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Electromyographic analysis of upper limb muscles for automatic wheelchair propulsion control

Abstract: *Equipping hand-propelled wheelchairs with supplementary power assistance systems combining the advantages of manual and electric wheelchairs. The study aims to develop innovative automatic steering strategies for assistive drive systems. Our approach involves regulating the intensity of power assistance using one upper arm's electromyography (EMG) signals, significantly simplifying the control system. However, the inherent asymmetry between the actions of the right and left upper limbs (handedness) poses a challenge. To address this, we set out to identify the upper limb muscle group exhibiting the least propelling asymmetry between the left and right sides, thereby determining the most suitable candidate for controlling the assistive drive of a wheelchair. The study used a standard manual-powered wheelchair and a single non-disabled research participant. Muscle activity in each upper limb during wheelchair propulsion was measured using EMG equipment. Eight muscle examinations were performed on each upper limb: biceps brachii (A), triceps brachii (B), medial epicondyle (C), extensor carpi radialis longus (D), anterior epicondyle (E), posterior epicondyle (F), trapezius, middle region (G), and subscapularis (H). The mean maximal muscle EMG signal was analyzed based on six cycles of wheelchair propulsion. The asymmetry of EMG values for the left and right limbs can vary from 15% to 53%, depending on the muscle studied. Our findings reveal that the D muscle displays the least muscular asymmetry during wheelchair propulsion, suggesting that the tension signals of this muscle can effectively regulate the intensity of assisted wheelchair propulsion.*

Streszczenie. *Wyposażenie wózków inwalidzkich z napędem ręcznym w dodatkowe napędy wspomagające łączy zalety wózków ręcznych i elektrycznych. Wymaga to jednak opracowania nowatorskich strategii automatycznego sterowania dla takich systemów napędu wspomagającego. Nasze podejście polega na regulowaniu intensywności wspomagania za pomocą sygnałów elektromiograficznych (EMG) jednego kończyny górnej, co znacznie upraszcza system sterowania. Wyzwaniem jest jednak asymetria pomiędzy działaniami prawej i lewej kończyny. Aby rozwiązać ten problem, postanowiliśmy zidentyfikować grupę mięśni kończyny górnej wykazującą najmniejszą asymetrię napędową pomiędzy lewą i prawą stroną, określając w ten sposób najbardziej odpowiedniego kandydata do kontrolowania napędu wspomagającego wózka inwalidzkiego. Badanie obejmowało standardowy wózek inwalidzki z napędem ręcznym i jednego pełnosprawnego uczestnika. Aktywność mięśni każdej kończyny górnej podczas poruszania się wózkiem inwalidzkim mierzono za pomocą aparatury EMG. Na każdej kończynie górnej wykonano pomiary dla ośmiu mięśni: dwugłowego ramienia (A), trójgłowego ramienia (B), nadkłykcia przyśrodkowego (C), prostownika promieniowego długiego nadgarstka (D), nadkłykcia przedniego (E), nadkłykcia tylnego (F), mięśnia czworobocznego (region środkowy) (G) i podłopatkowego (H). Analizowano średni maksymalny sygnał EMG każdego mięśnia na podstawie sześciu cykli napędu wózka inwalidzkiego. Badania wykazały, że asymetria wartości sygnału EMG dla kończyny lewej i prawej może wahać się od 15% do 53%, w zależności od badanego mięśnia. Grupy mięśni charakteryzujące się małą wartością różnicy EMG najlepiej nadają się do sterowania napędem w oparciu o sygnał EMG z pojedynczej kończyny. Mięsień D wykazywał najmniejszą asymetrię mięśniową. Wyniki te sugerują, że sygnały tego mięśnia mogą skutecznie regulować intensywność wspomaganego napędu wózka inwalidzkiego.(**Analiza elektromiograficzna mięśni kończyn górnych do automatycznej kontroli napędu wózka inwali***dzkiego)

Keywords: assistive technology, hybrid drive, muscle asymmetry, laterality
Słowa kluczowe: technologia wspomagająca, napęd hybrydowy, asymetria mięśni, lateralność

Introduction

Manually operated wheelchairs are the most prevalent among wheelchairs, constituting approximately 70% of all wheelchairs globally [1]. The advantages of this apparatus category are that it is highly accessible and supports the physical activity of its users [2]. The disadvantage of manually powered mobility aids is the limited propulsive energy users can generate with this device [3], which limits mobility. Innovative solutions for people with disabilities are mechanical transmissions and assistive drive systems, especially electric ones. Mechanical transmissions used in manual wheelchairs require multiple gear changes, necessitating a break in the wheelchair's propulsion [4] or handbike [5]. In manual-electric hybrid drive wheelchairs, the value of electric motor assistance can be fixed, declared by the user, can be changed by control algorithms based on signals from, for example, gyroscopic sensors that recognize elevation [6], or other methods of automating control can be used. In recent years, Brain-Computer Interfaces (BCIs) have gained popularity as potential systems for controlling brain-controlled wheelchairs (BCWs). A significant and unsolved challenge in BCW development is extracting a single control instruction from the electroencephalogram (EEG). Research in this area focuses on EEG signal acquisition, command decoding, and the working mechanism of the control system.

The development of BCW is proceeding in the direction of using dry, multimode electrodes and asynchronous control. The imminent commercialization of BCWs and widespread adoption in rehabilitation engineering are anticipated [7]. In wheelchair control research, combining two or more control methods (hybridization) is a new emerging trend. This approach leverages the strengths of electroencephalography (EEG) with its fast response and user-friendliness. EEG is often paired with other methods like functional near-infrared spectroscopy (fNIRS), electromyography (EMG), electrooculography (EOG), or eye tracking. This hybridization aims to achieve a wider range of control commands. Combining signals leads to more precise control. Faster response times enhance the user's well-being. This is why EEG + fNIRS and EEG + EOG combinations are commonly used [8].

Single-modal wheelchair control systems, often called "unimodal" systems, employ a single input signal [9], primarily electromyography (EMG) signals, to translate the user's intentions into wheelchair movement. In single-modal EMG control, sensors are affixed to the user's muscles to detect their electrical activity. A computer then analyzes the EMG signals to set the user's intended direction of movement and speed.

Single-modal EMG control presents several advantages over multimodal control systems. It is simpler to learn and utilize. The wheelchair user only needs to concentrate on a single muscle or muscle group, making it less cognitively demanding and more natural-feeling. The user is not required to make steering movements or hold down buttons or a joystick, which can help to reduce fatigue and discomfort. It can be more streamlined. The processing of a single signal requires a minimal amount of equipment. Research suggests that electromyography (EMG) signals can be effectively employed for unimodal control of the direction and speed of electric wheelchairs, primarily utilizing facial and neck muscle signals [10], [11] or hand gesture control [12].

Nevertheless, EMG signals have not been employed yet for control in hybrid-powered wheelchairs, which integrate electric motors to augment manual propulsion. An earlier study demonstrated the feasibility of utilizing muscle tension signals from one upper limb to regulate the intensity of an electric motor assisting manual wheelchair propulsion [13]. However, identifying the most appropriate muscle group for this application poses a significant challenge, mainly due to the inherent laterality of the human motor system [14], extending to the upper limbs and their asymmetry during wheelchair propulsion [15], [16]. However, reading signals from one limb simplifies the design of the control system. However, the problem is the asymmetry between the sides of the body. The dominant hand exhibits stronger and more varied EMG signals than the non-dominant hand [17]. Various factors, including wheelchair propulsion technique, wheelchair design, and hand dominance, influence the asymmetry of the EMG signal during wheelchair propulsion.

This study aimed to identify the upper limb muscle group exhibiting the slightest asymmetry between the left and right body sides, allowing the utilization of EMG signals from only a single limb to control the intensity of assistive electrical propulsion in manual-electric (hybrid) wheelchairs effectively.

Materials and methods

A typical lightweight manual wheelchair (V300, Vermeiren, Trzebnica, Poland) was used in this study. The wheelchair's overall dimensions were 1040 mm (length) × 880 mm (height) × 660 mm (width), with a total weight of 15.5 kg. The wheelchair's drive wheels measured 600 mm in diameter, while the front wheels were 150 mm. All wheels had pneumatic tires inflated to a nominal pressure of 0.2 MPa.

The study included a single non-disabled participant with a height of 170 cm, a body mass of 66 kg, and an age of 24 years. The participant demonstrated a maximum right-hand dominant pushing force of 282 N. The participant held wheelchair usage experience acquired during rehabilitation following lower limb surgery.

Surface electromyography (EMG) signals of the study participants' upper limb muscles were acquired using a TeleMyo Noraxon Mini DTS system (Noraxon, Scottsdale, AZ, USA) featuring four channels. EMG data were analyzed and recorded using Noraxon MR3 software. Circular electrodes with 20-mm diameters and gel were placed over the central belly regions of each muscle being examined. The EMG data acquisition sampling rate was set to 1500 Hz.

EMG data were collected from eight upper limb muscles on each limb (Fig. 1): biceps brachii (A), triceps brachii (B), deltoid, middle head (C), extensor carpi radialis longus (D), anterior deltoid (E), posterior deltoid (F), trapezius, middle region (G), and subscapularis (H). Figure 1 illustrates the anatomical locations of these muscles.

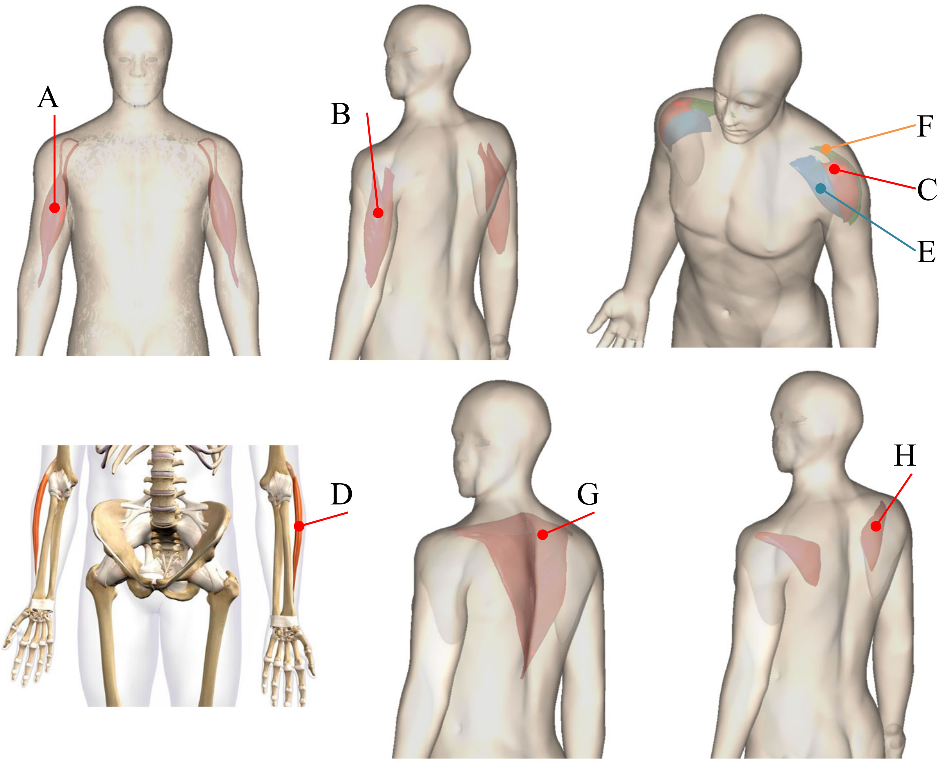

Fig. 1. Muscles analyzed in the study: A – biceps brachii, B – triceps brachii, C – deltoid, middle head, D – extensor carpi radialis longus, E – anterior deltoid, F – posterior deltoid, G – trapezius, middle region, H – subscapularis (own study, made using Kousaku Okubo's BodyParts3D database in Anatomography, maintained by the DBCLS, on CC license)

Preceding the assessment of muscle EMG activity, a standardization procedure was enacted in adherence to the manufacturer's guidelines for the instrumentation [18]. This procedure sought to determine the individual reference value of maximum voluntary contraction (MVC), which is crucial for subsequent calculations. Five exercises were implemented to acquire the reference MVC value for each muscle under examination (selected based on prior studies [15]). Standardization was undertaken one day before the test to allow the muscles to recover from the preceding exercise.

Six measurement trials were conducted to assess EMG activity while the test subject propelled a wheelchair along a straight path on a level surface. The acquired EMG data were normalized by calculating the average peak amplitude within a fixed 1000-millisecond window, representing each trial's maximum EMG amplitude (EMGmax). RMS algorithms with a window width of 150 milliseconds were employed for normalization.

Results and discussion

The test results comprise the EMG values from eight muscles in both upper limbs. These readings are presented in Table 1.

Table 1. Measured muscles' EMG values while propelling a wheelchair

Muscle	Upper limb	Trial number						Mean EMG_{max}
		1	2	3	4	5	6	
		EMG_{max} (mV)						(mV)
A – biceps brachii	Right (R)	1883.0	2061.0	2039.0	2395.0	2537.0	2721.0	2272.67 ± 343.95
	Left (L)	1417.0	1356.0	1116.0	1096.0	1101.0	1111.0	1199.5 ± 153.53
B – triceps brachii	Right (R)	687.9	589.7	384.7	522.5	625.0	513.6	553.9 ± 110.6
	Left (L)	1086.0	1069.0	1100.0	1110.0	1344.0	1321.0	1171.67 ± 131.76
C – deltoid, middle head	Right (R)	1202.0	1132.0	890.2	982.8	720.0	724.5	941.92 ± 212.31
	Left (L)	744.5	780.5	758.7	744.4	768.3	697.3	748.95 ± 30.32
D – extensor carpi radialis longus	Right (R)	2128.0	2137.0	2115.0	2292.0	2676.0	2423.0	2295.17 ± 233.16
	Left (L)	1769.0	1837.0	1942.0	1881.0	2110.0	2162.0	1950.17 ± 163.19
E – anterior deltoid	Right (R)	1369.0	1530.0	1376.0	1567.0	1743.0	1426.0	1501.83 ± 150.21
	Left (L)	1294.0	1119.0	915.1	896.8	1169.0	1078.0	1078.65 ± 163.19
F – posterior deltoid	Right (R)	865.3	787.6	789.3	789.7	868.0	731.2	805.18 ± 55.2
	Left (L)	586.3	565.7	651.3	619.1	574.2	606.2	600.47 ± 33.40
G – trapezius, middle region	Right (R)	634.9	553.1	569.9	547.4	450.3	489.1	540.78 ± 67.62
	Left (L)	341.5	341.4	385.2	367.1	343.1	387.9	361.03 ± 23.14
H – subscapularis	Right (R)	190.2	188.7	194.7	187.2	238.5	225.6	204.15 ± 23.23
	Left (L)	157.5	147.1	145.9	147.7	193.7	204.0	165.98 ± 27.28

The averages of the EMG measurement data, shown in Table 1, are summarized in Figure 2. This figure shows that the muscles with the highest mean EMG_{max} values are the biceps brachii (A), triceps brachii (B), and deltoid (middle-head) (C). The muscles with the lowest mean EMG_{max} values are the extensor carpi radialis longus muscle (D), anterior deltoid (E), posterior deltoid (F), trapezius (middle-region) (G), and subscapularis (H).

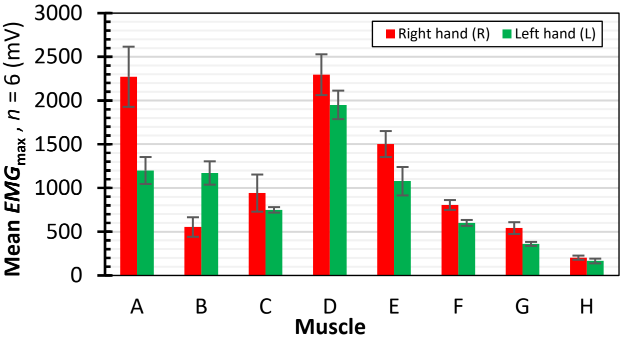

Fig. 2. Mean EMGmax values for the right and left upper limbs: A – biceps brachii, B – triceps brachii, C – deltoid, middle head, D – extensor carpi radialis longus muscle, E – anterior deltoid, F – posterior deltoid, G – trapezius, middle region, H – subscapularis

There is a significant difference in the mean EMGmax values between the right and left hands for some muscles. For example, the mean EMGmax value for the biceps brachii (A) is 2250 mV for the right hand and 1500 mV for the left hand. The mean EMGmax value for the triceps brachii (B) is 2000 mV for the right hand and 1250 mV for the left hand. This difference in EMG_{max} values is due to hand dominance. The participant of this study were right-handed, reflected in the higher mean EMGmax values for the right hand.

An analysis of the EMG data presented in Table 1 and Figure 2 corroborates previous findings, suggesting a significant asymmetry attributed to laterality between the EMG parameters of the left and right hand [19], [20]. Some studies performed by other methods have confirmed this type of propulsion asymmetry. Kukla and Maliga used a motion capture technique to analyze the biomechanics of wheelchair propulsion for side-to-side differences. They found that the mean values for individual participants show greater asymmetry than the mean positions of the markers for the entire group of participants. They concluded that the assumption of bilateral symmetry in wheelchair propulsion is not valid for individuals [21]. However, this asymmetry has different values depending on the experiment performed. Soltau and co-authors measured three-dimensional kinematics and handrim kinetics on a stationary ergometer from 80 subjects with paraplegia. The authors stated that the bilateral symmetry assumption appears reasonable during manual wheelchair propulsion in subjects without significant upper-extremity pain or impairment [22]. Bakatchina and co-authors reached similar conclusions when examining the kinematics of the upper limbs parameters of wheelchair rugby players [23].

This EMG study revealed significant and varied muscle asymmetry in the upper limbs. The extent of this asymmetry, quantified as a percentage difference in EMG parameters, is presented in Figure 3.

As mentioned in the introduction, controlling wheelchair propulsion using an EMG signal from a single limb benefit from utilizing information about muscle tension, which exhibits similar values between the left and right upper limbs. This approach mitigates the risk of errors in controlling due to a reading from a much stronger or a much weaker upper limb, which could contribute to an erroneous selection of the parameters of the supporting electric motor. Such automatic wheelchair propulsion control necessitates a control algorithm. The concept of such an algorithm is presented in a patent application [24] and described in an earlier publication [13]. Figure 3 demonstrates the smallest measured asymmetry of EMG signals between the right and left limbs in muscle D (long wrist extensor), with a value not exceeding 15%. This characteristic makes muscle D suitable for a control system that utilizes EMG signals from a single upper limb, either left or right.

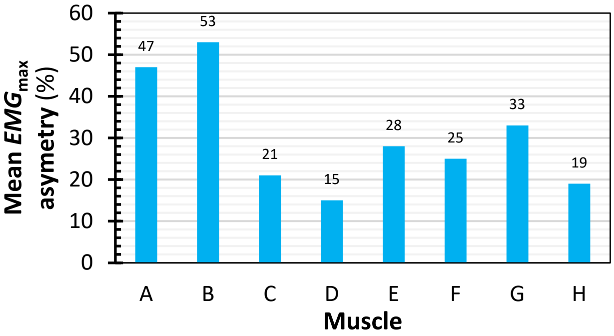

Fig. 3. Percentage differences between mean EMGmax values for the right and left upper limbs: A – biceps brachii, B – triceps brachii, C – deltoid, middle head, D – extensor carpi radialis longus muscle, E – anterior deltoid, F – posterior deltoid, G – trapezius, middle region, H – subscapularis

Notably, the EMG activity of muscles during wheelchair propulsion has been investigated in scientific studies. Most publications report peak EMG values [25], [26], [27], [28], [29], [30], [31], [32], while five focus on average EMG activity during propulsion [25], [32], [33], [34], [35]. The muscles analyzed in these studies vary, with a majority examining the anterior deltoid and pectoralis major muscles [25], [26], [28], [31], [32], [34], [35]. Only one known study describes measuring the long wrist extensor muscle's activity [13]. This study identifies this muscle as exhibiting the slightest asymmetry and confirms these earlier conclusions.

On similar ramps, different tests yielded different EMG values. However, it was observed that the measured activity of all the muscles tested increased steadily with the degree of incline of the ramp. This means that the EMG activity of the muscles is a good signal that controls the intensity of additional assistive propulsion.

The typical mean EMG signal asymmetry between the left and right upper limbs during wheelchair propulsion is approximately 15-20%. This means that the EMG signal from the left and right muscles is typically about 15-30% different in amplitude during the pushing phase of wheelchair propulsion. However, this difference may reach up to 53% [13]. The EMG signal asymmetry during wheelchair propulsion can be much higher for individuals with upper limb impairments.

Conclusions

Electromyographic (EMG) signals can be employed automatically to regulate the intensity of electric motor assistance in hybrid manual-electric drive systems. This control strategy can also be applied to manual drives with additional variable-ratio transmissions to change the gear ratio.

Previous studies have shown that EMG signal asymmetry between the left and right upper limb muscles during wheelchair propulsion can reach up to 53%. Among the eight muscles examined in this study, the extensor carpi radialis longus muscle (D) exhibited the lowest asymmetry (15%), suggesting its suitability as the primary muscle for controlling the intensity of an electric-manual wheelchair's assistive drive using EMG signals from only a single upper limb.

Study limitations

While studies have shown that the extensor carpi radialis longus muscle is the best control signal, inference from the presented results is limited, as the study was performed on a single person using only one wheelchair propulsion scenario.

Declarations

Ethical statement

The study participant completed an informed consent process before they began their participation. The study was conducted following the Declaration of Helsinki, and the protocol was approved by the Bioethics Committee at the Poznan University of Medical Sciences (Project identification code 1100/16). The research data in the article have been anonymized to ensure the confidentiality of the participant.

Competing interests

On behalf of all authors, the corresponding author declares that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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Availability of data and materials

The authors confirm that all data analyzed during this study are included in this published article

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