DYNAMICALLY OPTIMIZED MUSCLE ACTIVITY PATTERNS FROM A NOVEL HANDLE BASED PROPULSION MOVEMENT FOR A WHEELCHAIR

Nithin Babu Rajendra Kurup[1], Markus Puchinger[1] and Margit Gföhler[1]

Institute for Engineering Design and Logistics Engineering, TU Wien, Vienna, Austria [1]

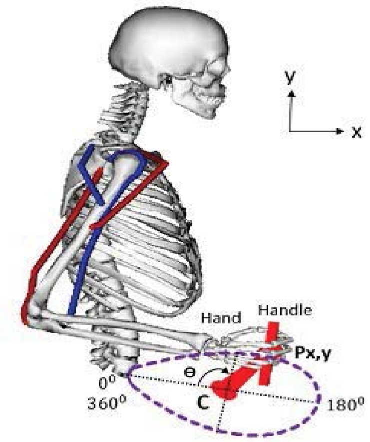
The purpose of this study was to determine the muscle activity patterns resulting from dynamic optimization of a novel continuous wheelchair propulsion movement having a circularity ratio of 0.89. For the study four major muscle groups were selected and a bang-bang control strategy was adopted to reduce the complexity and time for the optimization with a cost function to increase the net propulsion power. The successful completion of the optimization resulted in muscle excitation and activation curves for each actuator and a net power > 30 watts. The proposed propulsion mechanism can act as a substitute for the normal propulsion mechanisms used in daily life and sports activities.

KEY WORDS: wheelchair, optimization, muscle activity.

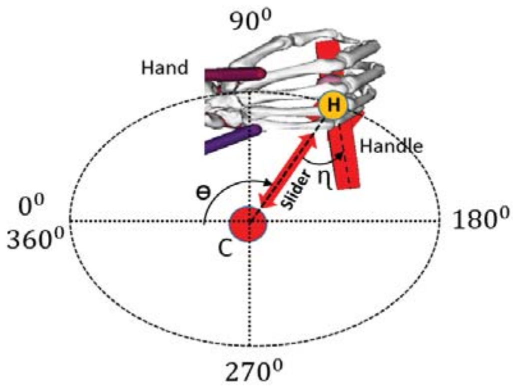
INTRODUCTION: Wheelchairs are conventionally used as a means of transport for persons having disabilities and for rehabilitation purposes. Nevertheless a considerable population of the users utilize them for sports and more physically engaging activities such as wheelchair marathons, wheelchair football etc. Out of the many propulsion techniques available for wheelchair users the push rim based propulsion is the least efficient and leads to serious upper extremity injuries due to discontinuous arm movements (Woude et al., 2001). It is noted that arm-crank propulsion mechanisms that commonly applied in tricycle sports are more efficient in terms of higher peak drive power and significantly lower physical strain. Based on this concept a novel propulsion mechanism “handle-based propulsion” in the parasagittal plane of the wheelchair defined by the wheels is introduced that has a unique propulsion pattern and provides a continuous hand-handle movement within the ergonomic ranges of motion of the upper extremity joints.

Previous studies have used dynamic optimization routines to solve optimal control problems in 3D musculoskeletal models and many studies have used these models to study kinetic and kinematic relationships involved during wheelchair propulsion, hand cycling etc. (Arnet et al., 2012). The aim of this study is to use a dynamic optimization routine to obtain the muscle activity patterns from the selected major muscle groups for the provided path of propulsion for the wheelchair. The resultant muscle forces and the propulsion power will be noted. It is expected that the obtained propulsion power from the path will be sufficient to drive a conventional wheelchair, hence acting as an alternative to the conventional modes of propulsion.

METHODS: For this study an upper extremity 3D model containing 7 degrees of freedom (dof) was selected and modified (Saul et al., 2015) as shown in Figure1a. by utilizing the biomechanics software OpenSim 3.2 (Delp et al., 2007). For this preliminary study four major muscles were selected Deltoid anterior (Delt1), Deltoid posterior (Delt3), Biceps long (Biclong) and Triceps long (Trilong). The force generating properties of these selected actuators were defined by the dynamic muscle model (Thelen, 2003) as proposed by Thelen having muscle activation and deactivation time constants of 0.015 and 0.050 milliseconds respectively and a maximum fibre contraction velocity set at 10 meters per second. The novel wheelchair propulsion mechanism is located in the same parasagittal plane as the wheel. This mechanism consists of a crank rotating around the crank centre (C) which is represented by a pin joint, a slider that moves along the crank and hence can change the effective crank length (l_C) as a function of the crank angle during the rotation, and the handle connected to the slider with the pin joint H. In total the mechanism has two degrees of freedom, the crank angle (ɵ) and the angle between crank and handle (η). To complete the closed loop structure, the hand and the handle components are welded rigidly. The initial configuration of the propulsion mechanism is such that the crank is in a horizontal position pointing towards the thorax with the handle in a near perpendicular position with respect to the crank. The crank rotates in the clockwise direction. For simplicity the crank rotation was divided into two phases, the push phase ranging from 0^0-180^0 and the pull phase from 180^0-360^0. The handle follows a path having a circularity ratio of 0.89 and was obtained as a result of a path optimization performed in a parallel study, with variables defined from a parametric equation provided by (Weisstein, 2017). Further details of path optimization and its variables are not elucidated in this paper. Generation of the propulsion path involved the conversion of the Cartesian coordinates of the path Px,y obtained from the aforementioned optimization as depicted in Figure 1, to a polar form and then obtained l_C was used to prescribe the slider joint with respect to the crank angle. The shape of the path was formulated in manner such that the motion of the upper extremity components were within the ergonomic joint range of motions thereby avoiding over extrusion of the joints. The crank angular velocity was set to a constant 50 revolutions per minute (rpm) to emulate an isokinetic ergometer.



a.



b.

Figure 1 a) Musculoskeletal model connected to the propulsion mechanism with the prescribed handle path (dotted lines) b) Indicating the model components and angles present in the propulsion mechanism.

For the dynamic optimization a bang-bang control strategy was implemented for the muscle actuators in order to simplify the optimization process, reduce computational time and decrease the number of optimization variables. By following this approach the muscle actuators will be at an instance completely excited or at an instance completely turned off. The parameterization of this control strategy involves using 2 optimization variables for each actuator as illustrated in Figure 2: the time (t1) at which excitation in the range from 0 to 1 starts and the duration (duration1) of the excitation. In total 8 parameters of the muscle actuators were optimized using the Interior Point optimization algorithm with an objective function to increase the net propulsion power (in Watts).

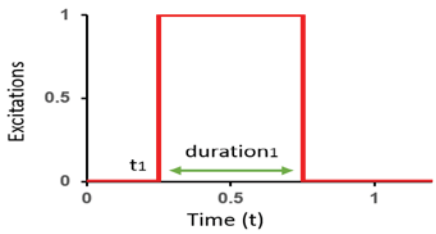


Figure 2 Representing the bang-bang control for the muscle excitation optimizations

RESULTS & DISCUSSION: The dynamic optimization was successfully performed for the 8 variables describing muscle excitation patterns at 50 rpm, and the corresponding trajectories for muscle activation were obtained (Figure 3a).

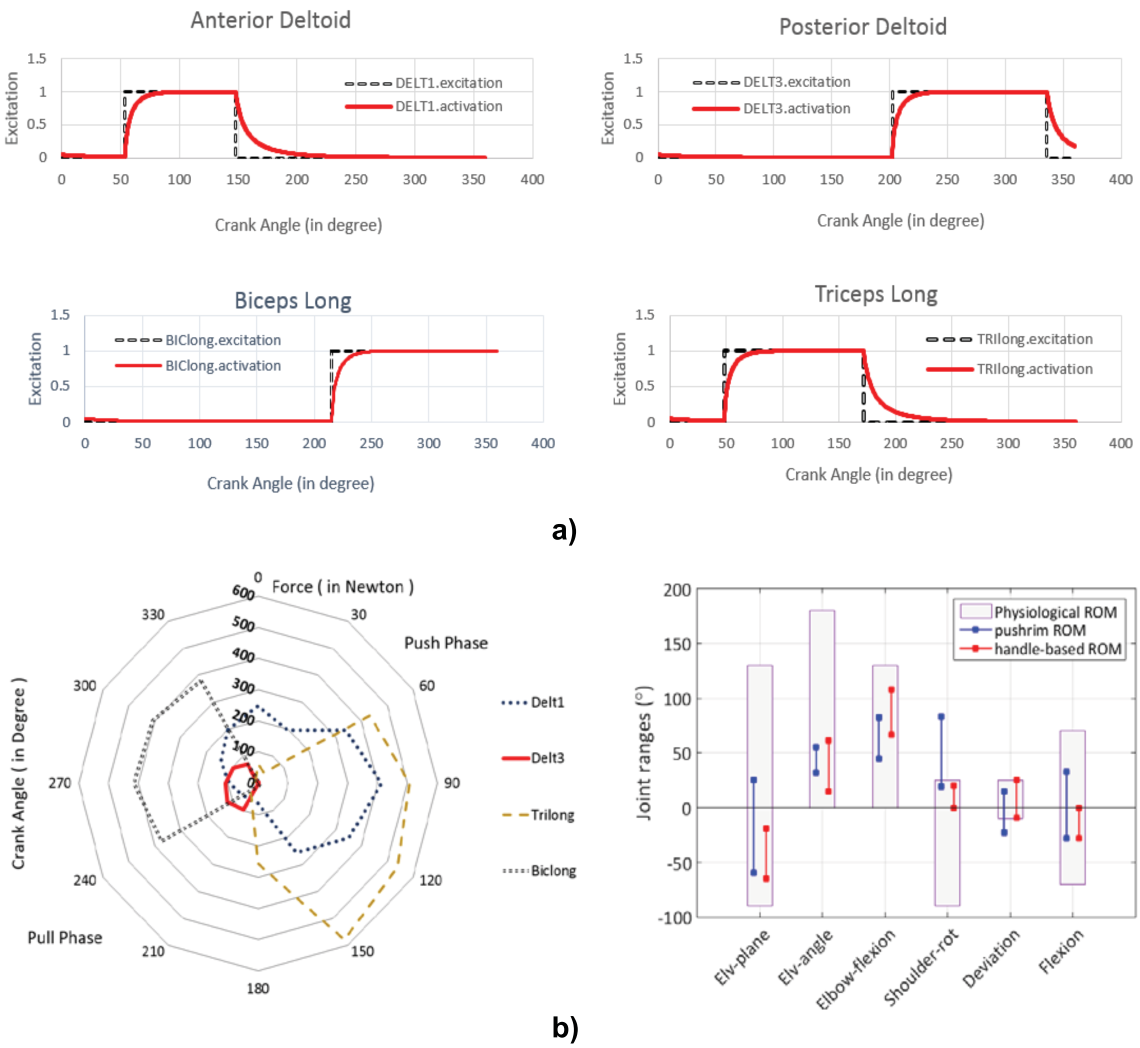


Figure 3 a) Bang-bang muscle excitations and the related muscle activation patterns resulting from the optimization. b) Overview of the muscle forces (N) generated by the actuators during the phases of propulsion (left) and a comparison of the range of motion during push-rim propulsion and handle based propulsion (right).

The optimization for the novel path having a circularity ratio of 0.89 resulted in an overall propulsion power of 36 watts , which is in a normal range needed for push-rim propulsion for daily life activities (Richter et al.,2007), increasing the rpm values above 50 rpm can generate higher propulsion power and can be applied for sports activities. Since propulsion on the novel path generated a power of the magnitude required for normal wheelchair propulsion, the “handle-based propulsion” method can be considered as an alternative mode of propulsion. It was observed from the muscle activity patterns (figure3a) that both Anterior deltoid and Triceps long were activated in the initial push phases, where they showed maximum muscle activity then switching into an off state before the transition from push to pull phase. The muscle groups of Posterior deltoid and Biceps long had greater muscle activity in the pull phase of the propulsion cycle. As Biceps and Triceps are antagonist and agonist in nature, the Triceps contributed by generating elbow extension resulting in a forward push, conversely the Biceps produced an elbow flexion causing a pulling motion of the handle. Figure3b. (left) depicts the force profile produced as a result of optimization. The force values and the joint range of motions as shown in Figure3b (right) are in the same range as results presented in literature for both wheelchair and hand cycle propulsion (Morrow et al., 2014). These studies were performed on 3D human models and validated using experiments on human subjects. The force characteristic of the muscles of the 3D model used in this study was designed based on a 50^{th} percentile adult male. It was observed that the anterior deltoid exhibited force values above 200N during the initial starting position as well as maintaining equivalent force values in the pull phase even though the muscle activations were quite low, the reasonable explanation for this would be the passive stretch exhibited by the muscle at the beginning and terminating position resulting in the production of considerable force.

CONCLUSION: Wheelchairs are very important for daily mobility, recreational activities and sports for disabled persons. Using a 3D human model, a dynamic optimization was performed on a novel propulsion pattern, and by considering muscle excitations as optimizing factors a net propulsion power required for daily activity and sports was obtained. As expected, the obtained propulsion power from the optimized path is in the same range as for conventional wheelchair propulsion, Further studies need to be performed by considering more muscles in the 3D model along with real experimental data to validate these simulation results. The bang-bang control approach used here has a serious drawback as it only allows a single excitation phase during the entire crank rotation with constant amplitude, while in physiologically muscles can undergo multiple excitations with varying amplitude, this should be replaced with a better control strategy for future studies.

REFERENCES:
Arnet, U., Drongelen, S., Scheel-Sailer, a, Woude, L., & Veeger, D. (2012). Shoulder load during synchronous handcycling and handrim wheelchair propulsion in persons with paraplegia. *Journal of Rehabilitation Medicine*, *44*(3), 222–228.

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T.Thelen, D. G. (2007). OpenSim: Open source to create and analyze dynamic simulations of movement. *IEEE Transactions on Bio-Medical Engineering*, *54*(11), 1940–1950.

Morrow, M. M., Rankin, J. W., Neptune, R. R., & Kaufman, K. R. (2014). A comparison of static and dynamic optimization muscle force predictions during wheelchair propulsion. *Journal of Biomechanics*, *47*(14), 3459–3465.

Richter, W. M., Rodriguez, R., Woods, K. R., & Axelson, P. W. (2007). Stroke Pattern and Handrim Biomechanics for Level and Uphill Wheelchair Propulsion at Self-Selected Speeds. *Archives of Physical Medicine and Rehabilitation*, *88*(1), 81–87.

Saul, K. R., Hu, X., Goehler, C. M., Vidt, M. E., Daly, M., Velisar, A., & Murray, W. M. (2015). Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model. *CMBBE*, *18*(13), 1445–1458.

Thelen, D. G. (2003). Adjustment of muscle mechanics model parameters to simulate dynamic contractions in older adults. *Journal of Biomechanical Engineering*, *125*(1), 70–77.

Weisstein, E W. (2017) "Teardrop Curve." Retrieved from *MathWorld*--A Wolfram Web resource. http://mathworld.wolfram.com/TeardropCurve.html.

Woude, L. Van Der, Dallmeijer, A., Janssen, T., & Dirkjan Veeger. (2001). Alternative Modes of Manual wheelchair ambulation, (October), 765–777.

Acknowledgement
This work was funded by the Austrian Science Fund (FWF), grant P 25507- B24.