Movement, Health & Exercise, 7(1), 15-25, 2018

DEVELOPMENT OF WEARABLE ELECTROMYOGRAM FOR THE PHYSICAL FATIGUE DETECTION DURING AEROBIC ACTIVITY

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(Received 29 December 2017; accepted 8 January 2018; published online 29 January 2018)

To cite this article: *Ahmad, Z., Jamaludin, M. N., & Omar, A. H. (2018). Development of wearable electromyogram for the physical fatigue detection during aerobic activity. Movement, Health & Exercise, 7(1), 15-25.* http://dx.doi.org/10.15282/mohe.v7i1.225
Link to this article: http://dx.doi.org/10.15282/mohe.v7i1.225

Abstract

Physical fatigue or muscle fatigue is a common problem that affects people who are vigorously involved in activities that require endurance movements. It becomes more complicated to measure the fatigue level when the dynamic motion of the activity is included. Therefore, this paper aims to develop a wearable device that can be used for monitoring physical fatigue condition during aerobic exercise. A 10-bit analog to digital converter (ADC) micro-controller board was used to process the data sensed by Ag/AgCl electrodes and real-time transmitted to the computer through Bluetooth's technology. The wearable was attached to the knee and connected to the biopotential electrodes for sensing the muscle movement and convert it into the electrical signal. The signal then processed by using the fourth-order Butterworth filter to filter the low-pass filter frequency and eliminate the noise signal. The results reveal that the fatigue level increased gradually based on the rating of perceived exertion (RPE), using 10-point Borg's scale, which is rated by the subject's feeling. Both muscle's activities in lower limb rise as speed is increased, and it was also observed that the rectus femoris is functioning more than gastrocnemius due to the size of muscle fiber. Furthermore, it was established that the maximum volumetric contraction (MVC) could be used as a reference and indicator for measuring the percentage of contraction in pre-fatigue but not to fatigue induced experiment. However, this wearable device for EMG is promising to measure the muscle signal in the dynamic motion of movement. Consequently, this device is beneficial for a coach to monitor their athlete's level of exhaustion to be not over-exercise, which also can prevent severe injury.

Keywords: Physical fatigue, exercise, wearable device, EMG.

Introduction

Most sports-race related activities such as marathon, cycling, and long-distance running require vigorous and repeating movement of the body limbs to win the games. The determination of the winner of such competitions is based on the endurance capability of the athletes. This type of sport categorizes as an aerobic activity which depends on the fitness and competency of the athlete to sustain their energy to the end. Monitoring of the muscle fatigue during dynamic movement is one of the biggest challenges in wearable devices. It requires the persistent reliability of the device to detect any type of movement. In addition, a wearable device to detect physical fatigue solely based on the heart rate, such as Polar Heart Rate does not represent the muscle fatigue level explicitly.

One of the methods to measure the activity of the musculoskeletal system during sports activity is by using the surface electromyogram (sEMG) signal. sEMG is a measurement of muscle response or electrical activity in response to a nerve's stimulation to the muscle (Elamvazuthi et al., 2015). It is widely used in the clinical (Hawkes et al., 2015), rehabilitation (Elamvazuthi et al., 2015), ergonomics (Jia & Nussbaum, 2016) and sports applications (Taha et al., 2017; Wang, Hong, & Li, 2014). Most of the sEMG used in the previous research are from commercial sensor systems such as Shimmer (Ahmad et al., 2014; Taha et al., 2017), Step 32 (Di Nardo et al., 2016), and Noraxon TeleMyo (Noraxon USA Inc., Scottsdale, USA) (Sterzing, Frommhold, & Rosenbaum, 2016). Nevertheless, this sEMG device is possible to be developed to allow for customization of the algorithm used (Ganesan, Gobee, & Durairajah, 2015). It is interesting to note that such customized wearable device is capable of detecting and predicting fatigue to up to 90% accuracy (Al-Mulla, Sepulveda, & Colley, 2011). The decrease of the EMG amplitude signifies that the muscle is in the fatigue condition for an isometric contraction activity (Ahmad, Najeb, Amir, & Hafidz, 2017).

There are several existing methods that could be employed to process the sEMG raw data. Some of the conventional methods used are wavelet analysis, time-frequency approach, auto-regressive model, and artificial intelligence (Raez et al., 2006; Al-Mulla et al., 2011; Camic, Kovacs, VanDusseldorp, Hill, & Enquist, 2017; Montgomery, Abt, Dobson, Smith, & Ditroilo, 2016). It is worth noting that the aforementioned methods are suitable for offline measurement of the EMG owing to the ease of data manipulation as well as low-computing power. Other researchers (Ahmad & Mong, 2016), have also attempted in online or real-time data processing method via Processing software and immediately plot the EMG signal graph on the computer. Therefore, the purpose of this study is to develop a wearable electromyogram device to measure the level of muscle fatigue of an athlete during aerobic sports activity.

Methodology

Wearable Device Development

Electromyogram (EMG) is an electrical signal that amplifies the physical movement. It has two-stage amplifiers of the bio-amplifier in between two integrated circuits (IC) op-amp with a high-pass filter, which removes any DC generated noise from the electrodes. For the first stage (refer Figure 1), it amplifies by an instrumented amplifier (INA126), and the second stage is a standard non-inverting op-amp (OPA347). To sense the muscle activity, wet electrodes of Ag/AgCl with the 5cm diameter were connected through an electrode jack. The output signal of the second stage was read by the 10-bit micro-controller in analog to digital converter (ADC) and powered by 3.3 V operational voltage. The micro-controller will stack up on the female header of EMG for easy maintenance and programming processes. The obtained data were transmitted to the computer by HC-05 (Bluetooth module) wirelessly.

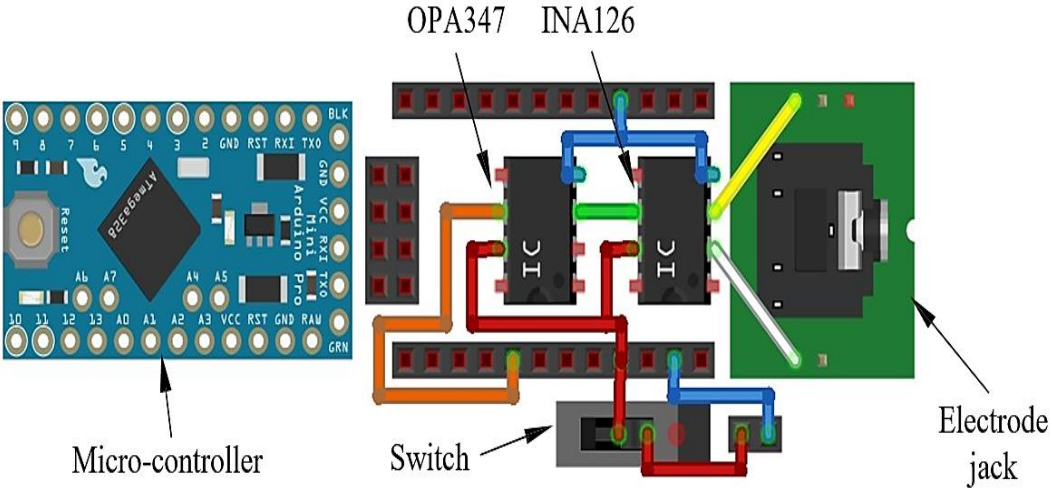


Figure 1: Main components circuit (excluded resistor and capacitors)

Since the measurement of EMG was selected on the rectus femoris (thigh) and gastrocnemius (calf) muscles, therefore, this wearable device was attached near to the knee. This is to ensure the distance between both electrodes are not far from the main board (as shown in Figure 2). When the subject was performed the treadmill running, this device can operate as an independent device by setting the maximum value of contraction for the buzzer and vibrator to give an alarm to the user. In the data-storage implementation, this device applicable to send the signal directly to the computer or just keep in the SD card for offline processing.

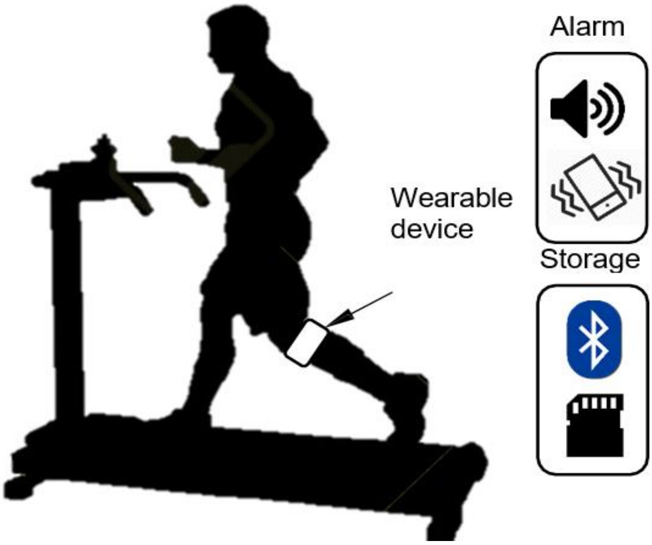


Figure 2: Location of the wearable device on the knee

Subjects

Three male volunteers participated in this study after briefed extensively on the protocol and method to achieve the objectives of this study. The physical characteristics are presented in the format of (mean ± SD): Age (31.7 ± 1.2) years, body mass (70.7 ± 4.2) kg, height (169.3 ± 2.1) cm and BMI (24.6 ± 0.9). These volunteers were from the Sports Innovation and Technology Group, Faculty of Biosciences and Medical Engineering, UTM, Malaysia. All of them were completed a health history questionnaire and signed a written informed consent prior to testing.

Protocol

This protocol was designed for the pre-fatigue, and fatigue induced condition as shown in Figure 3. Prior to the commencement of the experiment, wet electrodes were attached to the selected lower limb muscles, i.e., rectus femoris (RF) and gastrocnemius lateralis (GL). Interelectrode distance is about 5 cm from each location with is targeted on the muscle belly in order to obtain the maximum active muscle contraction.

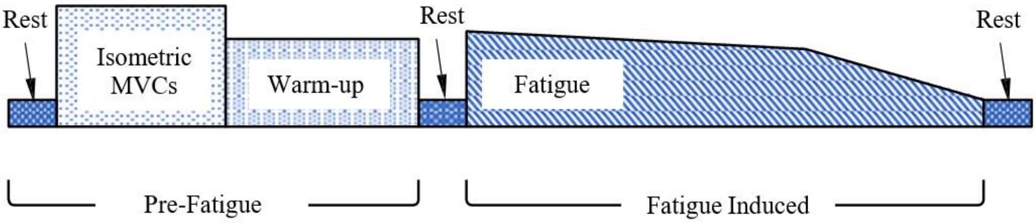


Figure 3: Schematic of the experimental protocol.

Pre-Fatigue

The experiment began by acquiring the required vital sign parameters such as blood pressure, heart rate, and body temperature were measured in three positions of this protocol (pre, warm-up and post). This is to investigate the effectiveness of physical activities to the body's physiology. Then, isometric of maximum volumetric contraction (MVC) for Gastrocnemii: subjects were instructed to stand on toe-tips and maximally contract their shank muscle; while for the Quadriceps: sat on a chair with their hips flexed to 90˚ and their knee fully extended, they need to resist a force being applied downwards (Ghazwan, Forrest, Holt, & Whatling, 2017). The procedure was repeated three times for 5 seconds contraction and 2-second interval. The maximum contraction of the voltage was recorded as a relative indicator of the fatigue induced signals. After that, the subject was asked to stand on the treadmill to prepare for 5 minutes walking warm-up with 4 km/h speed. At the same time, the EMG signals are recorded as well the muscle activities during warm-up.

Fatigue Induced Protocol

Before the fatigue induced experiment was taken place, the vital sign parameters were measured again to indicate the effect of warm-up towards the physiology of the body. This session takes less than 2 minutes to complete with three times measurement. Firstly, the treadmill speed was set as a warm-up position to make subject used with that acceleration. After 2 minutes, the speed was increased by 1 km/h. The RPE method is used in the experiment, and the subject rates their level of fatigue. The protocol will be stopped when achieved one of the following criteria: 1) exceeds the maximum heart rate; 2) after 30 minutes; and 3) volitional fatigue. The speed increment is maintained and retained at 12 km/h to prevent injury during running due to high-speed movement.

Signal Processing

Raw signals of EMG from the device were acquired to process for analyzing the muscle contraction during exercise. There are several steps to follow in order to get the clean signal. Figure 4 depicts the three steps employed by using MATLAB (version R2012a, Mathworks Inc.), the raw signals were band-pass filtered to remove the movement artefacts, by a bandwidth 10 – 500 Hz (Hassanlouei, Arendt-Nielsen, Kersting, & Falla, 2012; Montgomery et al., 2016). Prior to that, notch filter 50Hz was used to eliminate power line noise. Then, it was rectified by the absolute value of the signals into the positive side, and this method called "full wave rectification." The most important process is low-pass-filtered by a discrete version of a traditional low-pass filter such as Butterworth or Chebyshev. The 4th order of Butterworth filter is commonly used by researchers to capture and "envelope" the signal (Camic et al., 2017; Hsu et al., 2017; Montgomery et al., 2016).

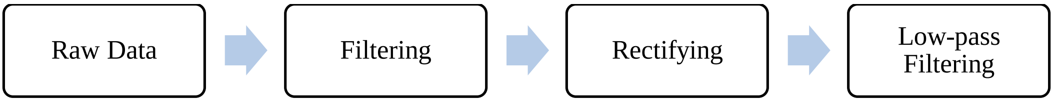
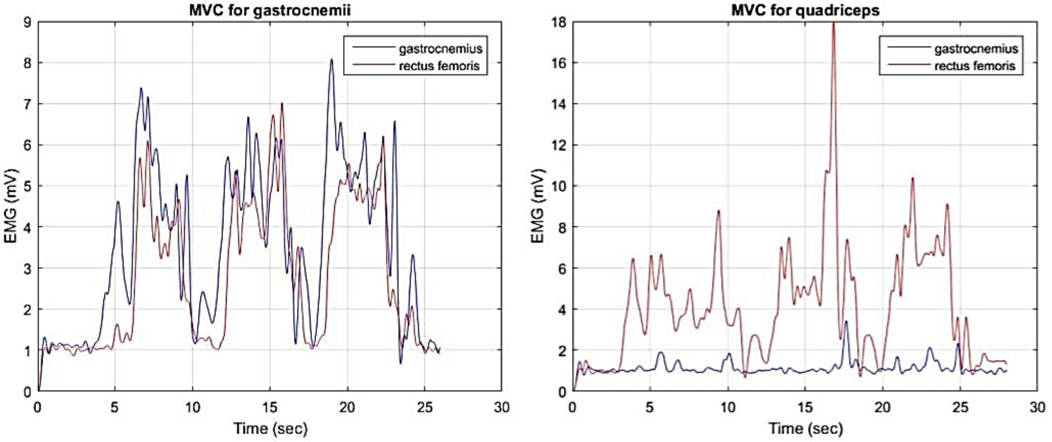


Figure 4: Schematic diagram of the signal processing

Results and Discussion



(a) (b)

Figure 5: MVC of muscles for (a) gastrocnemii and (b) quadriceps.

Two types of MVC are applied for the gastrocnemii and quadriceps muscles as indicated in Figure 5. The function of MVC is to determine the maximum contraction of specific muscle by different activity provided. Significantly, each MVC will produce the highest contraction compare with the others as illustrates in Figure

Figure 5(a) and Figure 5(b) illustrate the EMG signals for gastrocnemius and rectus femoris muscles, respectively. In addition, there are three times of contractions were performed to obtain the average value of MVC. Mean MVC for gastrocnemii is 7.3843 mV while for quadriceps is 12.4053 mV. There is a significant difference between both muscles as shown in Figure 5(b), it could be observed that there is no contraction for the gastrocnemius, whilst the femoris produced the greatest contraction in three attempts. It demonstrates that the subject performed the proper MVC procedure for the right selected muscle contraction in Figure 5(b) as compared to what he has done in Figure 5(a).

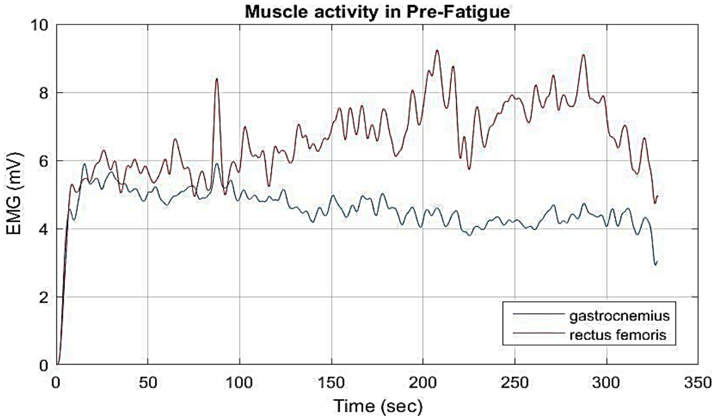


Figure 6: Muscle activation for gastrocnemius and rectus femoris during warm-up.

Figure 6 illustrates the muscle activity for 5 minutes warm-up walking on the treadmill with speed 4km/h. It was observed that the gastrocnemius muscle slightly decreased as the exercise time increased, and it is contrasted to the rectus femoris muscle. This is due to the walking pattern that is unique for each individual, and this can be proven via gait analysis. As compared to the MVC, the maximum contraction for gastrocnemius in pre-fatigue is near to 6 mV or can be calculated in percent 81.25% MVC whereas for rectus femoris is approximate to 72.55% MVC. The dynamic force movement in pre-fatigue walking generates more muscle fiber to be active and produce the pattern for prediction in the fatigue induced protocol. Since this is a constant load with same walking speed, the changes of muscle activity slightly differ from the beginning of the exercise.

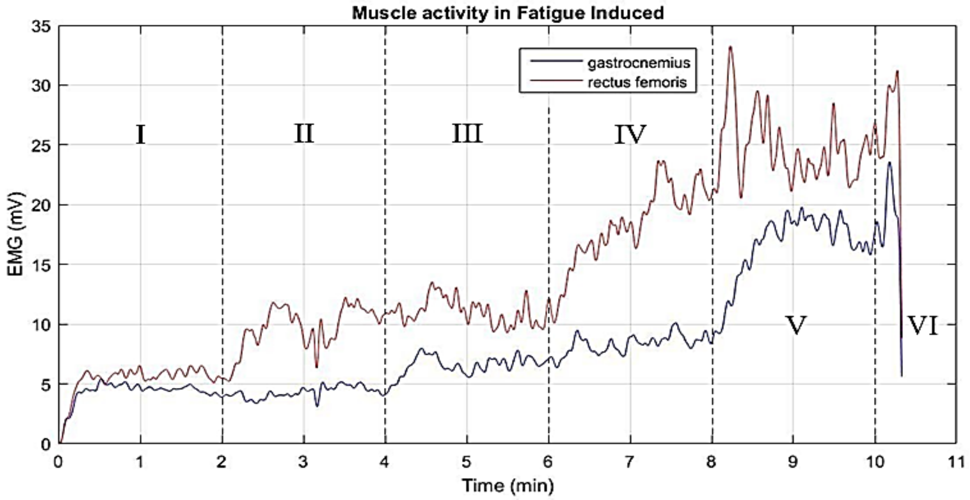


Figure 7: Comparison between muscles in the fatigue induced protocol.

Based on two selected muscles at the lower limb, Figure 7 indicates the muscle activity along the fatigue induced experiment. In general, both muscles show the same pattern of growth as speed increases, however, it is apparent that the rectus femoris is more active compared to the gastrocnemius. This is might be the size of muscle fiber in the thigh is bigger than the calf; therefore, the contraction in the quadriceps is stronger than gastrocnemius. Unfortunately, MVC value in the first place cannot be used in this fatigue induced protocol since this contraction is higher than MVC. This signifies the MVC performed in this study is only capable of comparing low-speed movement or static position exercise. When divided into six regions of stages, naturally the muscles were much activated at higher speed. It complies with Newton's 3rd Law of motion, which considers the action-reaction mechanism of force impact to the ground. This theory is referring to the ground reaction force (GRF) when the foot touched and contacted to the ground. The reaction force from GRF works as the normal force exerted from the ground is equal to the internal force that applied to bone and muscles. Hence, the increasing GRF is directly reflecting the high muscle activation to make the system to be in an equilibrium condition. For more details, those regions are extracted as an individual 10-second graph for gastrocnemius muscle are depicted in Figure 8.

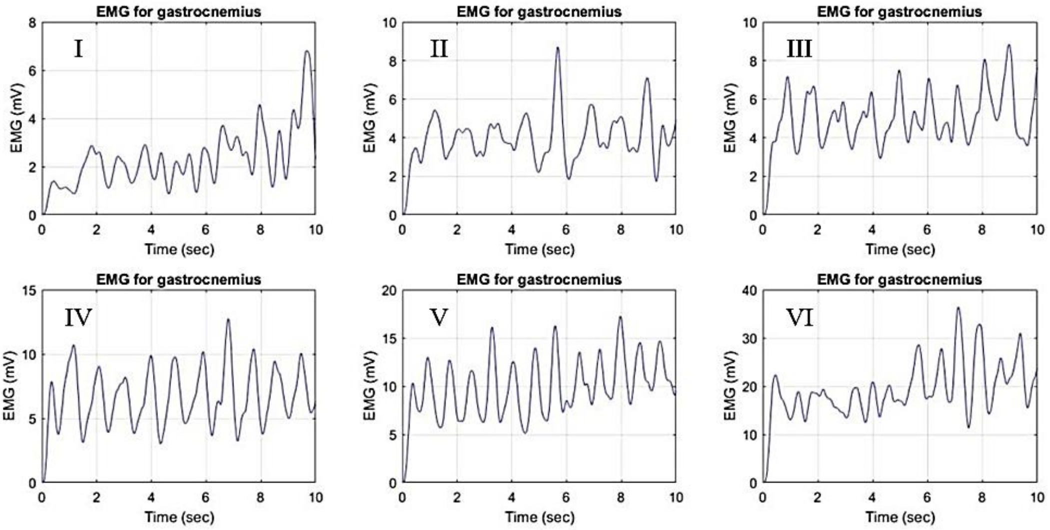


Figure 8: Specific region for gastrocnemius.

For the first three stages in Figure 8, the EMG fluctuated and gave the mean value 2.3182 mV, 3.9776 mV, and 4.9924 mV. In this stage, the subject was walking instead of running because the speed in stage III is 6 km/h and still could manage it. Nevertheless, stage IV and V consistently form the repeated cycle of contraction with an increasing mean value as 6.6621 mV and 9.8895 mV. Consequently, the transition-to-fatigue are visualized in the VI stage where the signal was interrupted by the movement artefact caused by fatigue. The shape of the signal oscillates without a pattern before the end the experiment at 10 minutes and 21 seconds.

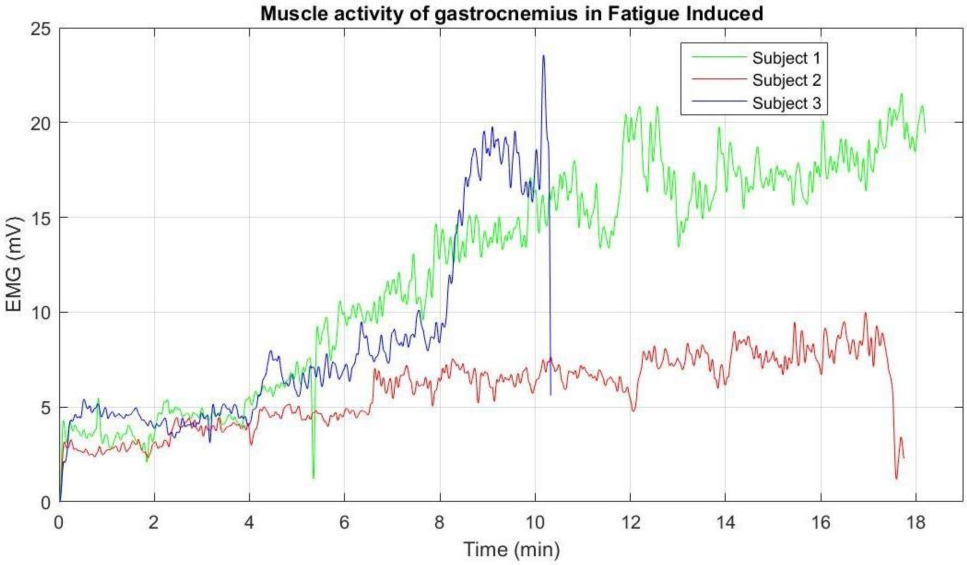


Figure 9: Comparison of gastrocnemius muscle in three subjects

The final results in this section (Figure 9) explored all the physical activities of each subject volunteered for this study for the fitness investigations through the fatigue induced protocol. It is focused on the gastrocnemius muscle alone for the parameter's comparison. It could be clearly seen that the muscle activity produces the same trend of the signal by increase steadily over time. From three volunteers, subject 3 had to stop the experiment earlier due to volitional fatigue while the rest continued to exceed 17 minutes. In this experiment, body fitness is closely related at the time of aerobic exercise can be sustained, and it is evident that the subject 1 and 2 has good fitness. On the other hand, muscle activity for subject 2 is lower compared with the others and might due to the method or position of the foot during running. Even so, the signal trend of EMG is still acceptable as it rises steadily until the experiment ends.

Conclusion

As the conclusion, the objective of this study is to develop a wearable device that can be used in measuring physical fatigue was achieved. This device is capable of monitoring the whole activity in fatigue protocol started from MVC and ended with volitional fatigue. The trend and pattern of the signal also indicate the consistency of this wearable device in determining the EMG.

Acknowledgment

This work was financially supported by the Universiti Teknologi Malaysia under the Research University Grant, Tier 2 (Q.J130000.2645.13J73) and Ministry of Higher-Education Malaysia.

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