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CONTRIBUTIONS OF ARM'S MAJOR MUSCLES DURING MANUAL WHEELCHAIR PROPULSION IN RANDOM SPEED BY HEALTHY PERSONS

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ABSTRACT

Propulsion of manual wheelchair demands physical strength of upper limb and users would be exposed to injuries and muscle fatigue for long-term. Therefore, power assist system operated on surface electromyography (sEMG) signal from arm muscles developed aggressively few years back. However, an important prerequisite for selecting which muscles as reference is to understand each muscles contribution during contact and recovery phases. The primary purpose of this study was to investigate motor unit action potentials (MUAP) for Biceps Brachii (BIC), Triceps Brachii (TRI), Extensor Carpi (EXT) and Flexor Carpi (FIX) muscle groups located in human arm during both phases. MUAPPEAK in every contact and recovery phases for each muscle groups were recorded from 13 subjects. Then, mean and standard deviation (SD) value determined. Result shows that the highest mean value belongs to Flexor Carpi muscle group 2.85V and highest standard deviation (SD) ±0.28V for Triceps Brachii. Mean value indicate which muscle contributed most to perform activities in contact and recovery phase, meanwhile SD is for propulsion speed. These finding would provide useful guidelines or suggestions for research related EMG-based interface instrumented wheelchair.

1. Introduction

Based on World Health survey, there are around 785 million people aged above 15 years with disabilities in 2010 population and 110 million with severe disabilities [1, 2]. Huge numbers of patient affect the cost for rehabilitation due to more physiotherapist must be hired. Few years back, automatic machine or robotic device for rehabilitation exercise has become popular among researchers to overcome the cost of rehabilitation and reducing burden of physiotherapist. In early stage, most of the rehabilitation assist devices are controlled by joystick or keyboard interface to operate it. Location of joystick or keyboard depends on the type of disabilities [3]. But now, bio-signals operated device has become choice by researchers.

Electrooculography(EOG), Electroencephalography (EEG), Electromyography(EMG) and Mechanomyography(MMG) are examples of bio-signals and widely used as indicator to control the rehabilitation devices. EOG signal is measured from electrical potential between front (cornea) and back (retina) based on movement human's eyes movement and these this technique has been implemented for extremely limited peripheral mobility conditions [4, 5]. For a totally paralyzed person, electric powered wheelchair (EPW) with EEG interface are the most suitable method to regain their independence by monitoring electrical potential generated by the brain[6, 7]. Even though lots of controls mode developed, but each of it has own disadvantages such as noise would affect the voice interface and slow processing time for vision based method. Joystick control is still the easiest to implement and no clear standard control yet that match the accuracy of it [8]. EMG and MMG signals are more preferable for control mode and used widely in hand prostheses, robotic arms and instrumented wheelchair [9-12]. There are much researches on EMG-based instrumented wheelchair control mode conducted and shown that it can be effective as an alternative especially for rehabilitation purpose [8].

The electrical potential of the motor unit (MU) that is obtained from muscle fibers during contraction called as motor unit action potential (MUAP) [13]. Motor Unit (MU) is the smallest functional unit of the muscle [14]. It's summation of actions potential happens at muscle fibers that is connected to the same MU in the uptake area of electrode [15]. Electrode's size, shape, configurations and inter-electrode distance are factors that has to consider because of it would affect quality of recorded MUAP [16]. MUAPs from different MUs tend to have different shapes, which remain almost the same for each discharge. Thus, MUAPs can be identified and tracked using pattern recognition techniques.

MUAP can be measured by EMG and MMG technique but EMG detects on electrical activity and MMG on mechanical vibration signal. These two (2) techniques have their advantages and disadvantages. EMG widely used all over the world and there are many guidance such as SENIAM guidelines to place the electrode sensor at the correct position on targeted muscles [17, 18]. Buchthal et al are among the earliest researchers that introducing quantitative EMG decomposition method where MUAPs were documented and analyzed

[19]. EMG signal is easier to analyze and the result is accepted worldwide [17, 20]. EMG signal collected from skin surface is called as surface EMG or known as sEMG. Compare to MMG, there is no such guidelines yet but study shows that it good in signal-to-noise ratio (SNR) and easy to place the sensors on skin [21-23]. MMG sensors contains of accelerometers, piezoelectric transducers, Laser Distance Sensors (LDS) and hydrophones that attached to skin without shaved and cleaned with alcohol first.

Possibility for sEMG signal to produce error during recording process is high because of single channel signal and the subjective measurement of the MUAP parameters of interest that lead to various problems for intelligent wheelchair researchers to make it perfectly working [24]. There are many methods developed by researchers such as transform sparsity principle [25], combination with another sensors [12, 26, 27] to reduce the misreading of the signal. But still the method is not perfect yet for control process. But the development of EMG interface instrumented wheelchair isn't completed yet to move all directions. University of Tokyo developed an instrumented wheelchair from manual wheelchair and focused on acceleration and deceleration phase for a smoother and safer movement [11, 28]. Additional of joystick to control the speed and sEMG signal from selected muscle to control directions based on user's desire [29, 30]. For a person with cerebral palsy, it is hard for them to do precise movement to control the joystick and if they are over pull it, it can cause harm to them [31].

The physical demand in propelling a manual wheelchair can be broadly classified into two phases. The first is contact phase and second is recovery phase [32]. Contact phase is when the user's hand holds the pushrim and push forward to move the wheelchair. The recovery phase is when the hand return to initial position before contact phase is started. In contact phase, MUAP is higher compare to recovery phase due to amount of force to push the wheelchair plus the weight of user. The objective of this study is to investigate the difference in terms of MUAPs between forward dynamics simulation of contact and recovery phase of wheelchair propulsion to observe arm's major muscles contributions during concentric and eccentric contraction in completing the task. This understanding has great impact on selecting appropriate reference muscles to develop sEMG interface wheelchair that able to differentiate between contact and recovery activities to activate the assistive system based on MUAP value.

2. Subjects And Methods

Evaluation was performed to collect MUAPPEAK from a population of Malaysian subjects. Each subject's details such as gender, age, height and weight are taken and recorded. Hand movement pattern was briefed in advanced to ensure subjects propel the same technique throughout the experiment. Subjects are prepared to place sEMG muscle sensors on targeted area to record MUAPPEAK in every phases. Data was acquired by Matlab software and stored locally for analysis purpose. In general, the five processes in this research are illustrated as a research work flow as in Figure 1. Every subject was required to perform at least three times of the routine at their own convenience as the data collection was held in the university laboratory.

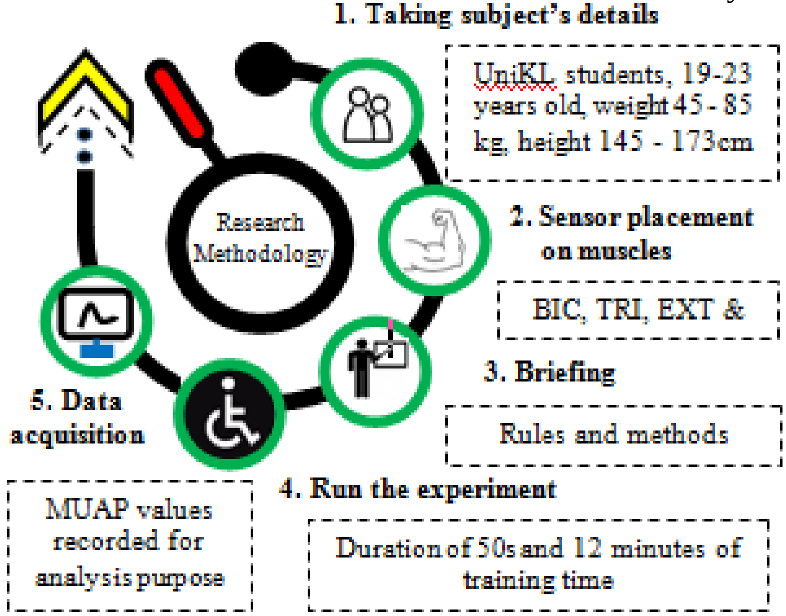

Figure 1. *Research work flow*

A. Subjects

Experimental data were collected at University Kuala Lumpur Malaysia France Institute campus by recruiting 13 able-bodied and healthy subjects who are inexperience to manual wheelchair propulsion and voluntarily participated in this experimental study. Exclusion criteria were any prior experience with manual wheelchair propulsion, intensive regular upper-body exercise or no known history of joint injuries or movement limitations.

All subjects were briefed about the nature of the study before giving voluntary written informed consent for the experimental trials, which was approved by the Institutional Review Board. All 13 subjects are university students with a mean ± SD age 21 ± 2 years, height ± SD 160 ± 15 cm, weight ± SD 65 ± 20 kg. 8 are males and 5 are females. Prior to the experiment, a practice session was given for 12 minutes which is minimum time for healthy person to increase the mechanical efficiency, work per push and reduce power losses [33-35]. Subject's handedness is not considered in this experiment. Subject details and average propulsion time shown in Table 1.

Table I *Subject Details and average propulsion duration*

Subject (Gender)	Age (years)	Height (cm)	Weight (kg)	Contact time (s)	Recovery time (s)
1 (M)	20	167	64	0.74	0.97
2 (M)	19	170	68	0.49	1.44
3 (M)	20	171	66	0.58	2.22
4 (M)	20	167	62	0.92	1.88
5 (F)	21	173	52	0.78	1.78
6 (F)	21	158	45	0.93	0.79
7 (M)	19	145	51	0.66	1.88
8 (M)	19	168	85	0.96	1.20
9 (F)	22	155	55	0.85	1.19
10 (F)	22	155	67	0.89	1.19
11 (F)	22	160	65	0.74	0.78
12 (M)	23	163	65	0.65	1.06
13 (M)	19	170	68	0.80	0.91

B. Experimental Design

Wheelchair propulsion consist of two phases, contact and recovery. Contact phase is where subject propelling forward from point A to B and recovery phase happens when they return their hands to point A. Point A and B is shown in Figure 2. Point A is where angle between shoulder-elbow-wrist is perpendicular and recovery phase is when the angle become 180° at point B and subject's fingers remain grasping the pushrim. In order to optimize the force transferred from user's arm to pushrim, the angle of shoulder-elbow-wrist must be at 90° [36, 37]. Subject's body is in straight position or called neutral for both phases. Neutral body position provide stability during moving forward and any changes of distance shoulder to pushrim due seating position change would affect the shoulder and elbow extension torque [38, 39].

Hand movement pattern is a propulsion technique for manual wheelchair. Figure 3(a) shows the hand movement pattern for contact phase called arc. Meanwhile there are 4 types of hand movement pattern for recovery phase namely arc, single loop, double loop and semi-circular pattern as in Figure 3(b) [40]. The arrows show direction of hand movement and wheelchair direction is to the right. During the contact phase, subject's hands is constrained to the pushrims from point A and point B. In recovery phase, hands moved to point A without touching the pushrim and regrasphandrim when reached to point A. Arc pattern implemented in this study due to amount of stress on the muscle is the highest [40].

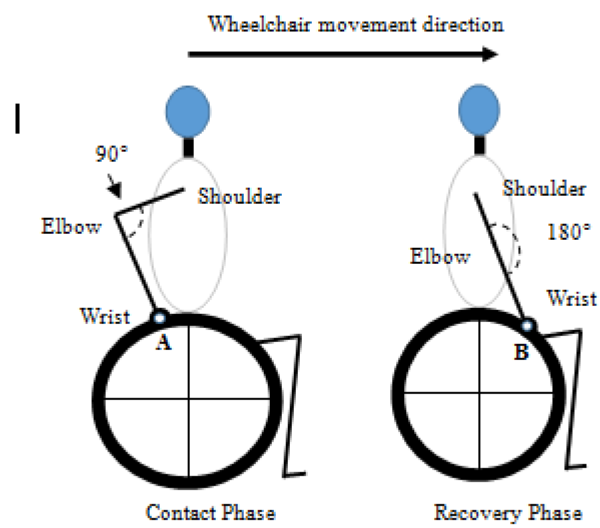

Figure 2. *Hand position in contact and recovery phase*

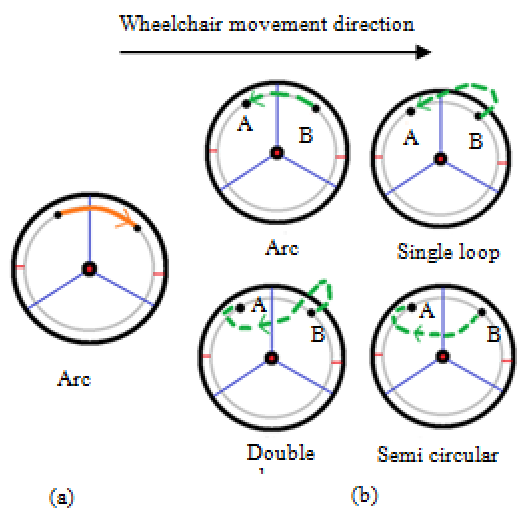

Figure 3. *Hand movement patterns for contact (a) and recovery (b) phase*

Experiment duration is 50s and consist of 5 phases of contact and recovery. MUAPPEAK determined in every phases and recorded for analysis purpose. Experiment timeline as in Figure 4. Adjacent windowing technique implemented for data segmentation to separate MUAP patterns in both phases as in Figure 5. This technique is where another windows started just after previous window ended, processing time (t) happens in the next window and decision (d) made at the end of it. It is suitable for low performance processor such as Arduino board [41]. A manual wheelchair without any modification are used and experiment done on ceramic tiles floor. Experiment conducted in this way to clearly differentiate MUAPs in contact and recovery phases.

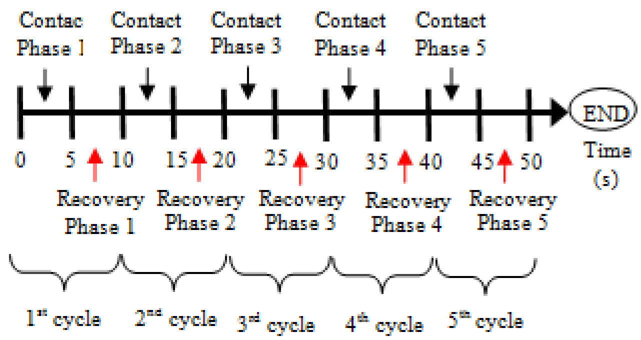

Figure 4. *Experiment timeline consists of 5 contact phase and 5 recovery phase*

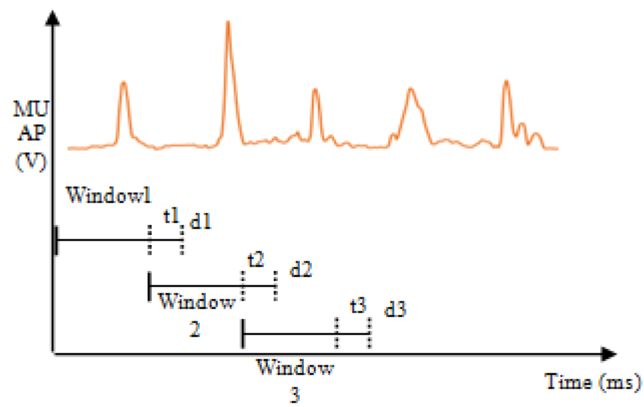

Figure 5. *Adjacent windowing technique*

Three dimensional model for upper extremity developed for all muscles and joints in hand in order to measure moments arm and maximum isometric joint moments during wheelchair propulsion [42]. Triceps Brachii contributed more forces during early contact phase and Biceps Brachii take the place when approaching end of contact phase [43]. Couple years later, study on relation on altering cadence, peak force and contact angle with upper extremity muscle power and stress has been conducted [44]. The result is Extensor and Flexor muscles are contributing the most in contact and recovery phase. Biceps Brachii, Triceps Brachii, Extensor and Flexor are major muscles in human arms that has smaller muscles located near to each other. Therefore, these muscles were selected and named to

Table II *Musculoskeletal Model*

Muscle	Origin	Insertion	Actions
BIC			
Biceps brachii, short head	Scapula	Radius	Flexes elbow
Biceps brachii, long head	Scapula	Radius	Flexes and abducts shoulder Supinates joint in the forearm
TRI			
Triceps brachii, long head	Scapula	Ulna	Extends forearm
Triceps brachii, lateral head	Humerus	Ulna	Arm adduction Extends shoulder
EXT			
Extensor carpi radialis longus	Humerus	2nd metacarpal 3rd metacarpal	Extend and abduct the wrist
Extensor carpi radialis brevis Extensor carpi ulnaris	Humerus	5th metacarpal	
Extensor digitorum	Humeral head Lateral epicondyle	Phalanges	
FIX			
Flexor carpi radialis	Humerus	2nd & 3rd metacarpal	Flexion and abduction at wrist
Flexor carpi ulnaris	Humerus	5th metacarpal	

BIC, TRI, EXT and FIX as in Table 2.

C. Data Collection

No data recorded in practice time. Data collection starts when subjects are ready to start the experiment and made sure that nothing disrupting and feel comfortable to propel the wheelchair. Maximum (MUAPPEAK) (x) for each phases determined after the phase ended. Meanwhile mean ($\bar{x}$), standard deviation (SD) (σ) were calculated after the experiment finished using Eq. (1) and Eq. (2). Sample size, N is 5 equal to number of cycles and sampling rate is 14 readings per seconds. Experiment on data collection flowchart as in Figure 6. Start with N=0, for the first 5s is for contact phase and all reading were recorded and for the next 5s is for recovery phase. MUAPPEAK determined after each phase ended and this routine repeated for 5 times until N = 5, then the experiment stopped.

$$\bar{x}=\Sigma x/N \qquad (1)$$

$$\sigma=\sqrt{1/N \; \Sigma(x-\bar{x})^2} \qquad (2)$$

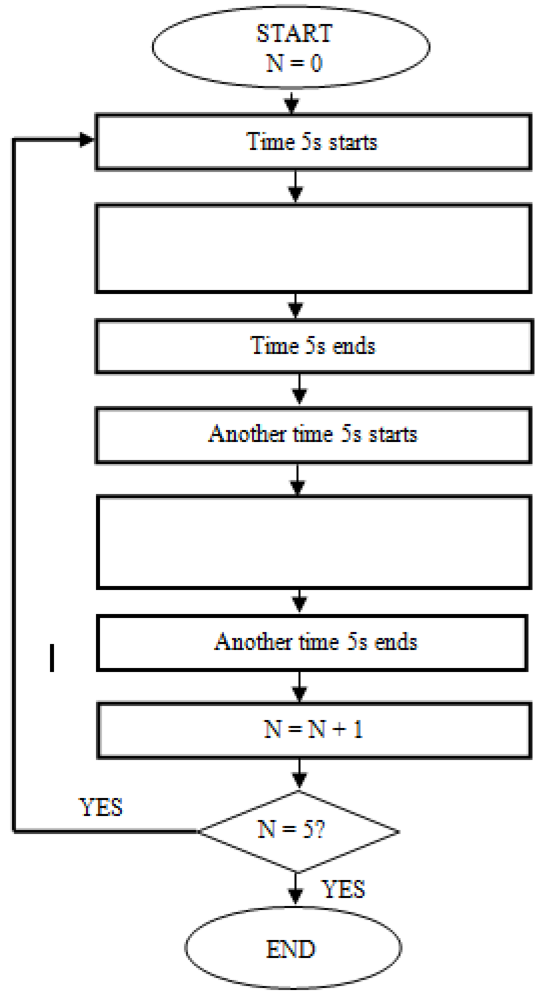

Figure 6. *Data collection flowchart*

3. Kinematics Data

In order to measure and record the potentials from the body, it is necessary to provide interface between body and potential measuring electronics apparatus as in Figure 7, 4 sEMGMyoware muscle sensors, Arduino board and Matlab software. There are three main components represent the main devices to perform all the task [45]. First, for data detection, Silver-Silver Chloride (Ag-AgCl) surface electrodes were used to detect changes in electrical potential on muscle. It is a gelled electrode that has a chemical (AgCl) interface between skin and metallic (Ag) for the current to move freely between electrolyte and electrode[46]. These surface electrodes are used in the EMG signal acquisition since they provide a stable transition with relatively low noise, low electrode–skin impedance [47, 48].
The changes will be converted and refined by amplifying and filtering process that is done by sensor processor board (Myoware muscle sensor (SEN-13723)). SEMG potential range is between 50µV to30 mV [49]. Second is Arduino board which would convert the signal into 1024-bit system where changes of

29µV MUAP is equal to 1bit. Then converted again in terms of 0 - 5V for 1 bit represent 4.8mV. Analog signal converted into digital signal done by Arduino board and transmit to third main component, a computer. A computer installed with Matlab (The Mathworks, Inc) software were used for displaying and storing locally the acquired data obtained from Arduino board.

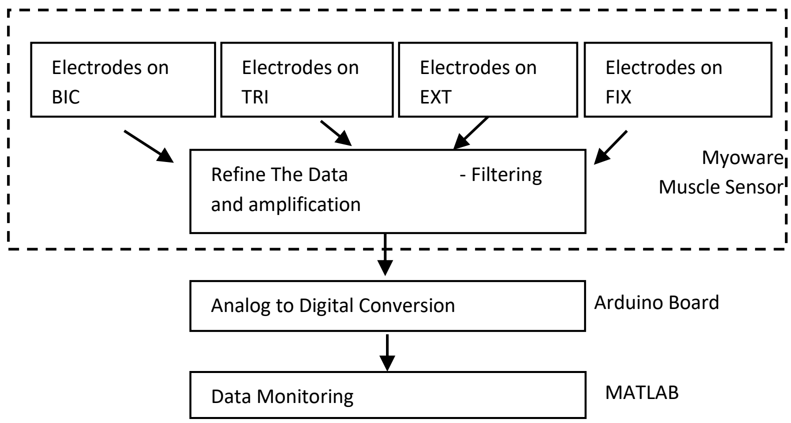

Figure 7. *SEMG data acquisition system*

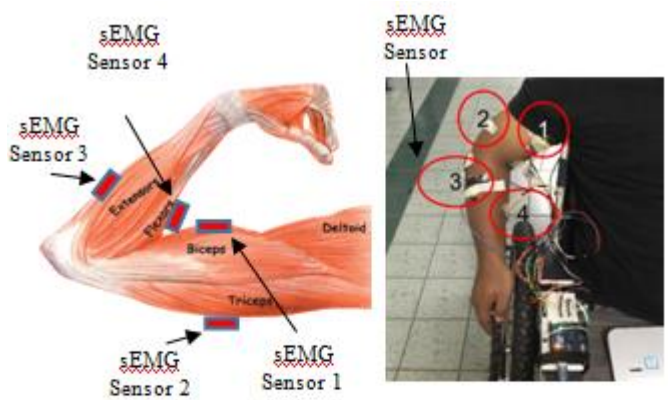

Figure 8. *Arm's major muscles and sEMG sensors placement*

BIC, TRI, EXT and FIX are chosen because of these 4 muscles group are major muscle in human's hands shown in Figure 8. Subject's skin was shaved and cleaned with alcohol before surface electrodes placed on each targeted muscle[50]. Placement on the location which area of the muscle is according to Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guideline and reference electrodes placed on electrically neutral muscle which is near to targeted muscle. Sensor 1 on BIC, Sensor 2 on TRI, Sensor 3 on EXT, Sensor 4 on FIX. Reference electrode for sensor 1 and 2 placed on Brachialis muscle and sensor 3 on Pronator Teres and sensor 4 on Supinator. The output will be between 0 - 5V and it will be indicator for power-assist system that will be installed later.

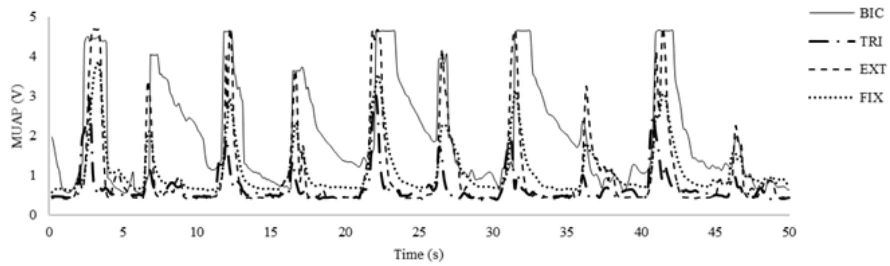

Figure 9. *MUAPs result in 5 cycles for 4 muscle groups*

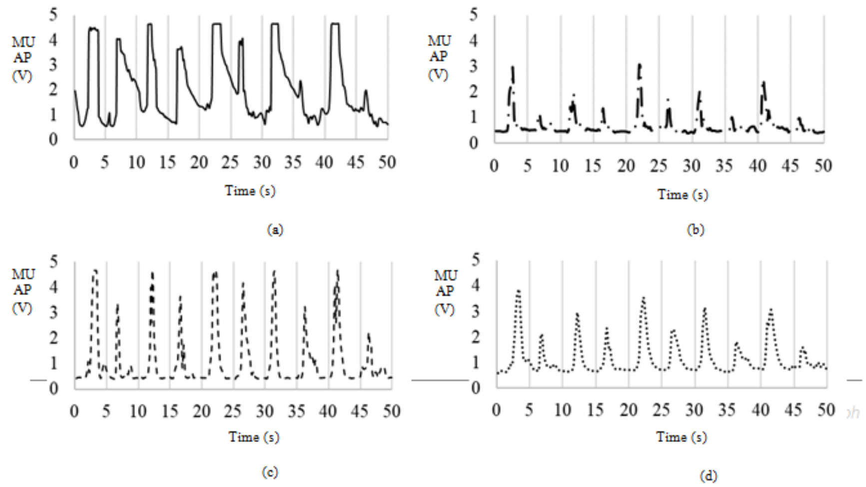

Figure 10. *MUAPs result in 5 cycles (separated). (a) is BIC, (b) is TRI, (c) is EXT and (d) is FIX*

4. Result and Discussion

Experiment were successfully done on 13 subjects which are 8 males and 5 females. Result for one of the subjects as in Figure 9. Clearly showing that MUAPPEAK is higher in contact phase compare to recovery phase in all 5 cycles.

Sudden increment in every phases indicate when the contact and recovery activities performed in each phases. Highest MUAPPEAK for all muscles group is belong to BIC in contact phase 3rd, 4th and 5th cycle where it reached to 4.66V. Meanwhile, highest MUAPPEAK in recovery is 4.16V for EXT in cycle 3. Higher the MUAP's value, higher strength produced by the muscles. Lowest MUAP is 0.43V and happened to all muscle groups in all phases.

Most of the time, MUAP stays at low level due to muscles is in resting condition waiting for next phase's activity. Separation graph on each muscle groups as Figure 10 revealed which muscle groups that are active or contributing in contact and recovery phase.

Average maximum MUAP in contact for BIC is 4.63V, EXT 4.66V, FIX 3.31V and for TRI it's just 2.49V. Therefore, for this subject, EXT is most contributing and less active is TRI to perform forward stroke. Identical things happened in recovery phase where highest is EXT (3.32V) and fewest is TRI

(1.24V). Bregman et al found that EXT contributing the most in the end of contact phase and FIX contributing at early stage but the amount is lesser [51].
Bar graph in Figure 11 shows the average of MUAPPEAK for 5 cycles. A general trend we can see for contact phase require more MUAP compared to recovery phase[40]. The highest MUAPPEAK is produced by TRI muscle group with 2.90 V in contact phase. These findings match to a research stated that Flexors and Extensors consistently contributing more during contact and recovery phases [44]. Biggest difference between phases is in 1st cycle for BIC which is 30.08% higher for contact phase. Higher in MUAPs means that the muscle group contributing more forces during completing the activity. Rankin et al discovered that muscle power is required higher in contact compared to in recover phase [44].
The obvious different for TRI is in 4th cycle, 24.72%. 22.20% is highest average different between phases that is belong to BIC. Followed by TRI 11.78 %, EXT 11.39% and lowest is FIX 7.85%. Low in different shows that both activities in contact and recovery required almost the same amount of force of that muscle. During propulsion which is in contact phase, forces is needed to push the rim forward due to weight of user and wheelchair itself [43]. Compare to recovery phase, user's hands move to point B to A without touching the rim and the weight is just the hands. As the result, required forces in contact phase is higher than recovery phase. Propulsion speed is not fixed through all the experiment. Subjects would propel based on their desire speed but position of hand is the same for each subject. Due to different speed for every cycles, the amount of force generated is dissimilar and higher the propulsion speed higher the MUAP values [52].
Figure 12 shows mean and SD for contact and recovery phase. Mean for TRI is contact phase higher comparing to opposite muscle (BIC) [53] and FIX higher than EXT. Highest mean belongs to FIX followed by EXT, TRI and BIC. The same pattern for EXT and FIX obtained by Rodgers et al where these both muscle groups were the strongest in producing force during wheelchair propulsion [35]. High SD indicates that the variation is big and low SD shows that the data is close to mean. Highest in SD for contact is TRI muscle group (±0.28) and the lowest is FIX (±0.08). 1st cycle contact phase for Tri is 2.72, lowest in 2nd cycle, 2.07 and the difference is 0.65. Comparing to FIX, difference is 0.21 where highest is 2.94 and lowest is 2.73. FIX muscle group is least effected when the speed is changing but the contribution is the highest among 4 major muscle groups.

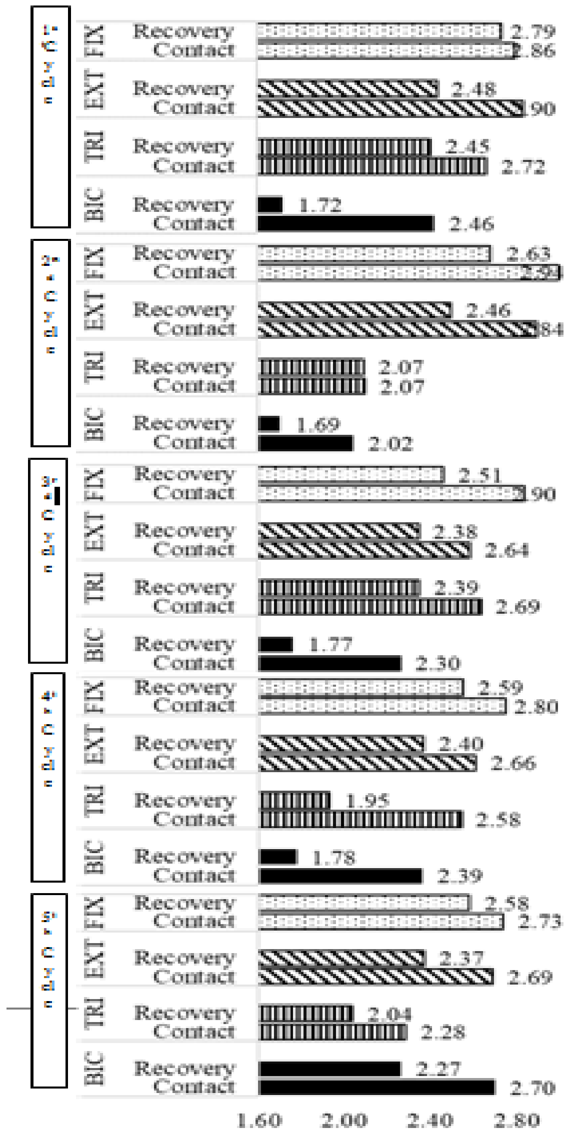

Figure 11. *Average of MUAPPEAK*

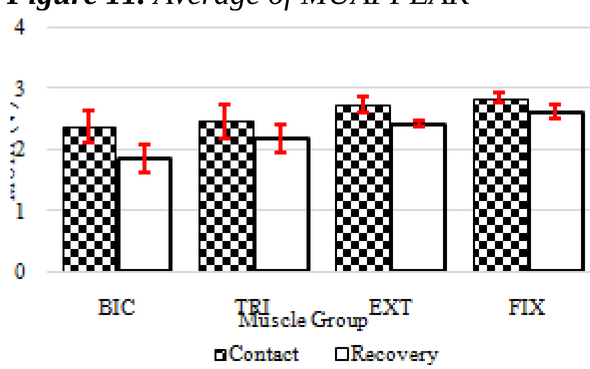

Figure 12. *Mean and SD for all subjects*

Wei et al obtained same result where EXT and FIX maintained similar level of contraction even force requirement is changing [54]. However, for TRI, it's most affected to speed propulsion and that's why the SD value is the highest. This finding suggests BIC and TRI are most suitable as reference muscles when propulsion speed is not consistent throughout the experiment. On the other hands, EXT and FIX are more appropriate on condition that speed is not variable and fixed. There are few limitations that has to be considered such as stroke time, muscles size, subject's weight and handedness.

5. Conclusion

Experiments on wheelchair propulsion with 13 healthy subjects using manual wheelchair with standard pushrim while 4 sEMG sensor located on four major muscles in human arm were performed, MUAPs recorded and analysed based on contact and recovery phases. During contact phase, extra force is needed to propel wheelchair due to weight of user and wheelchair's weight. On the other hand, less force in recovery phase to raise user hand back to position A on the pushrim. Analysis of the MUAPPEAK pointing out that the muscle contributes more during performing the activities either in contact or recovery phase.

Propulsion speed is not fixed to certain value but depends on subjects to propel on their desired speed. Highest MUAPPEAK is in contact phase for FIX muscle group and shows that it maximally recruited to perform propulsion activity. FIX contribution is consistent in every cycles due to SD is very low even though propulsion speed is different. Low SD means that FIX is not influenced the speed but contribute the most compared to others during both phases because of the mean value are the highest.

The different between both phases is the lowest indicates that wheelchair propulsion activity is not the reason mean value is highest but due to movement of arm's part which is wrist to perform activities in both phases. Contraction types happens for FIX and EXT would be different every time wrist is moved[55]. Concentric contraction where muscle is shortening as it contacts while the opposite muscle lengthening called eccentric contraction. Consequently, SD for EXT and FIX is lower than BIC and TRI. FIX and EXT result is opposite with BIC and TRI.

SD value for BIC is second highest even though mean value is the lowest. It is the less contributor for contact phase but the most affected when speed is changing. TRI functions is to extend forearm as in contact phase and causing higher MUAP and contributing more than BIC. Therefore, TRI mean value higher than BIC and highest in SD value. This study of muscle's MUAP during wheelchair propulsion suggests that type of muscles to focus if there are researchers that would like to develop instrumented wheelchair for disable person. Combination signal from TRI and BIC is much reliable if propulsion speed is dynamics and the signal required from the forearm because the different in output clearly seen during contact and recovery. FIX and EXT is more suitable if the signal from wrist is needed for the developed interface and it has consistent output in both phases.

6. Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

7. Conflict of Interest

The authors report that there are no conflicts of interests.

8. Acknowledgment

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9. Nomenclature

The authors report that there are no conflicts of interests.

x – MUAPPEAK value
Σx – total MUAPPEAK value for 5 phases
$\bar{x}$ – Mean
σ – Standard deviation (SD)
N – Number of phases (5)

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