database, for the therapist's remote supervision from hospital. A single healthy subject was recruited to investigate the system functionality during improperly performed exercise. The system can potentially be used in automated, remote monitoring of variety of physical therapy exercises, rooted in strength or coordination training of specific muscle groups.**

***Key words*—Home rehabilitation, Wearable sensors, Biofeedback, Smartphone, Exercise monitoring.**

I. INTRODUCTION

In 2012, an estimated 7,000,000 Americans older than 20 have had a stroke. Each year, 795,000 Americans suffer a new or recurrent stroke [1]. Projections show significant increase in people will have had a stroke by 2030 [2], mainly due to aging. Appropriate technological adjuncts need to be developed to improve patient's quality of life post-stroke.

The total direct and indirect cost of stroke was $34.3 billion in 2008 [1]. Room charges (50%) and medical management (21%) comprised the major costs of the short-term care [3]. The county-level report in 2002 has shown that, 21% of US counties did not have a hospital and 77% did not have a hospital with neurological services [4]. The inability to afford medications among stroke survivors has shown significant increase and lack of transportation, no health insurance and low annual income were reported as the major factors for leaving the medications [5]. This is a strong indication toward the need for remote, home-based rehabilitation adjuncts so as to expedite patients' smooth discharge from hospital. The effective home rehabilitation setting will provide the possibility for long-term physical therapy that can evoke full recovery potentials in stroke patients. The comfort of the home environment is an additional asset that would increase life satisfaction levels amongst patients and their families [6].

However the home rehabilitation setting will also result in a distant barrier which leads to the loss of regular, supervised patient monitoring. Accordingly, establishing an effective framework to collect, monitor and evaluate the selected physiological data at the home setting is a necessity for this paradigm. In such a framework, the data can be fed back to the patient, in an appropriate comprehensible format, and also can be regularly transmitted to the therapist, by telemedical services. Biofeedback is a method of collecting physiological variables and delivering back to the subject. This feedback will increase subjective physiological awareness and help individuals learn to effectively manipulate the targeted physiological process [7]. The same or augmented type of information can be regularly transmitted to the therapists in the rehabilitation center to facilitate the expert's supervised assessment.

One of the most crucial physiological variables to be considered for the rehabilitation process is the electromyography (EMG). Myoelectric is a product of recruited muscle fibers by descending motor commands, driven from higher neural centers. This signal is detectable at the skin level and can be used to evaluate the function of the neuromuscular sub-systems. The EMG biofeedback can help individuals practice objectively contracting a selected group of muscles by observing the actual motor outcome [8]. The effectiveness of EMG biofeedback was shown in rehabilitation of stroke patients with severe arm impairments in order to normalize muscle tone, achieve normal active movement and aim for functional goals [9]. The audiovisual EMG biofeedback system was shown to improve hand functions in group of hemiparetic stroke patients [10], and haptic biofeedback was also successfully benchmarked in a long-run home rehabilitation study of children with cerebral palsy [11].

Heart rate is another informative bio-signal to be considered in the home rehabilitation setting. Heart rate has been used to estimate total energy consumption [12-14], classify physical activity intensity [13], and detect and prevent fatigue and overtraining [12, 14]. Heartbeat is a consequence of heart muscle depolarization triggered by autonomous nervous system that can be perceived using wireless transducers.

The common medium to televise the physiological data to the subject is traditionally based on specific platforms such as pre-programmed liquid crystal display or lights. However, using a conventional smartphone platform can reduce the final manufacturing cost as well as the total device weight. The worldwide smartphone sale's prediction shows a sharp positive trend in the near future [15]. Smartphone can be considered as a cost-effective portable audiovisual medium which have the added advantage of being personally and socially linked with people [16]. Other advantages of the smartphone are internet access, text and picture messaging, keyboard and options for touch screen, universal serial bus (USB) and Bluetooth interfaces. Smartphone has low initial and maintenance cost, and user friendliness and application of this platform is growing rapidly in health care and monitoring as well [7].

In 2010, Rubisch et al. presented a novel cell phone based heart rate biofeedback system to regulate the subject's pace of workout [17]. The error from targeted heart rate was converted into the opposite musical tempo that was played by the phone during endurance running. For the purpose of cardiac rehabilitation at home, a portable measurement system and interactive phone software, Tunewalk, was developed in a cell phone platform [18]. The system was equipped with self-adhesive electrocardiography (ECG) electrodes to record cardiac activity and accelerometers to estimate workout. Fusing the ECG and accelerometers data, the mobile application performed the analysis of physical activity and gave guidance to the patient during home exercise. The application also stored long-term information regarding the progress of rehabilitation program.

To enhance the systems' ease of use in the non-medical environments and avoid bio-sensors' obtrusiveness, numerous studies have been conducted on developing wearable sensor technologies [19]. Accordingly, smart sensorized textiles have been introduced to detect physiological variables such as heart rate, blood pressure and respiration [19-21]. The LifeShirt system is a vest with embedded sensors in the fabric that was used to monitor respiratory, heart rate and physical activity [20]. The Smart Shirt was made of washable fibers with built-in electrical fibers to detect body temperature and respiration rate. This undergarment, with electronic circuit, can wirelessly transmit the data to the assigned destination [21].

In this paper we present the design and concept validation of a smart shirt, called SQUID, equipped with smartphone application and an online database. The smart shirt incorporates a six-channel EMG and heart rate data acquisition circuit and delivers effective haptic and audiovisual biofeedback to the user. The design objective was to enable the patient, by wearing an unobtrusive smart shirt, to monitor the rehabilitation exercise based on the delivered real-time biofeedback. The collected physiological data were also stored in a pre-allotted online database for the purpose of personal monitoring and distant therapist's supervision. The hardware components and recruited interfaces are explained. The system functionality was tested on a single healthy subject during improperly performed exercise, and the acquired results are discussed.

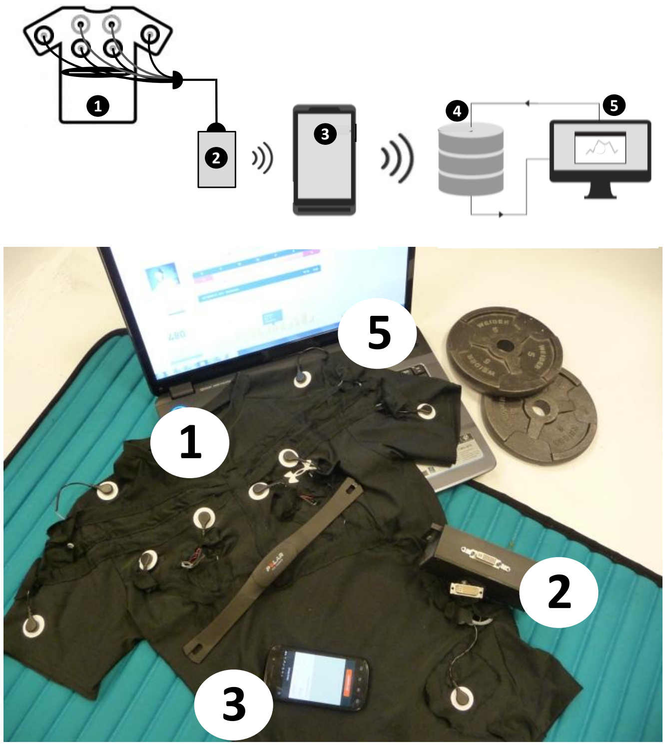

Fig. 1. Schematic and physical components of SQUID system. 1- Smart shirt that integrates 6 vibration motors; and wiring and interface for 13 surface EMG electrodes; and a wireless heart rate detector/transmitter on the torso, 2- Electronic housing which homes electronic amplifiers and data acquisition circuit, 3- Smartphone, 4- Online database, 5- Personal computer.

II. System Description

Figure 1 illustrates the physical components of the SQUID system and Fig. 2 shows the actual usage during representative weight lifting exercise. The system acquires the muscle activity and heart rate data and delivers the audiovisual and haptic biofeedback to the user via two independent mediums:

- A smartphone graphical user interface (GUI),
- Vibration motors.

Each interface was employed to convey a different concept to the user. The EMG and heart rate data are also stored in an online database for more elaborate evaluations. The design and specifications of the underlying hardware elements and software components are presented.

A. Hardware

The physical components of the system during each exercise are composed of surface EMG (sEMG) electrodes, the wireless heart rate sensor, the sensorized shirt and smartphone application. The acquired data are also transmitted to a virtual online address. The smart shirt integrates a compression shirt with specific holes and wirings for sEMG electrodes, vibration motors, and wireless heart rate sensor. Embedded wirings and electrode sites were especially designed on a compression shirt to facilitate the donning procedure. The electronic housing hosts the circuit to acquire sEMGs and heart rate data and triggers the desired haptic or audiovisual biofeedback via vibration motors and smartphone application respectively.

Fig. 2. Healthy human subjects wearing the sensorized shirt during weight lifting exercises.

The upper body including arms, chest, back and shoulders was the area of focus for the rehabilitation exercise in this study. To facilitate the ease of use and enhance unobtrusiveness, a compression shirt (Under Armour compression) was customized, depicted in Figs. 1-2. The Pectorals, Deltoids and the Latissimus Dorsi muscles were selected due to their dominant activity in variety of exercise. To ensure proper replacement of the EMG sensors, small holes were created in the compression shirt. The holes expedite the process of replacing and removing the surface electrodes prior and subsequent to the exercise. Surface electromyography is the differential voltage measured across two surface electrodes placed on muscles at skin level. Accordingly 13 holes (fold up flaps) were created on top of the selected muscles and the snap leads were fitted into each flap, so that the shirt appeared to be one solid piece. Twelve self-adhesive solid gel electrodes (Vermed A10050-60) were placed on the muscles and 1 reference electrode was also incorporated, to reject the offset voltage produced by the skin-electrode resistance. Snap leads (Vermed VMB20900-24-BLK) were used to provide robust secured electrical connection to the electrodes especially during demanding dynamic tasks. The leads were long enough to cover the variability in the muscle size and shape across different subjects so as to efficiently collect the targeted sEMG data. Conducting wires were attached to the inside of the garments to carry the sEMG signals from the sensors to the electronic housing. A fabric path was sewed on top of the wires and they were connected to the electronic housing via a digital visual interface (DVI) connector.

The wireless ECG strap (Polar OEM T31 transmitter) was used to detect and transmit the heartbeat activity. The complementary RF receiver (Polar RE07) was integrated into the electronic housing to receive the heartbeat data. Two pockets were designed on the internal layer of the compression shirt to home the heart rate detector/transmitter around the user's upper torso.

The common type of biofeedback is usually auditory (beeping) or visual (LED indicators or graphs on monitors). These forms of feedback can be potentially distracting to the people nearby (audio) or require the full attention from the patient (visual). In this study the vibration motor (Sparkfun Electronics ROB-08449) was implemented to provide the haptic feedback, in addition to the audiovisual smartphone-based biofeedback. Accordingly 6 vibration motors were sited inside the enclosed pockets on the shirt, in close proximity of each targeted muscle. The vibrators were activated if the peak EMG activity declined below the assigned threshold of the registered maximum voluntary contraction (MVC).

For each channel, the raw EMG data were filtered (f_L = 100 Hz and f_H = 2 Hz), amplified (G = 150-15,000) and rectified using a single muscle sensor (Advancer Technologies-v2). The adjustable gains in the circuit were useful for adapting the system to a different user or changing the targeted muscle. The stream of analog data from the muscle sensors were acquired by the 10-bit built-in analog to digital convertor (ADC) in ATMEGA 168 microcontroller (Mini Arduino Pro). The ECG data were also received by the microcontroller and the heart rate was computed in beats per minute (bpm). During the repetitive exercise such as disc lifting, the number of repetitions (REPS) was calculated by counting the number of EMG peaks. The heart rate, EMG and repetitions were wirelessly transmitted, at every 10 msec, to the smartphone application via Bluetooth interface (Bluetooth module RN-42).

The system operates on three 9-volt alkaline batteries (Duracell-MN1604). The muscle sensors, heart rate RF receiver, Arduino microcontroller, Bluetooth module and batteries are all enclosed in the electronic housing (15.2 cm × 8.2 cm × 4.1 cm), Figs. 1-2. The total weight of the electronic housing (with internal circuits and batteries) is 0.375 kg. The box was built by rapid prototyping (fused deposition modeling) and the two slots at the ends can be used to strap the box to the subject's belt.

B. Smartphone Interface

The smartphone application provides the audiovisual biofeedback to the user with respect to the workout phase. It also stores the data from the smart shirt and sends them to the website manager at the end of each trial. Repetitions (REPS) correspond to the number of repeats of a single cycle (muscle loading and unloading) of the prescribed exercise. Prior to the exercise, a summary of the session is displayed on the phone, e.g. the weights and number of repetitions. The smartphone application then calibrates the EMG sensors if needed and establishes a connection via Bluetooth to the smart shirt. During exercise the real-time heart rate, repetitions and elapsed time are presented to the user, Fig. 3. At the end of each trial the workout summary is displayed, i.e. maximum intensity of each involved muscle, averaged workout, number of repetitions, symmetry of the muscle groups and heart rate.

During the exercise, if the EMG amplitude drops below the specified adjustable threshold, a short period haptic feedback (250 msec) in addition to audiovisual biofeedback will be triggered. This is to warn the user in case of under-using specific group of muscles which has numerous practical applications in physical therapy.

At the end of each trial, the workout variables (EMGs, heart rate and repetitions) will be sent to the website manager, Fig. 4, located on the Northeastern University server, via a Wi-Fi connection. So the patient and physician have access to the EMGs and heart rate data across different muscles throughout the practice. The website is composed of 3 main pages. On the homepage, patient can enter his/her personal information, i.e. age, weight, gender and height, and create an account. On the workout page, all exercise data that was collected over time is stored to provide the possibility for browsing and objective evaluation of the performed practice, e.g. better understanding the progression of the occurred fatigue. On the goals page, users can create or see the prescribed or programmed goals. Upon completion of these goals a reward system will be activated to provide motivation to the patient.

Fig. 3. Exemplary snapshot of smartphone application during workout.

Fig. 4. The online database to store individual's long-run data.

III. Preliminary Results and Discussion

The purpose of physical therapy is to improve motor functions after an accident or event. Subjects are usually prescribed long-term rehabilitation, in an incremental procedure, to practice in the in-person therapy at a rehabilitation center or hospital. SQUID provides the ability to work and focus on specific muscle targets and improve their strength in the distant setting at home while still under a practitioner's supervision.

In order to assess, in a preliminary pilot study, the functionality of the smart shirt and smartphone application interface, a benchmark exercise to recruit four group of muscles was designed. A single healthy subject was recruited to perform the alternating chest fly exercise, as shown in the top row Fig. 5. The subject was instructed to lie on the ground with both arms fully extended perpendicular to his body, keeping a 5 lbs disc in each hand. The task was to fly the discs with left and right arms alternatively, so as to exercise the arms independently. Each fly comprised of lifting the disc from the ground level over the chest and return it back to the rest position, on the ground, within a specified time period.

Evidently, the subject could fly the discs using the elbow-joint locked or flexed and hence perform the same task following two different strategies. Although both strategies achieve the same goal, they are recruiting different group of muscles by utilizing the multiple degrees of freedom in the musculoskeletal system. This can happen involuntarily when one muscle group is overloaded and the other muscles automatically try to compensate. This is a critical issue from the rehabilitation perspectives, since the targeted muscles might not be recruited according to the therapist's desired prescription. This fact was utilized in amending the chest fly experiment to investigate the practical application of the biofeedback system. Accordingly, the elbow-locked (EL) strategy was prescribed as the default procedure to exercise both arms. The subject was told to intentionally follow the elbow-flexed (EF) strategy in the left arm at some random periods throughout the trial. The subject was instructed to perform the EF strategy for minimum two consecutive trials and notice the observable audiovisual warnings. After receiving the expected biofeedback warnings, the subject was allowed to correct his movement back to the EL strategy.

In order to better instruct and track the EMG activity, two different audio cues, low and high pitch, were played to signal the left and right arm movements. The audio cues were collected in the same data file as workout variables. The subject was instructed to synchronize his movements, i.e. left/right disc fly, with the respective audio cues. The time interval between consecutive cues was 2.5 sec, in which the subject was supposed to initiate and complete each fly.

Six pairs of self-adhesive electrodes were connected to the muscles in the arm and chest areas: left and right Pectorals (L-P, R-P), left and right Deltoids (L-D, R-D) and left and right Latissimus Dorsi (L-L, R-L), top row in Figure 5. Surface EMG electrodes were placed symmetrically on the left and right side of the subject's upper body. The reference electrode was placed on the subject's hip to reject the constant voltage offset. The subject wore the shirt and the heart rate transmitter was placed inside the shirt layer. EMG, heart rate and audio cues were collected simultaneously and they were stored in the smartphone application as well as the online database.

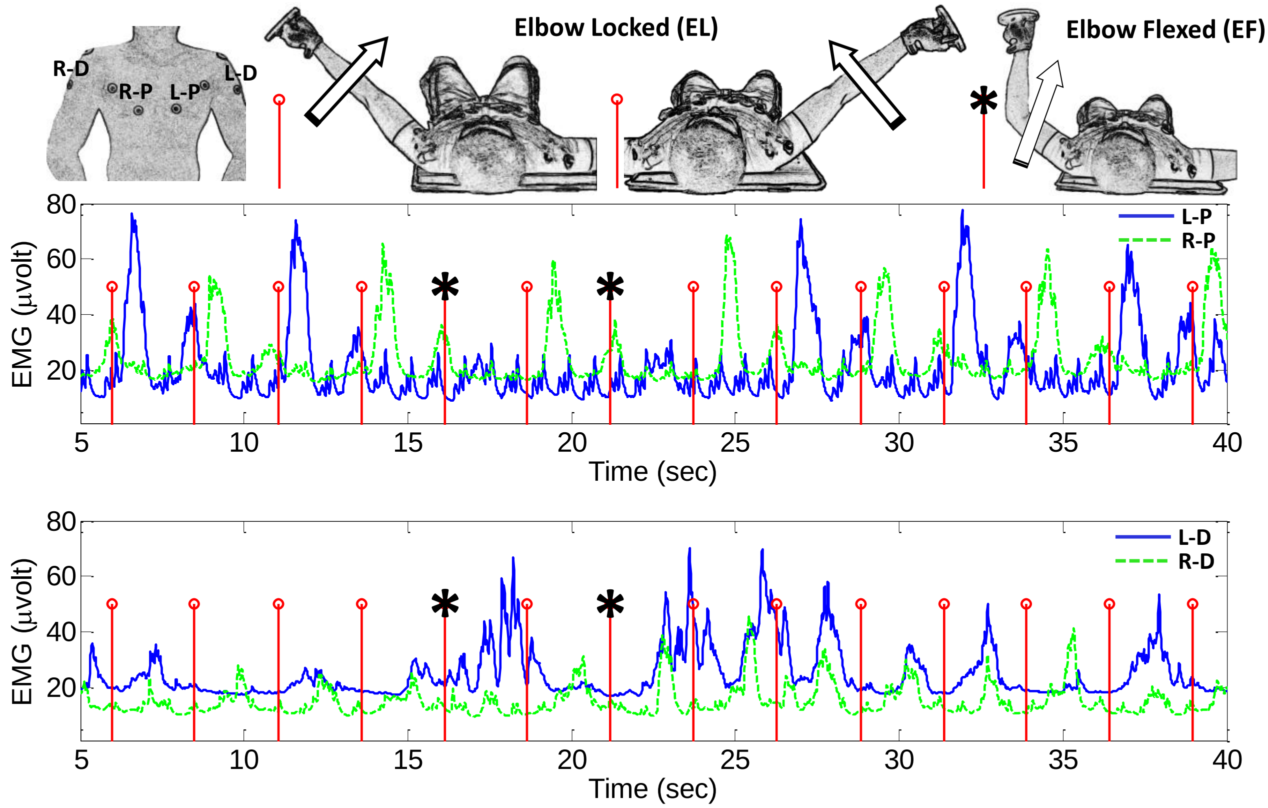

Fig. 5. Muscle activity during alternating chest fly exercise on the ground. Top row; four channels of surface EMG electrodes as placed on the targeted muscles and subject's perspective, lying on the ground, during elbow-locked (EL), or elbow-flexed (EF) chest fly with left or right arm; the arrows indicate movement direction. Middle row; EMG amplitudes of the left Pectoral (L-P) and right Pectoral (R-P). Bottom row; EMG amplitudes of the right Deltoid (R-D) and left Deltoid (L-D). The periodic (2.5 sec) vertical lines indicate the audio cues to signal left and right chest fly. The "*"indicates the flies in which the left arm has adopted the improper EF strategy to perform the exercise. The disc weight was 5 lbs.

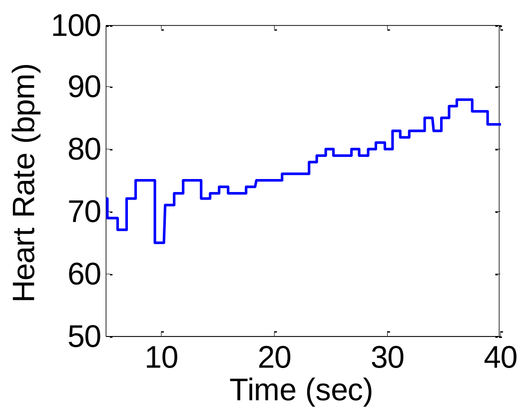

Fig. 6. Heart rate (bpm) during alternating chest fly exercise on the ground.

The EMG amplitudes associated with MVC were recorded in the beginning of the experiment, and the audiovisual warning threshold was set to 50% of MVC. The EMG channels were adjusted according to the corresponding pre-applied gain (*G*).

The heart rate data is shown in Fig. 6. Accordingly the subject had an average 75 bpm which is normal during exercise. The data shows a rising trend, which is expected throughout exercise. In case of abnormal patterns in the heart rate, a preventive biofeedback can be delivered to the individual so as to cease the ongoing exercise or relay an alarm message to the caregiver at the clinic.

Figure 5, middle and bottom rows, shows the EMG activity of the chest and elbow muscles (L-P, R-P and L-D, R-D). The last two channels on the back muscles (L-L, R-L) are not shown due to lack of significant change in EMG amplitudes. The EMG activities are synchronized with audio cue signal (periodic vertical lines), i.e. the subject is flying the left and right discs (each for 2.5 sec) alternatively. While the right hand is following the EL strategy throughout the trial, the left hand shows a sequence of two EL flies followed by a randomly performed two EF flies (indicated by *). In the prescribed EL flies both left and right Pectorals show significantly high EMG amplitudes and due to the less workload on the Deltoids, they show less but still significant amplitudes. The result of changing the strategy from EL to EF is evidently reflected in the left Pectoral and Deltoid. While the left Pectoral shows close to baseline activity, left Deltoid shows significantly higher amplitudes, which is due to higher workload on the Deltoid during EF strategy. Subsequently the loud enough audiovisual warning was fed back to the subject. After receiving two consecutive warnings, subject transiently corrected his movements back to EL strategy, which is exhibited as a trend toward higher left Pectoral and lower Deltoid EMG similar to the beginning of the trial.

IV. Conclusion and Future Works

A new technological adjunct to provide further automation and facilitate home rehabilitation was introduced. SQUID is an unobtrusive smart shirt that integrates EMG and heart rate data to create an objective biofeedback so as to guide the user to follow the correct procedure as prescribed by the physical therapist. Workout variables are wirelessly transmitted to the smartphone application and simultaneously stored in an online database to enable therapist's remote supervision.

Recruiting a single healthy subject, a proof of concept benchmark exercise was investigated. The effectiveness of audiovisual EMG biofeedback to correct erroneous exercise strategy was shown experimentally. SQUID can be used to target and quantify the activity of particular group of muscles. The heart rate data can also be used as an augmented measure in the home rehabilitation framework so as to have more preventive supervision on the patient. Accordingly the system has the potential to be used in a set of physical therapy activities that are rooted in defined intensity or coordinated activity of group of muscles.

In the future work, the design of an undergarment for monitoring the muscle activity in lower extremity will be investigated. The wireless EMG sensors can enhance the system's ease of use and robustness. The presence of a high performance microcontroller offers the prospect of hosting advanced real-time signal processing algorithms. This can be utilized in the applications such as fatigue detection, which is a common cause of injury and early frustrations. The smartphone application will be further developed to provide exercise directions to the user, such as a virtual trainer. The economical cost of the system can lead to the introduction of SQUID as an adjunct for everyday gym exercise of healthy individuals to monitor exercise effectiveness.

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