Pushrim kinetics and coordination patterns of shoulder muscles during surface and incline wheelchair propulsion

Qi L[1], Ferguson-Pell M[1], Grange S[1], Pilarski P[2]

1. Faculty of Rehabilitation Medicine, University of Alberta, Edmonton, Canada
2. Alberta Innovates Centre for Machine Learning, University of Alberta, Edmonton, Canada

Abstract

The objective of the study was to investigate how the coordination patterns of shoulder muscles and wheelchair kinetics change with surface and incline during wheelchair propulsion. The wheelchair kinetics and EMG activity of 7 muscles were recorded with surface electrodes on 15 able-bodied subjects during wheelchair propulsion on a stationary ergometer and on a wooden ramp (4 degree slope). Kinetic data were measured using SMARTWheel. The kinetics variables were compared for 2 sessions using the paired t-test. Muscle coordination patterns across 7 muscles were analyzed by principal component analysis (PCA). Push forces on the pushrim increased significantly during incline propulsion, which was coincident with higher EMG activity in the push muscles,anterior deltoid (AD), (pectoralis major)PM, and (biceps brachii)BB. Incline propulsion showed a significant longer push phase than level propulsion, which was associated with significantly longer EMG duration of the push muscles during incline propulsion. These results suggest that different muscle recruitment strategies were present in different wheelchair propulsion conditions. The muscle coordination patterns were affected by propulsion condition and posture.

Introduction

People with spinal cord injuries (SCI) usually rely on their ability to propel a manual wheelchair for independent mobility[1]. Achievement of the highest degree of independence in a manual wheelchair often depends on the user's ability to negotiate a range of environments and overcome indoor and outdoor obstacles. Ramps of varying degrees are frequent outdoors and within indoor settings. Laboratory investigations have revealed shoulder joint forces [2, 3] and muscle demands [4] are greater during inclined propulsion than during level propulsion. Wheelchair users therefore adopt different postures and employ different stroke techniques to suit different locomotion tasks [5]. When moving up a ramp they tend to lean forward more than when moving along a level surface moving their centre of gravity forward; and on the incline they tend to push the wheel by arcing strokes rather than by the semi-circular motion used in level propulsion. It is unclear as to how shoulder muscles are coordinated to adequately perform inclined propulsion. The various muscles that maintain the stability of the shoulder joints through coordinated and balanced activation will thus show markedly different recruitment patterns between incline and level propulsion.

Surface electromyography (sEMG) is a non-invasive method for quantifying muscle activity. Several studies have reported shoulder muscle activity during wheelchair propulsion [6, 7]. Advanced signal processing techniques have enabled the analysis of muscle coordination patterns. Wavelet analysis offers possibilities to optimize the analysis with respect to time- and frequency-resolution of non-stationary physiological signals [8]. In the present study, principle component analysis (PCA) was chosen as the method for quantifying the coordination patterns across several muscles. To better understand the applicability of shoulder EMG data, kinetic data were integrated to confirm when certain muscles are active during different phases of wheelchair propulsion. The purpose of the present study was thus to investigate, using EMG and kinetics, the shoulder muscle coordination patterns during ramp versus level wheelchair propulsion on able-bodied participants. The hypothesis was that incline propulsion would change muscle recruitment patterns of the shoulder muscles. A better understanding of the muscle coordination pattern is important for developing appropriate and effective therapeutic exercise programs for wheelchair users in order to enhance their performance and to prevent injuries.

Materials and Methods

Participants

15 able-bodied participants (8 males, 7 females, age: 30±4 years, weight: 65±12 kg) volunteered to participate in this study. They all gave their informed consent in accordance with the procedures approved by the University of Alberta Ethics Committee. None reported any previous history of upper extremity pain or neuromuscular disorder. Participants were instructed not to perform any exercise 48 h before measurements.

Surface electromyography

Surface electromyography (sEMG) activity of upper extremity muscles was recorded using parallel-bar EMG Sensors (DE-3.1 double differential sensor, 1mm in diameter and separated by 10 mm, Bagnoli^{TM}, Delsys Inc., Boston, MA, USA). Double differential electrodes were used to reduce crosstalk from deeper muscles. sEMG signals were detected on seven muscles: *anterior deltoid* (AD), *middle deltoid* (MD), and *posterior deltoid* (PD), *pectoralis major* (PM), *upper trapezius* (UT), *biceps brachii* (BB), and *triceps brachii* (TB) of the right shoulder after prior removal of the hair and cleaning with alcohol swipes.

Kinetics

The SMARTWheel (Three Rivers Inc., LLC, Mesa, AZ, USA) was used for the collection of kinetic data. The SMARTWheel is a modified mag-wheel capable of measuring three-dimensional forces and moments occurring at the pushrim. The pushrim kinetic data were collected at 240 Hz. The SMARTWheel was placed on the right side of the test wheelchair fitted with a standard foam cushion. This test wheelchair was mounted on an ergometer which was connected to a LCD display placed in front of the participant to provide visual speed feedback. Kinetic and EMG recordings were synchronized.

Procedure

Maximum Voluntary Isometric Constraction (MVIC) test

To facilitate comparison between studies, the EMG signals were normalized by performing maximum voluntary isometric contractions (MVIC).

Wheelchair propulsion at ergometer and ramp

Wheelchair ergometer: A test wheelchair with each participant was aligned and secured over the rollers of an ergometer. The ergometer consists of two independent steel cylindrical rollers, one for each wheel, supported by pillow-block bearings (NSK P208 Japan). Participants were given several minutes to get used to propelling the wheelchair and to establish a comfortable propulsion technique. Data were recorded at a speed of 1m/s for 1min during propulsion. 1m/s was selected because it is close to minimally safe speed[9].

Ramp: A wooden ramp of 4° was constructed. It is 4.1m long and 1.3m wide. The ramp led to a 1.3m*1.2m platform. Each participant performed 2 trials of incline propulsion along the ramp at a self-selected speed.

Kinetics data analysis

The key kinetic variables calculated were mean resultant force (F_{tot}), mean tangential force (F_t), and mean propulsion moment (Mz). The resultant force (F_{tot}) is the total force applied to the push rim. The tangential force (F_t) is the force directed tangentially to the pushrim. Mz is the moment acting to cause forward motion. Mechanical effectiveness (ME) was calculated by F_t / F_{tot}. % push phase is the percentage share of the push phase in the total propulsion cycle. In addition, by using the output of the SMARTWheel, the push frequency (number of pushes per second) and push length (length of palm-on to palm-off, in degrees) were determined.

Wavelet and principal component analysis (PCA) of the EMG signal

All signal processing was performed using custom programs written in Mathematica (version 6.0, Wolfram Inc., Champaign, IL, USA). EMG data were normalized to the percentage of cycle time and synchronized with kinetic data. The EMG signals were resolved into intensities in time-frequency space using wavelet techniques [8]. The EMG intensities from all 7 muscles were used to construct grids that define the muscle coordination pattern for each propulsion cycle, and principal component analysis (PCA) was used to identify predominant coordination patterns during the propulsion cycle. PCA analysis takes as input the set of muscle coordination patterns across all tested propulsion cycles and finds the principal components (PCs) that describe the major features within these coordination patterns.

Results

Kinetics

F_{tot}, F_t, Mz, push length increased significantly during ramp propulsion (Table 1). Ramp propulsion shows a significantly longer %push cycle than the level propulsion. No significant differences were found in mechanical effectiveness between level and ramp propulsion.

Table 1: Kinetics variables for level and ramp propulsion. Data were reported as mean ± SD.

Condition	Level	Ramp
Speed (m/s)	0.9 (0.1)	0.6 (0.1)
mean F_{tot} (N)*	33.8 (9.9)	83.4 (17.5)
mean M_z (N.m)*	6.2 (1.1)	17.5 (2.8)
mean F_t (N)*	24.1 (4.4)	67.9 (12.2)
Push Length (degree)*	60.1 (7.3)	67.5 (12.2)
% Push Phase*	42.9(6.4)	67.2(6.9)
Mechanical Effectiveness	0.7(0.1)	0.8(0.1)

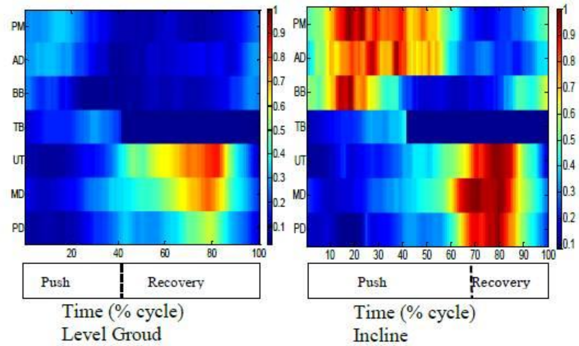

Figure 1. Reconstructed EMG intensity for the level and ramp propulsion from the tested 7 shoulder muscles. EMG intensity scales are normalized to the maximum intensity for each muscle in the range of [0, 1] where the color map represent the intensity of EMG signal. Time base of propulsion cycle was normalized to 100% with push phase denoting hand-on-hand-off moment of the pushrim.

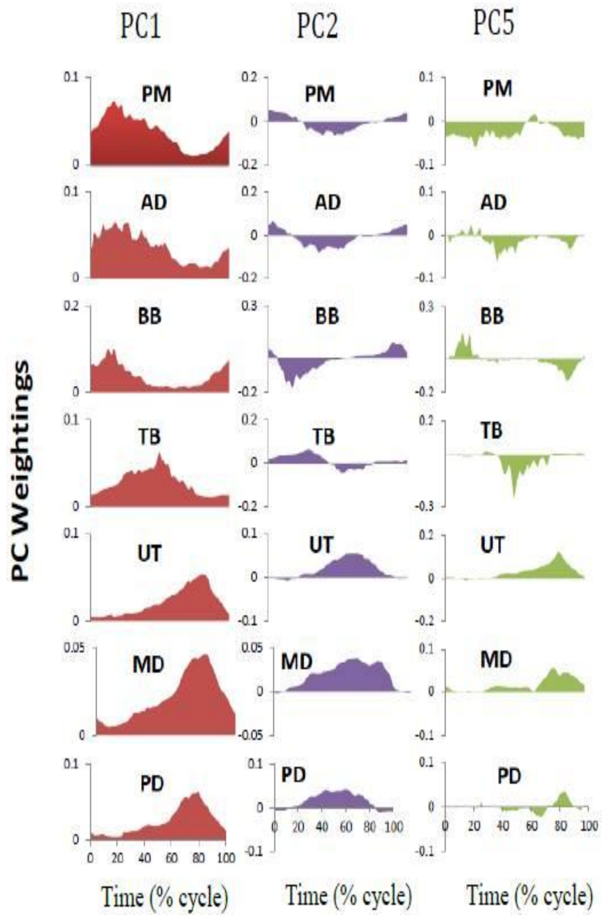

Figure 2. The weightings of PC1, PC2, and PC5. PC1 explains 24.5% of the overall coordination patterns. PC2 and PC5 explain 7.4% and 5.3% of the overall coordination patterns respectively. Time base of propulsion cycle was normalized to 100%.

Compared to level propulsion, AD, PM, and BB had a significantly longer EMG duration in the ramp propulsion. Ramp propulsion showed a significantly shorter EMG duration in UT, MD, and PD than the level condition, which is consistent with the shorter recovery phase in ramp propulsion (Fig.1).

PC1, PC2, and PC5 loading scores were significantly different between incline and level propulsion. The EMG intensities were reconstructed from the sum of the products of the PC weights and their loading scores for each cycle, using the first 10 PCs (more than 50% of the signals), that describe the major features of the coordination (Fig.2).

Discussions

The shoulder muscles are activated for distinct periods within each propulsion cycle. The push phase synergy is dominated by the AD, PM, and BB [6, 7], whereas UT, MD, and PD have their primary activity during the recovery phase. The significantly longer EMG duration of the push muscles during incline propulsion was coincident with the longer %push phase, which demonstrates an effective adaptive response of the synergistic muscles to the environmental requirements.

Previous authors have suggested differences in muscle recruitment between incline and level propulsion using measures of EMG amplitude [10], which do not directly quantify coordination across muscles. Integrated with kinetic measurements, each propulsion cycle could be analyzed with respect to the global patterns of muscle coordination. Principal component analysis was used to capture the most relevant features of the original EMG activation patterns across muscles. Positive or negative weighting of PCs 2 and 5 in Fig. 2 denote positive or negative contributions of those PCs to the coordination pattern for a specific condition. PC2 loading scores were different between the two conditions, which represents a different coordinated motor behavior between incline and level propulsion. Most participants applied the semicircular stroke during level propulsion, which is associated with arms moving behind the body to start a push. This motion requires muscle activity of PM, AD, and BB in the late recovery phase as the arms return and prepare for the next push. During incline propulsion, participants adapted the arcing stroke and forward lean posture. Mean negative PC2 loading scores during incline propulsion were associated with more intense and longer EMG activity of push muscles in the push phase and less EMG activity of recovery muscles. TB was more active during incline propulsion. Compared to the descriptive EMG profile of onset, cession, and duration of individual muscles, PCA analysis captures most of the relevant features of the original EMG activation patterns across muscles. It is encouraging to see that PCA resolved functional differences in the coordination patterns that were not detectable using the traditional EMG statistics. This approach allows for patterns and trends in EMG characteristics to effectively and consistently map to patterns of physical activity, generating a 'signature' for the activity which can be likened to a 'tomogram' of electrical activity. This approach can be extended to create a library of predicted behavior that with machine learning, may be used to illustrate variance from predicted response to demand, and as with earlier work [11]on the impact of fatigue, this may be used to provide feedback to users or other control systems, to better coordinate muscle patterning activity.

Conclusions

The present study shows the differences in kinetics and EMG activity patterns of superficial shoulder muscles during level and ramp propulsion. EMG intensity of the push muscles increased significantly during incline propulsion, which corresponds with the increased kinetic data total force output in the incline condition. PCA was used in this study to quantify the coordination patterns between level and incline propulsion. The reconstructed EMG patterns using the 10 first PCs showed EMG activities of push muscles, PM, AD, and BB, in the early push phase and late recovery phase during the level propulsion, whereas in the incline propulsion, push muscles showed more and longer EMG activities in the push phase. PD showed more EMG activities during the recovery phase, which may be associated with forward lean and downward push during incline propulsion. The application of PCA to EMG data shows that this method of capture features from surface EMG signals that can provide insight not only on the activation state of motoneurons, but also on the coordination of muscles, opening new windows for both neurophysiological and clinical/ rehabilitation studies.

References

1. Curtis, K.A., et al., *Shoulder pain in wheelchair users with tetraplegia and paraplegia.* Arch Phys Med Rehabil, 1999. **80**(4): p. 453-7.

2. Veeger, H.E., L.A. Rozendaal, and F.C. van der Helm, *Load on the shoulder in low intensity wheelchair propulsion.* Clin Biomech (Bristol, Avon), 2002. **17**(3): p. 211-8.

3. Lin, H.T., et al., *Muscle forces analysis in the shoulder mechanism during wheelchair propulsion.* Proc Inst Mech Eng H, 2004. **218**(4): p. 213-21.

4. Sabick, M.B., B.R. Kotajarvi, and K.N. An, *A new method to quantify demand on the upper extremity during manual wheelchair propulsion.* Arch Phys Med Rehabil, 2004. **85**(7): p. 1151-9.

5. Richter, W.M., et al., *Stroke pattern and handrim biomechanics for level and uphill wheelchair propulsion at self-selected speeds.* Arch Phys Med Rehabil, 2007. **88**(1): p. 81-7.

6. Mulroy, S.J., et al., *Effects of spinal cord injury level on the activity of shoulder muscles during wheelchair propulsion: an electromyographic study.* Arch Phys Med Rehabil, 2004. **85**(6): p. 925-34.

7. Mulroy, S.J., et al., *Electromyographic activity of shoulder muscles during wheelchair propulsion by paraplegic persons.* Arch Phys Med Rehabil, 1996. **77**(2): p. 187-93.

8. von Tscharner, V., *Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution.* J Electromyogr Kinesiol, 2000. **10**(6): p. 433-45.

9. Cowan, R.E., et al., *Preliminary outcomes of the SmartWheel Users' Group database: a proposed framework for clinicians to objectively evaluate manual wheelchair propulsion.* Arch Phys Med Rehabil, 2008. **89**(2): p. 260-8.

10. Chow, J.W., et al., *Kinematic and electromyographic analysis of wheelchair propulsion on ramps of different slopes for young men with paraplegia.* Arch Phys Med Rehabil, 2009. **90**(2): p. 271-8.

11. Qi, L., et al., *Changes in surface EMG signals and kinetics associated with progression of fatigue at two speeds during wheelchair propulsion.* Journal of Rehabilitation Research and Development 2012. **49**(1): p. 23-34.

Acknowledgements

This project is funded by a Dorothy Hodgkin Postgraduate Awards, Engineering Physical Sciences Research Council (EPSRC), UK, with support from the Royal National Orthopaedic Hospital Special Trustees.