Journal of Biomechanics 89 (2019) 119–122

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

A preliminary muscle activity analysis: Handle based and push-rim wheelchair propulsion

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ARTICLE INFO

Article history:
Accepted 9 April 2019

Keywords:
Wheelchair propulsion
Handle based propulsion
Muscle activity

ABSTRACT

Approximately ninety percent of the wheelchair users worldwide prefer the conventional push rim mode of propulsion for daily mobility and rehabilitation. Even though push-rim wheelchairs help to promote a healthy life style, the high muscular demand and the non-continuous push motions can lead to serious upper extremity injuries. In this study, muscle EMG data of ten healthy subjects were recorded for a newly introduced handle based propulsion mechanism (HBP) and compared to conventional push-rim propulsion at two workloads, 25 W and 35 W respectively. The results for the mean peak muscle activations at both workloads demonstrate that push-rim propulsion leads to higher peak muscle activity compared to HBP at a similar wheelchair forward velocity of 1.11 m/s. The generation of these high peak muscle activations with increasing loads in push-rim propulsion over time can lead to overuse injuries. Overall, the use of the HBP mechanism is less straining to the muscles and may reduce fatigue during prolonged propulsion.

1. Introduction

Wheelchairs are commonly used as a mode of ambulation and rehabilitation for persons suffering from injuries such as spinal cord injury (SCI) (Woude et al., 2001; Vanlandewijck et al., 2001; Van Der Woude et al., 2001). Studies on muscle activity during wheelchair propulsion with various styles have shown that there is a high muscular demand on a few specific muscles involved in wheelchair propulsion mainly due to low contact durations with the push-rim (Slowik et al., 2016), and the muscles used during the push phase become stronger over the course of time while the muscles used in the recovery phase remain at the same strength. These muscular imbalances can lead to fatigue and overuse injuries in the long term (Ambrosio et al., 2005). Studies on hand cycling (tricycle wheelchair arm crank propulsion) have shown that the continuous propulsion pattern used in this technique is less straining to the muscles and also facilitates to distribute the propulsion load to greater number of muscles (Arnet et al., 2012a, 2012b; Van Der Woude et al., 2001). Even though hand cycling is more biomechanically efficient and less physically straining, majority of the users prefer the push-rim over hand cycling as it is more easy to maneuver in small indoor spaces while hand cycles are better suited for outdoor activities due to their large frame size and difficultly in steering (Vanlandewijck et al., 2001). Using the above concepts, an alternative form of wheelchair propulsion mechanism was introduced in our simulation study and the results were promising as the new hand propulsion pattern followed ergonomic ranges of joint motion thus limited the chances of injuries when compared to push-rim (Babu Rajendra Kurup et al., 2018).

As a follow up of our simulation study, this study aims to compare the upper extremity muscle activations of subjects on the physically realised Handle Based Propulsion (HBP) and push-rim propulsion drive at two different workloads.

2. Methods

2.1. Participants

Ten able-bodied, nonskilled male subjects (mean ± SD; 27 ± 5 yrs, 1.81 ± 0.06 m, 88 ± 12 kg) were recruited for this study. All subjects were right handed and had no known history of joint injuries or movement limitations. All the subjects provided voluntary informed consent for the experimental trials, which was approved by the Institutional Review Board.

2.2. Experimental setup

A standard lightweight manual wheelchair was used for the study. The dimensions of this wheelchair are 0.420 m seat depth,

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https://doi.org/10.1016/j.jbiomech.2019.04.011
0021-9290/

altered backrest height of 0.220 m and a seat width of 0.500 m. The size of the wheel was changed based on the test setup: for the HBP test a reduced wheel size of 20 in. was used and for the normal push-rim test, an instrumented SMART^{Wheel} with standard wheel dimensions of 24 in. was used (Cooper, 2009). The wheel with smaller diameter was used for HBP to avoid collision of the rotating crank or hand with the wheel. Future designs of HBP mechanism may solve this problem. In order to maintain a constant propulsion power output and constant linear velocity of the wheels during propulsion a custom-made test rig, controlled by a LabVIEW (National Instruments Corp., Austin TX) program was built and attached to a standard wheelchair (Fig. 1). The test rig includes a controlled motor linked to a flywheel. During propulsion, the instantaneous angular velocity of the wheels was recorded and the corresponding instantaneous torque was calculated. In order to maintain a steady state of constant power, the magnitude of this torque was applied as a resistive torque by the motor linked to the wheels through timing belts (Puchinger et al., 2017).

The handle based propulsion unit was attached to the wheelchair in the parasagittal plane of the wheels and consists of a crank centre, attached to a sliding guide on which a handle was mounted as shown in (Fig. 1). The optimized propulsion shape with a shape factor of 0.95 was engraved into the shape plate. During propulsion, the crank changes its effective length forced by the sliding guide capable of moving back and forth in the shape plate, resulting in the novel propulsion movement for the HBP mechanism. The gear ratio of the HBP mechanism to the wheel is set as 2:1. The lower gear ratio was set for the HBP mechanism because the gear ratio of 1:1 will need greater exertion of force to the handle while the hand velocity and the muscle contraction drop and this may lead to fatigue (Van Der Woude et al., 2001). Also increasing the gear ratio may decrease the mechanical efficiency of the propulsion (Faupin, 2008). In addition, an adjustable mounting frame allows to set the position of the crank centre in the parasagittal plane. The centre was set for all subjects based on the protocol followed in our optimization study, thus ensuring all the subjects have similar arm kinematics during propulsion. A timing belt transfers the propulsion torque from the HBP to the wheels.

In this study, propulsion was unilateral. Even though the wheelchair attached to the test rig had wheels on both sides, only the right arm was used to propel in both propulsion modes, assuming symmetry of propulsion as the subjects were without any secondary injury or pain (Soltau et al., 2015), Naturally unilateral propulsion will be more demanding on the muscles when compared to bilateral propulsion where the propulsion work will be shared by both limbs. Hence the muscle activities observed in this study will be higher compared to values collected from bilateral propulsion. As the subjects in this study had very good trunk control and stability we assume that muscle activity of the shoulder muscles is not significantly influenced by the unilateral propulsion (Van Der Woude et al., 2001).

Muscle activations were recorded using DELSYS Trigno wireless surface electromyography (sEMG) electrodes. An 8-camera motion capture system (Motion Analysis Corporation) along with reflective markers placed on the propulsion units of HBP and SMART^{Wheel} at 120 Hz were used to manually determine the propulsion cycles. Further details of upper limb joint kinematics are not described in this paper.

2.3. Experiments

Prior to the experimental trials, the subjects were instructed about the propulsion modes (push-rim and HBP) and the testing protocols. Then the subjects were allowed to familiarize with both HBP and push-rim by propelling each of them for 5 min without any resistance provided by the test rig and further 5 min were given to the subjects to test the drives on each propulsion load with varying resistances provided by the test rig. For the tests with both the HBP and the push-rim, 2 workloads of 25 W (Watts) and 35 W at a wheelchair linear velocity of 1.1 m/s were set using the test rig. A visual interactive feedback was provided to the users to visually monitor the wheelchair speed and propulsion power and aid the users to reach the target propulsion power and speed for the tests. The subjects performed the experiments at 2 workloads for each of the propulsion systems in a randomized manner in order to minimize effects of training or fatigue on the results. Muscle activations of Anterior deltoid, Posterior deltoid, Pectoralis major, Biceps brachii and Triceps brachii were monitored. Further details on data acquisition and processing can be found in Appendix A.

A performance index (PI), was used to identify the change in the muscle recruitment between the workloads 25 W and 35 W, and the calculated values were compared between the two modes of propulsion. Eq. (1), represents the formula used to calculate the PI value in percentage for each individual muscle (ranging from

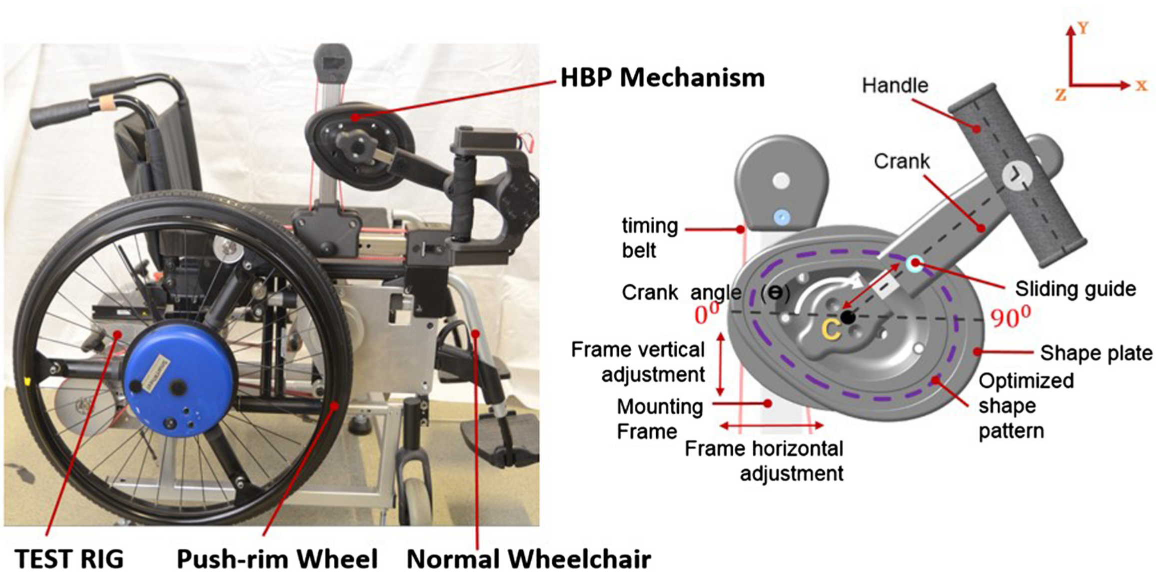

Fig. 1. Standard push-rim wheelchair attached to controllable custom made test rig (left) and handle based propulsion mechanism (right).

−100 to +100) (Pouran D Faghri, 2015) with EG_{peak} representing the mean peak EMG values from 3 individual propulsion cycles from each subject at each of the workloads.

$$PI = \frac{EG^{35W}_{Peak} - EG^{25W}_{Peak}}{EG^{35W}_{Peak} + EG^{25W}_{Peak}} \times 100 \quad (1)$$

The statistical analysis includes the determination of mean and standard deviation of the EMG_{peak} values for all the individuals across both workloads for each propulsion type. A two-way (propulsion-groups × workloads) analysis of variance (ANOVA) along with Bonferroni post-hoc correction was applied for the EMG_{peak} for both groups across the two workloads. In addition, a T-test was performed to find any significant differences between the PI values of the muscles in the two propulsion modes.

3. Results

From the study, the mean peak muscle activities of the subjects were calculated for both propulsion modes. A general trend of increase in the peak muscle magnitude was observed across the workloads (see Table1). The highest EMG_{peak} was exhibited by the Pectoralis major muscles (82.60 ± 10.11%) while propelling the push-rim wheelchair at 35 W power. A significant difference in EMG_{peak} ($p < 0.050$) was observed between all the muscles when compared between the HBP and push rim groups at 25 W and 35 W respectively. Push rim propulsion produced higher EMG_{peak} values at both workloads for Anterior deltoid, Posterior deltoid, Pectoralis major and Triceps brachii muscles, while Biceps brachii was the only notable muscle group with higher activity during the propulsion with HBP. No significant differences were found between the average PI of muscles when compared with HBP and push rim. A two percent increase in muscle recruitment was observed by the Anterior deltoid muscle in push rim when compared to HBP, due to increase in workloads. Conversely, Triceps brachii exhibited a greater PI value when propelling the HBP. Fig. 2 shows the muscle's activity intervals over a whole propulsion cycle for both HBP and push-rim propulsion. For both propulsion modes, muscles were active over the whole propulsion cycle, however the activation patterns were different. In HBP, the Biceps brachii muscle group is active over a much longer interval than in push-rim propulsion. The length of the activity intervals increases with increasing workload for both propulsion modes, with notable differences in the Triceps brachii and Biceps brachii muscle groups. In addition, with the increase in workload the onset of muscle activity is earlier in the propulsion cycle (Anterior deltoid, Posterior deltoid, Pectoralis major, and Biceps brachii). When comparing the onset and offset values of experienced push-rim users from literature to the values observed in our study, the anterior deltoid in our study showed a similar pattern as in literature but with a late offset after 20% of the propulsion cycle and an early onset in the later phase of the propulsion cycle for both workloads (Mulroy et al., 1996), while the deltoid posterior showed a reduced duration of activity at 25 W compared to 35 W. The onset of the pectoralis major was a bit late at 25 W, while activity duration was shorter at 35 W when compared to literature (Mulroy et al., 1996). The activity of biceps was similar to literature while the triceps had an earlier onset in both propulsion modes.

4. Discussion

Experiments on wheelchair propulsion with healthy subjects using an optimized handle based propulsion unit and standard push rim at two different workloads were performed, and the data were analyzed to compare muscle activations.

Analysis of the peak muscle activations indicates that the increase of workload leads to an increase in muscle activity for both propulsion modes, and is consistent with previous studies (Suzuki at al., 1982). The peak EMG values in push-rim propulsion indicate that for both workloads 25 W and 35 W, Anterior deltoid, Pectoralis major and Triceps Brachii were maximally recruited during the push phase of propulsion and Posterior deltoid for the recovery phase in this study. Whereas in HBP, all muscles contributed evenly to the propulsion. Positive values of the performance index PI gave an understanding of the percent of muscle fibers recruited with increasing workloads. As expected, in push-rim propulsion, the peak activities of agonist and antagonist muscles of the elbow region were highly mismatched, i.e., muscle groups of Triceps brachii had greater activity (see Table1) and duration (63%(25 W) and 74%(35 W)) than Biceps brachii (8%(25 W) and 25%(35 W)) during the propulsion stages. In HBP, on the contrary, the muscles had more balanced durations with Biceps brachii (50%(25 W) and 48% (35 W)) and Triceps brachii (31%(25 W) and 52%(35 W)). This suggests that the use of HBP can improve the load distribution on agonist and antagonist muscle groups of the elbow joint. The activity of these muscle groups can improve blood circulation and help to postpone the local muscle fatigue in the arms (Ambrosio et al., 2005; Dallmeijer et al., 2004). In addition, the over-exertion of the prime movers, especially Pectoralis major along with other rotator cuff muscles (not described in this study), in push-rim propulsion can lead to reduced muscle endurance which directly decreases the humeral head depression forces, which can lead to shoulder impingements (Santos Requejo et al., 2008). Pectoralis activity in HBP is lower when compared to push-rim propulsion, this may help to prevent injuries.

Table 1
Normalized EMG peak magnitude and performance Index (PI) across the two workloads for both propulsion modes (mean ± SD).

Workload (W)	25 W		35 W	
Propulsion	HBP	Push-rim	HBP	Push-rim
Anterior Deltoid*	28.72 (16.60)	58.84 (15.32)	36.07 (16.28)	80.20 (8.56)
Posterior Deltoid*	23.88 (10.01)	54.77 (18.43)	29.96 (13.23)	68.56 (22.79)
Pectoralis Major*	24.95 (13.65)	65.72 (15.61)	34.21 (23.29)	82.60 (10.11)
Biceps Brachii*	36.57 (7.50)	10.61 (5.67)	48.23 (13.76)	14.15 (9.29)
Triceps Brachii*	24.77 (9.00)	40.15 (10.56)	34.61 (12.36)	51.12 (10.92)
Muscles	HBP (PI) (%)	Push-rim (PI) (%)		
Anterior Deltoid	+16.36 (27.87)	+18 (12.40)		
Posterior Deltoid	+10.81 (8.65)	+11.33 (7.26)		
Pectoralis Major	+12.59 (15.20)	+12.38 (9.24)		
Biceps Brachii	+13.12 (7.40)	+12.12 (12.37)		
Triceps Brachii	+14.22 (10.91)	+12.27 (11.81)		

Note:
* Significance was set as P value less than 0.050 for all analyses.

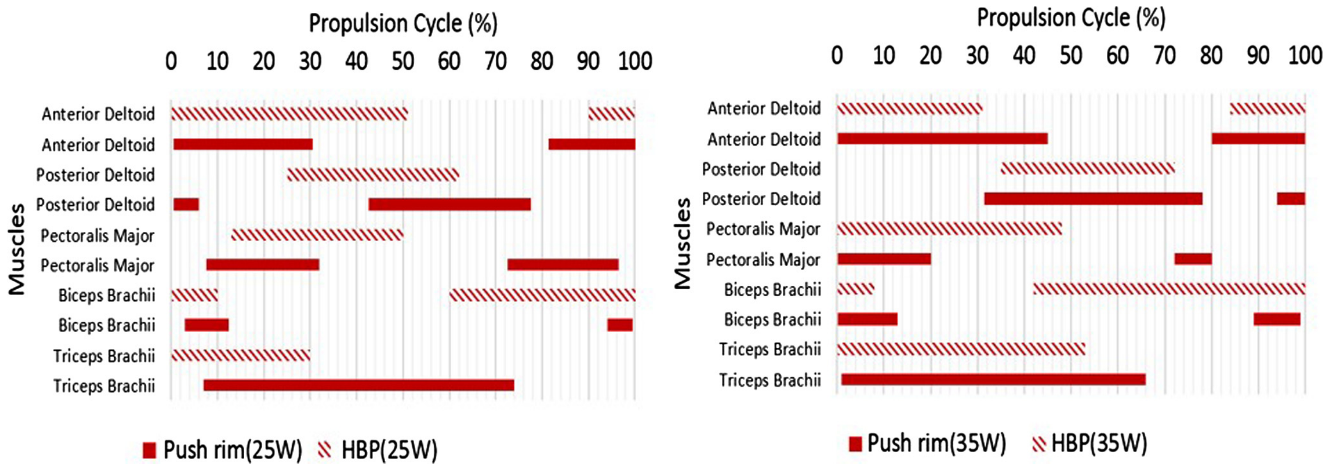

Fig. 2. Mean muscle activation intervals for the two propulsion modes at 25 W and 35 W workloads respectively.

There are a few limitation that need to be addressed. Firstly, all the subjects tested were non-wheelchair users, results of muscle activity may differ for prolonged wheelchair users who have already adapted to the push rim propulsion movement, but studies comparing experienced to novice push-rim users have shown that there is no significant difference in the movement pattern across the two groups (Veeger et al., 1992) and the abled bodied subjects in our study performed homogenous exercise at both propulsion modes as they had no restriction due to disability and they were equally inexperienced on both modes of propulsion. Secondly, the users were allowed to propel the push rim at self-selected styles, this can have an influence on the propulsion cycles, the muscle activity and the efficiency. Thirdly, quantification of muscle activity from surface EMG signals is problematic when movement is involved and motion artefacts and other electromagnetic noises may influence the signal levels. We tried to minimize disturbances by the applied signal processing and filtering routines, still artefacts may have small impact on the derived maximum muscle activations (Table 1).

This preliminary study of muscle activity on both propulsion modes suggests that HBP might be a suitable alternative to the push-rim, especially for prolonged wheelchair users who are suffering from joint injuries. The HBP mechanism can also be used for indoor rehabilitation purposes by long term wheelchair users, who are not physically active to use hand cycles and lack proper trunk control due to SCI. The HBP can help to improve their overall muscle strength, muscle imbalances and decrease their risk for overuse injuries.

Conflict of interest

The authors report that there are no conflicts of interests.

Acknowledgments

This research work was supported by Austrian Science Fund (FWF), grant (P 25507- B24).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2019.04.011.

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