EVALUATING MOVEMENT CONSISTENCY IN WHEELCHAIR PROPULSION USING FLOQUET MULTIPLIERS AND QUATERNIONS

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Wheelchair users may develop repetitive stress injuries that are associated with the wheelchair-stroke. Evaluating if a stroke pattern is consistent may reveal the existence of a possible injury. However, there is no standardized method to evaluate the stability of the wheelchair-stroke. The purpose of this paper was to develop a method to measure movement consistency during manual wheelchair propulsion without the need of norm-referenced tests. The method is based (a) on the Floquet theory, (b) on Poincaré, and (c) on quaternion transformations. The method was evaluated with experimental data and the results showed that the method is sensitive enough to identify instabilities in the wheelchair stroke cycle. Furthermore, the method can be generalized to study other aspects of human motor control.

KEY WORDS: transformation matrix, stability, non-linear dynamics, Poincaré maps

INTRODUCTION: Manual wheelchair propulsion (MWP) imposes strenuous demands on the upper extremities. Many manual wheelchair users (MWU) after some years of wheelchair use start to experience repetitive stress injuries on the upper extremities (Bayley et al, 1987, Wylie & Chakera, 1988). It is important then to identify the movement characteristics that will allow MWU to interact with the wheelchairs in an efficient way with minimal risk of injury. Efficiency has been related with movement consistency and stability. So a lot of times researchers are looking to find efficient patterns, that MWU can adopt, by finding stable movement patterns. However, a consistent movement pattern may indicate (a) that there is a properly learned efficient stroke cycle (Winter, 1989), or (b) that there is a forced tendency for a particular movement pattern because of an impairment or an injury (e.g. there is no variability in knee flexion if someone wears a knee-brace that does not allow the knee-flexion). Additionally, any impairment may impose decrease in movement speed but this speed reduction will not necessarily decrease movement variability (Dingwell & Cusumano, 2000). Moreover, in wheelchair propulsion there are only two studies (Boninger, Cooper, Robertson, & Shimada 1997; Vrongistinos, Wang, Pascoe, Hwang, Marghitu, 2000) that examined movement stability from cycle to cycle.

The above literatures converge to the conclusion that dynamic stability requires new analytical techniques beyond traditional methods (e.g. coefficient of variation). Dingwell and Cusumano (2000) used localized Lyaponov exponents to examine the rate of divergence of successive trajectories; whereas other researchers (Hurmuzlu, & Basdogan, 1994; Hurmuzlu, Basdogan, & Carollo 1994; Hurmuzlu, Basdogan, & Stoianovici, 1996; Marghitu, Kincaid, Rumph, 1996) have used Floquet Multipliers to evaluate when a movement solution converges to a stable phase. Its method has advantages and disadvantages. The localized Lyaponov exponents method does not assume periodic movements, but ignores certain spatial-temporal variations (a pendulum moving in the same pattern may be not moving consistently if its period is continuously decreasing, it is moving faster from cycle to cycle). On the other hand the Floquet method includes the first derivatives of the state variables but assumes periodic motions. A previous research about wheelchair propulsion (Vrongistinos, et al., 2000) used the Floquet method in a simple linear model to evaluate stability of the hand (end-effector). However the linear model does not represent a true state space model, and thus cannot capture all the states of the system.

The purpose of the study was to implement a model using the Floquet method to examine movement consistency during MWP, and thus to evaluate MWP stability using kinematics data of individuals without the need to make comparisons with other individuals.

METHOD: The model is based (a) on the Floquet theory that is used to solve periodic differential equations and to measure the stability of nonlinear oscillators, (b) on Poincaré maps that are used to extract information about differential equations, and (c) on state space representation of the system using quaternions. The model included three segments (a) upper-arm, (b) lower-arm, and (c) the hand. Experimental data were collected at 200Hz with a Watsmart system from a male subject that pushed a wheelchair on a roller for 30s at 40% and 80% of his maximum speed (measured before in an all out speed trial). Seven markers were used to calculate the kinematics data. The markers were placed on top of the fifth metacarpophalangeal joint (IM1), second metacarpophalangeal joint (IM2), the ulnar styloid (IM3), lateral epicondyle (IM5), and greater tubercle (IM7). Additional markers were placed (a) between IM3 and IM5, and (b) between IM5 and IM7 non-collinearly with the line defined by the other two markers. The markers were placed in such a way as to have a triplet of markers in each segment to define local coordinate reference systems.

Normalized quaternions (Euler parameters) represent transformation matrices as four-dimensional vectors. It is important to grasp that contrary to transformation matrices, that have infinite number of representations, quaternions have only two-representations that can be reduced to one if it is hypothesized that movements from frame to frame are happening through the shortest path. Thus, quaternions and their derivatives can be treated as state space variables; whereas Cardan (or Euler) angles are not state space variables as angular velocities cannot be represented as the derivatives of another vector. The state space model was constructed by using eight-degrees of freedom (four Euler parameters and their derivatives), for each joint (shoulder, elbow, wrist) for a total of 24 variables. Equation 1 represents the state of the system

$$[\,U\,] = [\,u_1, u_2, u_3, u_4, \ldots, u_{24}, \square_1, \square_2, \square_3, \square_4, \ldots, \square_{24}\,]^T \qquad (1)$$

where T means transpose, u is a state variable, and □ is the first derivative of u. So the system moves from cycle to cycle through a specific Poincaré section (a plane in three-dimensions) mapping itself through a transformation. The transformation is expressed with Equation 2 that maps the system from frame A to frame B on the same Poincaré section

$$[U_B\,] = [J]\,[U_A] \qquad (2)$$

where J is the Jacobean matrix. Thirty-one cycles were used to measure the stability of the system. As the state space variables were 24, 25 were the minimum cycles required. The two matrices (M_B, M_A) were 24 by 30 in size (different by one frame) and we used Equation 3 to find the Jacobean (24x24) that was subsequently used to calculate the eigenvalues of the system.

$$[U_B\,] = [J]\,[U_A] \quad => \quad [J] = [M_B\,]\,[M_A]^{-1} \qquad (3)$$

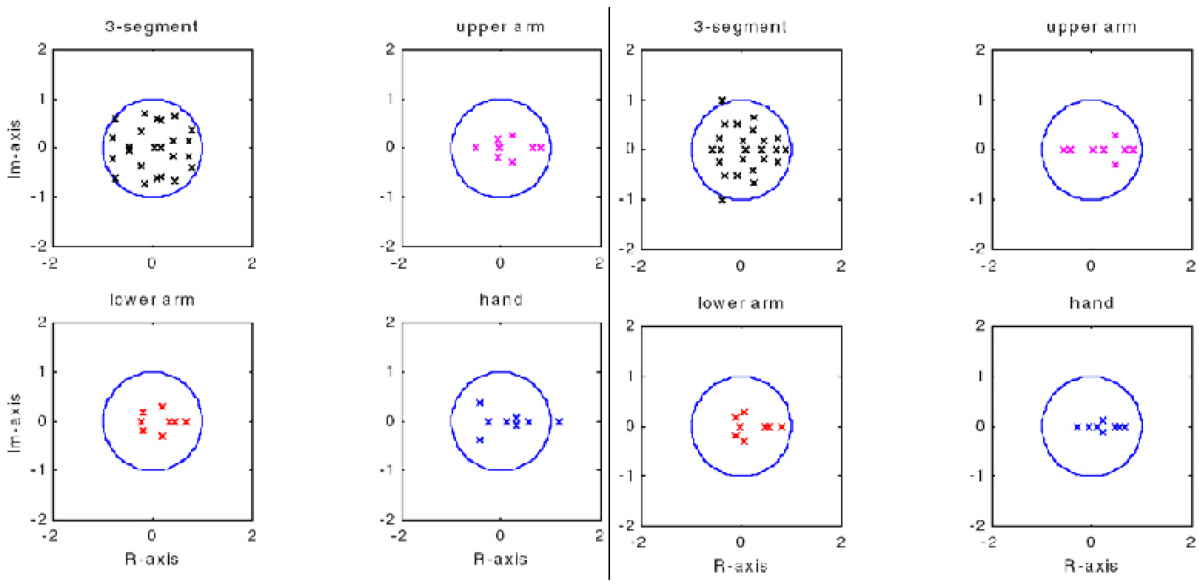
The Floquet multipliers are the eigenvalues of the Jacobean matrix and they determine the stability of the system. Floquet multipliers with magnitude (as most eigenvalues are complex numbers) less than one imply a stable model; whereas Floquet multipliers with magnitude more than imply an unstable model. If a Floquet multiplier has an eigenvalue exactly equal with one, then the system is marginally stable.

Instead of choosing an arbitrary plane as a Poincaré section to collect the state space data, two points of the stroke cycle were chosen. The first point was the point prior to the hand contact with the pushrim, and the second was the point of the release of the pushrim.

Although some authors (Hurmuzlu, & Basdogan, 1994) consider not necessary to measure different points in the cycle to determine the system's stability, other authors (Iooss, & Joseph,1990) support that the Floquet multipliers will have different values when the differential equation of motion is considered a force oscillation. Additionally, the stability of individual segments was examined in relation with the stability of the overall system.

RESULTS: The results indicated that at the low speed-condition (40%) the system was stable, as all the Floquet Multipliers (eigenvalues) had magnitude less than one in both contact and release points. Additionally the Floquet Multipliers of the three individual segments, if they were treated as a separate system, were within the unit circle.
However, the high-speed (80%) condition was marginally stable during the contact point, as two eigenvalues was equal with one. Interestingly the results showed that the hand, if it was treated as a separate system, would have been classified as unstable, whereas the other two segments would have been classified as stable (see Figure 1.(a).). The state of the system at the high-speed condition showed unstable behavior during the release point, as two eigenvalues were outside the unit circle (see Figure 1.(b).). However, if each segment was treated as an individual system they would have been classified as stable. The reader should note that the eigenvalues often appear as a pair of complex conjugates, so if one eigenvalue has magnitude more than one there will be another eigenvalue more than one unless the eigenvalue is real.

CONCLUSION: The results showed that during the low-speed condition the system was stable; whereas in the high-speed condition the system was unstable. Although it can make sense this result contradicts findings from other researchers (Dingwell, & Cusumano, 2000). The differences may exist because of (a) the different methodology and algorithms that were used, (b) the differences in neuromuscular control of gait and of wheelchair propulsion, (c) the current study is a case study and more subjects are needed for conclusive results. However, the results agree with previous findings of a linear model (Vrongistinos, et al., 2000) that showed that the lower-speed condition in MWP was more stable than the high- speed condition.
The results also demonstrated two other interesting points that can be generalized about the implementation of the current algorithm or the Floquet Method in general.
First, MWP should be considered a forced oscillation periodic movement, and not a freely evolving system. This assumption has face validity and it is supported by the experimental findings that two points in the cycle did not exhibit the same results. Furthermore, this result has sound theoretical support from the theory of differential equations (Iooss, & Joseph,1990).
The second point was that the stability of the three-segment system was independent from the stability of the individual segments. In the high-speed condition during contact point, where the system appeared marginally stable, the hand was unstable. It is logical that the hand as the end effector of the system will have more variability than the other segments, trying to compensate errors of the other two segments. So the whole system might appear to be stable or marginally stable when a specific segment alters its spatial-temporal configuration in order for the system to achieve its purpose. In MWP the hand demonstrated instability in order for the three-segment system to contact the pushrim in a consistent fashion. It is possible that the neuromuscular system makes arbitrary adjustments to compensate perturbations of the effector system without any regard to individual segmental stability. On the other hand, at the time of release the system demonstrated instability although the individual segments appeared stable. This is interesting to the practitioner because a lot of times researchers characterize something stable or unstable by one isolated variable when the whole system may be unstable. MWP impose a specific movement trajectory after the initial contact until the point of release. This does not mean that individual segments have to behave in a certain way from cycle to cycle but that the overall system will behave under the constrictions of the environment. The model showed that can discriminate between consistent movement patterns and inconsistent movement patterns. The method requires further exploration but the results showed that it can be used from the sports or clinical practitioner to examine consistency of movement patterns for individuals. The difficulty however for such a model is the data collection, as the model requires to collect data for eight cycles for each joint that is used in the model.



(a) (b)

Figure 1 - (a) Left 80% condition contact point, and (b) right 80% condition release point. Upper left graphs represent the 3-segment model, upper right graphs represent upper-arm models, low left graphs represent lower- arm model, and low right graphs represent hand models. A stable system has all the eigenvalues within the unit circle, an unstable system has at least one eigenvalue outside, and a marginally stable system has an eigenvalue equal to one.

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"BIOMSOFT": A SOFTWARE FOR BIOMECHANICAL ANALYSIS OF HUMAN MOVEMENT

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The package "BiomSoft" is a set of MATLAB functions blocked in modules, useful and user friendly which allow the parameterisation of general motor patterns. "BiomSoft" enables to treat digital signal in different ways, calculate kinematic and kinetic magnitudes, provide different anthropometric models and present results graphically, which is useful in teaching. The objective of "BiomSoft" is to provide a complete processing and analysing Biomechanics data system with the possibility of to incorporate new functions and to perform particular applications in sports, medical and occupational Biomechanics, as well as in teaching and learning.

KEY WORDS: biomechanics, human locomotion, signal processing

INTRODUCTION: Biomechanics of Human Movement is an interdisciplinary science that, with the support of other Biomedical Sciences, uses the knowledge of mechanics and different technologies to study the human body behaviour under the mechanical loads that it can be subjected to. The development of Biomechanics, mainly during the second half of the last century, is in consequence to its progressive applications in the medical and occupational fields, and also in sports, analysing sport technique and designing sport gear of high quality. Sport Biomechanics is one of the main fields of Biomechanics of Human Movement and continues to expand and to establish in the wide field of Sport Sciences. Nowadays, many applied research projects are orientated to the evaluation of the performer's technique in the totality of the sports and sport modalities. The major goals of the application of biomechanical methodology and results are to optimise load in training and performance improving the performer's technique in a sport or sport modality. Also, scientific research has contributed to design sport equipment with the high quality standards. Furthermore, the development of better measurement systems and/or instrumentation chains enables researchers to quantify with much more precision the biomechanical efficiency in sport activities, identifying the main characteristics of the most productive individual technique, the trainable factors that influence the performance, and, the mechanical loads on the muscle-skeletal system. Finally, the conception and design of technical solutions and aids for disabled help them to compete, improving their quality of life.