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Comparison of muscle activity during hand rim and lever wheelchair propulsion over flat terrain

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Purpose: The aim of this study was to compare the activity of upper limb muscles during hand rim wheelchair propulsion and lever wheelchair propulsion at two different velocity levels. *Methods*: Twenty male volunteers with physical impairments participated in this study. Their task was to push a lever wheelchair and a hand rim wheelchair on a mechanical wheelchair treadmill for 4 minutes at a speed of 3.5 km/h and 4.5 km/h in a flat race setting (conditions of moving over flat terrain). During these trials, activity of eight muscles of upper limbs were examined using surface electromyography. *Results*: The range of motion in the elbow joint was significantly higher in lever wheelchair propulsion (59.8 ± 2.43°) than in hand rim wheelchair propulsion (43.9 ± 0.26°). Such values of kinematics resulted in a different activity of muscles. All the muscles were more active during lever wheelchair propulsion at both velocity levels. The only exceptions were extensor and flexor carpi muscles which were more active during hand rim wheelchair propulsion due to the specificity of a grip. In turn, the examined change in the velocity (by 1 km/h) while moving over flat terrain also caused a different EMG timing of muscle activation depending on the type of propulsion. *Conclusions*: Lever wheelchair propulsion seems to be a good alternative to hand rim wheelchair propulsion owing to a different movement technique and a different EMG timing of muscle activity. Therefore, we believe that lever wheelchair propulsion should serve as supplement to traditional propulsion.

Key words: *biomechanics, assistive technology, muscle activity, EMG, wheelchair, lever*

1. Introduction

Hand rim wheelchair propulsion is a necessity in daily activities of many individuals with spinal cord injury or other lower limb impairments [22]. Mobility restoration, activities of daily living and sports require several different propulsion speeds. A minimum speed required to safely cross an intersection is deemed to be 1.06 m/s [4], while an average self-selected speed is 0.8 m/s for tetraplegia patients and 1.2 m/s for paraplegia patients [2]. Propulsion speed is known to influence muscle activity and wheelchair biomechanics. Numerous studies have documented shoulder kinetics and kinematics during wheelchair propulsion at multiple speeds [10]. It was revealed that shoulder joint forces and moments increased at faster velocities. Mercer et al. [13] found that manual wheelchair users who pushed at a greater speed and loaded a hand rim wheelchair more frequently were more likely to suffer from shoulder pathology or pain. Koontz et al. [10] reported that individuals changed their shoulder movement patterns depending on how fast they propelled. In general, moving on a wheelchair places significant stability and mobility demands on the upper limbs and is thought to contribute to the high incidence of upper extremity pain and injury, particularly in the shoulder [16].

Therefore, hand rim wheelchair propulsion is known to be an inefficient means of ambulation which has been associated with a high prevalence of upper limb injuries [7]. Such injuries are thought to occur as a result of a combination of repetitive movements, heavy loads

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on extremities, upper limb weakness and inefficient propulsive techniques [16]. Moreover, Pooyania et al. [15] pointed to the fact that, apart from shoulder injuries, such conditions as arm injuries or a common problem of dirty hands caused by wheelchair propulsion (particularly in winter, when there is snow) also deserve attention. For that reason, the use of the type of propulsion which is an alternative to traditional propulsion has the potential to prevent shoulder injuries in people at risk of overuse injuries and yet maintain a more optimal level of activity and independence.

While analysing the studies on wheelchairs and their functionality, it may be observed that in recent years, the evolution of technology has considerably improved their ergonomics. Wheelchairs are becoming lighter and more functional and are adapted to the needs and predispositions of individuals with disabilities. Lever wheelchair is one of the promising and well assessed types of wheelchairs. It is safer due to the fact that hands are in constant contact with levers, far from turning wheels. It was proved that lever propulsion mechanism provides a more effective transfer of power by increasing mechanical advantage and placing the arms in a more natural segmental position and orientation [8], [21], [22]. Moreover, lever-activated wheelchair propulsion has been described as more efficient and less physically straining than hand rim wheelchair propulsion. Energy expenditure studies [5], [12], [22] have shown that it is physiologically efficient and reduces energy consumption, compared to hand rim wheelchair propulsion. Apart from evaluating kinematic and kinetic parameters of upper limbs, muscle activity assessment is one of the most precise methods used when comparing the ergonomics of wheelchair propulsion. Recording muscle activity using surface electrodes made it possible to conduct detailed studies on the demands of specific muscles or groups of muscles involved in wheelchair propulsion. It is known that muscular imbalances can lead to fatigue and overuse injuries in the long term [11], [14]. Electromyography activity patterns of the deltoid, rotator cuff and superficial scapulo-thoracic muscles have been used to provide a critical insight into the mechanism of shoulder pathology associated with hand rim wheelchair propulsion [14]. The analysis of EMG activity of the shoulder and all upper limb muscles can be used to examine the shoulder and upper limb muscular demands associated with lever wheelchair propulsion and provide evidence-based recommendations for prescribing alternative modes of wheelchair propulsion as a strategy for preventing upper limb injury. Therefore, the aim of this study was to compare the activity of upper limb muscles during hand rim wheelchair propulsion and lever wheelchair propulsion at two different velocity levels.

2. Materials and methods

2.1. Participants

Twenty male volunteers in wheelchairs at a mean age of 33.8 ± 7.17 years, mean height of 170.5 ± 15.37 cm and mean body mass of 73.4 ± 12.53 kg participated in this study. The study group included seventeen people with acquired disability and three individuals with congenital disability. In the group of 17 men with acquired disability there were 12 subjects with spinal cord injury below Th_1, 3 subjects with lower limb amputation, 3 persons with spinal cord hernia below Th_1, one person with multiple sclerosis and one with poliomyelitis. Patients with acquired disability moved in a wheelchair for 20.3 ± 8.58 years (min. 5, max. 37). All participants reported that they had been physically active for an average of 9.3 ± 6.44 years and did additional sports once a week. The most commonly declared type of training was wheelchair basketball, cycling and gym workout. The study inclusion criteria was as follows. All participants used a wheelchair in their everyday life routine and they all had a full function of upper limbs (no impairment). In each case, at least 3 years passed from the incident after which they had to use a wheelchair. They had to fit in the tested wheelchair seat, because it was not regulated. Moreover, they had to have the ability two independently propel a manual wheelchair at the two specified speeds for 4 min. The study was conducted according to the ethical guidelines and principles of the Declaration of Helsinki. All persons signed an informed consent and they were informed that they could withdraw from the research at any stage. The study was approved by the Institutional Review Board (KEiB – 01/2018).

2.2. Procedures

The participants were asked to move in a mechanical wheelchair treadmill using lever and hand rim wheelchair propulsion for 4 minutes at a speed of 3.5 km/h and 4.5 km/h in a flat race setting (conditions of moving over flat terrain). The lever wheelchair was invented by Warsaw University of Technology, Faculty of Transport and a wheelchair manufacturer in the project called "Lever wheelchairs for the disabled", INNOTECH-K3/IN3/52/226230/NCBiR/13. It is a wheelchair which can be propelled by hand rims or by levers, according to the user's needs (levers are located near the wheels and can be pushed and pulled) (Fig. 1).

Fig. 1. Push-rim and lever wheelchair used in the research

The distance between levers was 48 cm and between push rims – 65 cm. The camber was 3 degrees and a single, multiplication gear ratio was at the level of 3. The levers were 49 cm long, their axis of rotation was positioned 7.4 cm behind and 5.1 cm above the axis of rotation of the back wheels. Lever braking was independent for both back wheels (the same solution as in bikes). The diameter of the wheels was 24 inches. The width of the weelchair was not regulated. The inclination of the back against the seat was 81 degrees.

During these trials, the activity of eight muscles of upper limbs was examined using surface electromyography and paraller-bar EMG sensors. Surface electrodes (Ambu Blue Sensor N-00-S/25) were placed in accordance with the SENIAM guidelines, with fixed 10 mm inter-electrode spacing on the following muscles: anterior deltoid, biceps brachii, extensor and flexor carpi, lateral head of triceps, pectoralis major, posterior deltoid and upper trapezius. The EMG signal was acquired at a sample frequency of 1500 Hz using TeleMyo2400 (Noraxon, USA). The kinematics of the arm during motion was measured using MyoMotion inertial sensors and was integrated with EMG signal. Before the measurements on the treadmill, maximal voluntary contraction (MVC) was registered for each muscle. Before starting the MVC tests, the volunteers performed a 5-minute warm-up. To limit a potential influence of the investigator, the MVC test positions were maintained using a steel structure rather than manual pressure [18]. It was possible to adapt the structure to both test positions and the specific size of the volunteers. During MVC, the volunteers were asked to maintain maximal exerted force and three trials of 5 seconds were performed for each muscle.

2.3. Data analysis

The EMG signal was first band pass filtered (20–500 Hz, zero-phase 4th order Butterworth) and then processed using a root-mean-square algorithm. MVC values were determined as the highest value from the course of muscle activity averaged through the RMS 500 ms (floating window of the Hamming type) achieved during the initial three measurement sessions carried out only for this purpose. For EMG treadmill recordings, the average EMG envelope over a time window (RMS filter) was calculated with 50 ms window size. From each trial on the treadmill, a representative one-minute ride was analysed for each study participant. All the comparisons were made for the minute "from the middle of the riding time". Treadmill tests were not tiring, so it was assumed that the work was constant within each passage. The EMG signals were normalised with the values obtained during the MVC tests and then expressed with regard to the elbow angle. For each subject, the kinematic and EMG data were averaged over one minute of dynamic trial. The muscle activation level during each trial was then expressed as a percentage of the MVC measured before.

The following data from MyoMotion system were taken into account: the number of push phases and their duration, the range of elbow motion, initial and final elbow joint angle for propulsion phase in hand rim and lever wheelchair propulsion during motion at a velocity of 3.5 km/h and 4.5 km/h. Next, in order to perform a detailed analysis of muscle activity, the whole push motion cycle was divided into two phases depending on the elbow joint angle. Phase I was defined as the range from 150° to 90° and Phase II from 90° to 0°, where 0° = full extension and 90° = the right angle. The beginning of the pushing phase usually started at values above 100°, sometimes even 140°. In these two phases, the maximum values of muscle activity were found. Afterwards, the values for two velocity levels in phase I and phase II were compared and the percentage values of an increase in muscle activity occurring while increasing the velocity in particular phases were calculated. Statistical analysis was carried out using the Statistica software (StatSoft, USA). The normality of distribution was tested using the Shapiro–Wilk test. Several parameters had a distribution significantly different from normal. Therefore, in next step, the nonparametric Wilcoxon test for comparing two dependent groups was used. The level of significance was set at $p \leq 0.05$.

3. Results

The following parameters had distribution significantly different from normal: time push phases duration for hand-rim at velocity of 3.5 km/h (p = 0.004) and 4.5 km/h (p = 0.0003), the initial angle in elbow joint at velocity of 3.5 km/h in both variation of wheelchair (p = 0.001) and the final angle in the elbow joint at velocity of 4.5 km/h for the lever wheelchair. While analysing the number of push phases and their duration (Fig. 2a), it was revealed that in the group of 20 people who participated in the study, an average number of push phases was greater for hand rim propulsion than for lever propulsion at two velocities. On the other hand, an average duration of push cycles was lower for hand rim propulsion at a velocity of 3.5 km/h. However, these values did not differ significantly for both speeds (Wilcoxon test, $p \leq 0.05$).

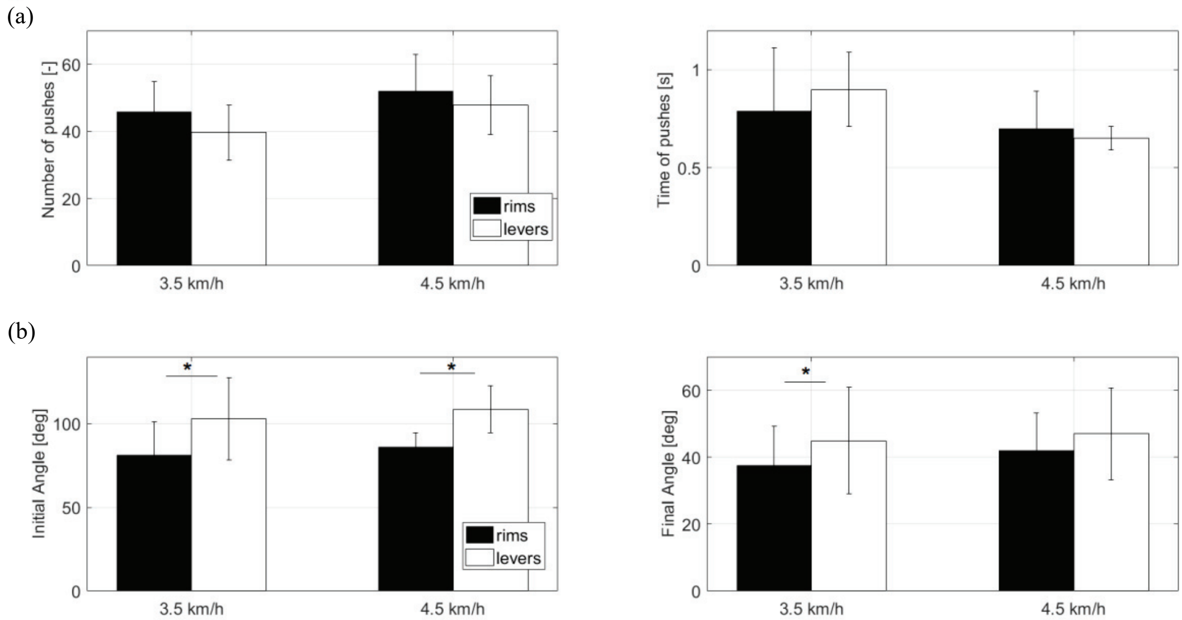

Fig. 2. Mean and standard deviation of: (a) push phases and duration of push cycles, (B) initial and final angles in the elbow joint for hand rim and lever wheelchair propulsion during motion at a velocity of 3.5 km/h and 4.5 km/h, where: * – statistically significant differences, $p \leq 0.05$

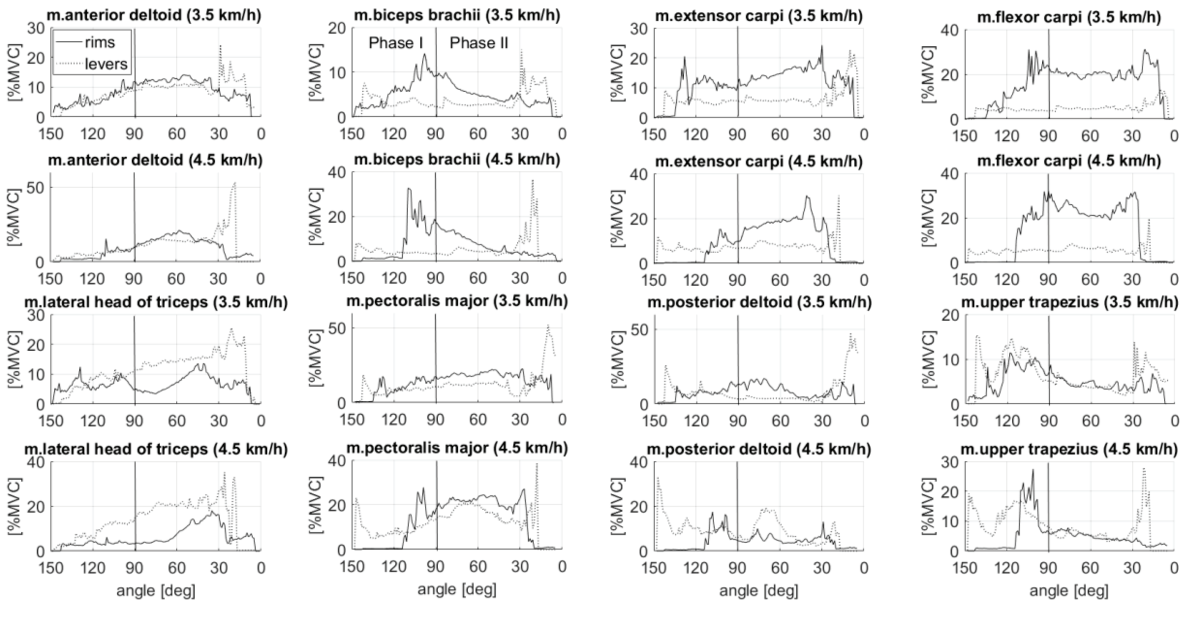

Fig. 3. Mean muscle activity in the elbow joint during mechanical treadmill tests at a velocity of 3.5 km/h and 4.5 km/h for hand rim and lever wheelchair propulsion

In Fig. 2b mean values and standard deviations of initial and final angles in the elbow joint in two variants of wheelchair propulsion are shown. After applying the Wilcoxon test, it was shown that for each velocity level, the initial angles were significantly higher (p = 0.0001) for the lever wheelchair, while the final angles for both types of propulsion did not differ significantly for the speed of 4.5 km/h and were also higher for the lever wheelchair propulsion.

Such results indicated that lever wheelchair propulsion in the studied group led to significantly greater ranges of motion in the elbow joint. For lever propulsion, the range of motion was 59.8 ± 2.43°, while for the traditional one, it was at the level of 43.9 ± 0.26°. Such values of kinematics resulted in a different activity of muscles (Fig. 3).

While discussing Fig. 3, it may be noted that much greater activation of the extensor and flexor carpi muscles is observed during movement with the use of an active wheelchair for both velocities. This is related to the grip of the wheel while pushing, which is not observed during lever wheelchair propulsion. The lateral head of triceps muscle was more active during lever wheelchair propulsion, especially in the final extension in the elbow joint. Its stimulation was proportional to the decreasing range of flexion of the forearm. Pectoralis major, posterior deltoid and upper trapezius muscles were similarly active in the study participants who used hand rim and lever wheelchair propulsion.

In order to examine muscle behaviour in detail, their activity was analysed in two ranges of the elbow joint angle. Phase I was defined as the range from 150 to 90°, while phase II – from 90 to 0° (Fig. 3). Maximal values of muscle activity were determined in these ranges.

When comparing the maximal values of EMG signal as a function of velocity, it was noted that the activity of all muscles increased both for traditional and lever wheelchair propulsion at the velocity of 4.5 km/h in phase I (Table 1). The highest increase in the activity of muscles for hand rim propulsion in phase I was noted in the case of upper trapezius muscle (139.87%), biceps brachii muscle (130.31%) and pectoralis major muscle (56.48%). In turn, the highest increase values for lever wheelchair propulsion in the same phase were observed for extensor carpi muscle (24.7%), posterior deltoid muscle (21.8%) and upper trapezius muscle (20.12%).

In the case of hand rim propulsion, the highest increase in phase II occurred in a different order than in phase I, i.e., biceps brachii muscle (89.8%), anterior deltoid muscle (49.5%) and lateral head of triceps muscle (32%). The increase values were also different for lever wheelchair propulsion, i.e., biceps brachii muscle (58.7%), anterior deltoid muscle (54.6%) and upper trapezius muscle (50.41%).

Therefore, the above results prove that the velocity change by only 1 km/h while moving over flat terrain

Table 1. Maximum EMG values for hand rim and lever wheelchair propulsion while moving at a velocity of 3.5 km/h and 4.5 km/h and percentage differences in two phases of movement in the elbow joint

Muscle	Hand Rim Propulsion		Percent [%]	Lever Propulsion		Percent [%]
	3.5 km/h	4.5 km/h		3.5 km/h	4.5 km/h	
PHASE I (150–90°)						
m. anterior deltoid	12.65	15.44	22.05	8.74	8.85	1.24
m. biceps brachii	14.15	32.59	130.31	7.53	8.17	7.83
m. flexor carpi	31.05	31.75	2.25	5.25	6.46	18.73
m. upper trapezius	11.46	27.49	139.87	15.32	19.18	20.12
m. posterior deltoid	15.08	17.45	15.72	25.94	33.18	21.82
m. lateral head of triceps	12.42	12.43	0.08	11.66	13.77	15.32
m. extensor carpi	19.51	19.67	0.82	9.11	12.1	24.71
m. pectoralis major	17.74	27.76	56.48	18.48	23.09	19.96
PHASE II (90–0°)						
m. anterior deltoid	14.15	21.16	49.54	24.14	53.28	54.69
m. biceps brachii	9.92	18.83	89.82	15.06	36.5	58.73
m. flexor carpi	31.18	31.98	2.56	13.38	19.64	31.87
m. upper trapezius	8.76	8.82	0.68	13.84	27.91	50.41
m. posterior deltoid	15.08	17.45	5.74	17.84	19.87	10.21
m. lateral head of triceps	13.64	18.01	32.04	25.49	35.11	27.40
m. extensor carpi	24.25	30.22	24.62	22.67	30.19	24.91
m. pectoralis major	22.49	27.1	20.50	51.96	38.58	N

brings about different timing of muscle activation depending on the elbow joint angle and on the type of wheelchair propulsion. Moreover, it is not constant activity in the angle function (Fig. 3).

When phase I and phase II for lever and hand rim wheelchair propulsion were compared, it was revealed that for both velocities, maximal muscle activity was higher in phase II (90–0°), with the exception of biceps brachii and upper trapezius muscle. These muscles were more active in phase I, as they were in the phase of concentric contraction. The situation was similar in the case of lever wheelchair propulsion. Here, upper trapezius and posterior deltoid muscles were more active in phase I.

The last comparison worth attention regards the values of maximal muscle activity for lever and hand rim wheelchair propulsion. While analysing this comparison, it was easy to notice that in phase II (90–0°), all the muscles were more active during lever wheelchair propulsion at both velocities. Extensor and flexor carpi muscles were an exception, as they were more active during hand rim wheelchair propulsion due to the hand grip specificity. In the case of lever wheelchair propulsion, in phase I (150–90°), higher activity was noted only in the case of 4 muscles (anterior deltoid, trapezius, posterior deltoid, pectoralis). Such activity of muscles is caused by the kinematics of upper limbs movement which is different for both types of propulsion.

4. Discussion

The aim of this study was to analyse and compare the activity of upper limb muscles during hand rim and lever wheelchair propulsion at a velocity of 3.5 km/h and 4.5 km/h in a flat race setting (conditions of moving over flat terrain). The comparison of human performance on various types of wheelchair propulsion can be a valuable source of knowledge for people with physical impairments looking for an optimal wheelchair that would meet their needs and for engineers designing new constructions.

The research in this field provides information on wheelchairs propelled by hand rims regarding, e.g., an impact of a hand rim tube diameter on propulsion efficiency and force application [19], effects of seat position [17], effects of a rear wheel camber [24] and effects of backrest angle [3]. Scientists have also investigated wheelchairs propelled by hand cycling in terms of e.g. the influence of crank length and cadence [9], effects of different handgrip angles [11] and effects of gear ratios [20]. The comparisons of wheelchairs can be found in several papers [25], however, they mostly address hand rim wheelchair propulsion. The comparisons of hand rim wheelchair propulsion with lever mechanisms are rare and were presented in [11], [16], [22]. Moreover, lever mechanisms available for wheelchair propulsion differ in design, thus creating different ride conditions for users of different mechanisms.

This paper extends the present knowledge with information regarding muscle activity during performance on a wheelchair which allows for propulsion with both levers and hand rims in everyday pushing conditions. The advantage of the research was the fact that in the case of the presented wheelchair, both propulsion modes can be compared without the change of tyres, seating conditions and many other factors that could hinder the comparison.

The analysis of upper limb kinematics presented in this study revealed that lever wheelchair propulsion requires significantly larger ranges of motion (59.8 ± 2.43°) than hand rim wheelchair propulsion (43.9 ± 0.26°). Such differences in angles result in different muscle activity. Van der Woude et al. [21] and Engel et al. [6] revealed that using lever wheelchair propulsion improves the process of rehabilitation as more muscles are engaged during this type of propulsion. This fact was confirmed in our study. We noted that in the range of motion of the elbow joint (90–0°), all the muscles, except for flexor and extensor carpi muscles, have higher values of maximal muscle activation (Table 1) during lever wheelchair propulsion. Much greater activation of extensor and flexor carpi muscles during hand rim wheelchair propulsion is related to the grip of the wheel while pushing, which is not observed while propelling a lever wheelchair. In turn, a more detailed analysis revealed that a change in the velocity only by 1 km/h leads to different timing of muscle activation depending on the elbow joint angle and on the type of propulsion. We noted that in phase I (150–90°), the highest increase in muscle activity in hand rim wheelchair propulsion was noted for upper trapezius (139.87%), biceps brachii (130.31%) and pectoralis major (56.48%). In turn, lever wheelchair propulsion in the same phase showed a completely different order of maximal values of an increase in muscle activity, i.e., extensor carpi muscle (24.7%), posterior deltoid muscle (21.8%) and upper trapezius muscle (20.12%).

In phase II (90–0°), the pattern in the case of hand rim wheelchair propulsion differs from that in the previous phase and is as follows: biceps brachii (89.8%), anterior deltoid (49.5%) and lateral head of triceps (32%). Increase values for lever wheelchair propulsion also differed: biceps brachii (58.7%), anterior deltoid (54.6%) and upper trapezius (50.41%).

This precise recruitment and coordination of the muscles not only provides optimal energy transfer from the muscles to the wheelchair but also offers protection to the joints. If any muscle becomes too strong or too weak, the disproportionate strength or weakness of this muscle may disturb the muscle coordination and put the joints at risk. Hence, identifying weak or too strong components in muscle synergies may improve the wheelchair propulsion performance and reduce the risk of injuries [11]. Having observed the above changes in muscle activity, it may be concluded that when one type of propulsion is used, one muscle activation and disactivation pattern can be noted. Due to the fact that our analysis focused on muscle activity during lever and hand rim wheelchair propulsion over flat terrain, i.e., during the most common type of effort, the following conclusions can be drawn.

If any particular muscle becomes too strong or too weak, the disproportionate strength or weakness of this particular muscle may disturb muscle coordination and put the joints at risk. Hence, identifying weak components in muscle synergies and strengthening them with specific muscle training or a different type of wheelchair propulsion may improve the wheelchair propulsion performance and reduce the risk of injuries. On the other hand, changes in composition of muscle fiber types might be associated with muscle overuse and muscle pathologies [1], [5], [23]. However, this problem was not analysed in this work.

Therefore, to sum up the above analysis, we believe that lever wheelchair propulsion should serve as a supplement to a traditional type of propulsion. The best option would be to have wheelchairs equipped with both mechanisms due to the fact that they require different muscle activity patterns and different angles which at times affects the comfort of movement.

5. Conclusions

The findings of this study have to be seen in light of some limitations. It is worth noting that in the study participated small sample size with different disability types. It might seem that the type of disability affects the results of the study. However, considering that the disability did not affect the upper limbs, the homogeneity of the group can be considered in terms of the wheelchair matching. The wheelchair used in the tests is adapted for people from 70th percentile and in this case, all subjects were in the norms. The next limitation concerns the variations in body anthropometrics (shoulder width) and the interaction between person and handrim/lever drive system, what could influencing muscle activity. Moreover, the muscle activity could be also influenced by variations in body mass from person to person, which affected rolling resistance and power output/work load. In addition, it should be mentioned about surface EMG artifacts, which, despite the fact that it was EMG wireless, always appear. The last limitation of this study is the participants' upper limb pain levels. However, the subjects declared that during the tests they did not have elevated upper limb pain. In summary, results presented in this paper must be interpreted with caution and some of mentioned limitations could be addressed in future research.

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