Clinical application of the upper limb motion analysis during wheelchair propulsion

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Abstract

Manual wheelchair propulsion results in a physical demand on the upper extremities that, due to its repetitive nature, leads to chronic pain, specially at wrist and shoulder joints. These problems are increasing because life expectancy of patients with spinal cord injury has incremented during recent years. In fact, the consequence of the long-term use of the wheelchair presents a biomechanical challenge as the upper extremities are not designed to support propulsion repetitive movements. Analyzing the manual wheelchair propulsion gesture with a biomechanical approach provides objective data on the loads and movements that the upper limb supports. Therefore, transferring this biomechanical analysis towards the clinical field through an application will help the facultatives on taking decisions. In this paper, an application which provides flexibility, all the needed information and a report with the key data of a propulsion test has been developed.

1. Introduction

The brain, together with the spinal cord, sets up the central nervous system (CNS). The spinal cord is the main pathway that transfers motor and sensory information from the brain and distributes it to the rest of the body and vice-versa.

The main challenge of this complex circuit is its dependence on the connection with the brain. Therefore, any dysfunction in this critical part, either complete or partial, creates important consequences. Although there is still a vast gap of knowledge about spinal cord injuries, important improvements have been made in the last century [1]. Most of the people who suffered from a spinal cord injury needs a wheelchair to move independently and the use of a wheelchair after a long period derives in pain, impairments and injuries in the upper extremity. This has a direct impact on the quality of living of these patients [2]. In the majority of the cases, patients only report pain when it gets severe or really painful. Movement analysis, as a biomechanical approach, has been used to estimate joint movements and loads. Estimating the upper extremity loads and movements during wheelchair propulsion may help to unveil the relationship between gesture, wheelchair used and movement intensity amongst others. Therefore, such analysis would support the determination of the origin of the pain, the improvement of the propulsion gesture, the analysis of the wheelchair configuration impact as well as the impact of the use of ultralight and lightweight wheelchairs versus the standard ones. Taking this into account, together with the fact that there is no application developed for the clinicians to conduct such an analysis, this work is presented.

A clinical oriented application, along with an experimental protocol would enable clinicians without specific skills and technical knowledge on movement analysis, to perform a biomechanical analysis of manual wheelchair propulsion. Therefore, the objective of this paper is to develop a clinical oriented application in which a complete biomechanical analysis is embedded, guiding the clinicians through the process of performing a wheelchair propulsion test and providing them with the necessary information to accomplish the analysis as well as to generate a comprehensive report with the outcome of the analysis. Therefore, a deep and objective study could be performed in a faster and more efficient manner.

The article is organized as follows: section 2 presents an overview of a traditional mathematical approach for biomechanical inverse dynamics analysis. Section 3 shows the technologies actually used. Section 4 presents the data processing implemented for the kinematic and kinetic analysis followed by the software application developed. Section 5 shows an experimental test accomplished using the methodology described and the results of the experimental test. Finally, section 6 presents the conclusions of this work.

2. Biomechanical analysis

The anatomy of the upper limb can be represented as a kinematic chain linked by different joints [3]. The shoulder, elbow and wrist are the joints and the trunk, the upper arm, the forearm and the hand are the segments connected by those joints. It is quite complex to represent accurately the human body with a kinematic chain, but a good approximation could be made in order to understand the physiological and biomechanical functions of each component. This approach will help to select the most suitable number of the degrees of freedom as it is key to find a compromise between precision and outcome pursued.

For implementation, different joints of the upper limb are analyzed: the wrist, the elbow and the shoulder.

2.1. Kinematic analysis

Kinematics describe movements of the body through space and time, including displacements and therefore velocities and accelerations but with no references to forces or moments involved in the movements. There are several methods to perform a kinematic analysis and the choice of the method depends on the problem to solve and the means available to develop a solution.

In this case, in which the upper extremity will be analyzed, the inverse kinematics method is used to obtain information of the positions of the different joints [4]. This analysis consists of obtaining the joints parameters when the final position of the kinematic chain is known. Therefore, for calculating the position of the different joints knowing the final position of the arm, the Euler angles will be used [5]. This rotation description is aligned with the most used method in Biomechanics in the clinical environment as it describes the movements of the upper limb in a more realistic manner, by combining movements from different movement planes. However, this method is complex as it needs to pay attention to the order of the rotations and therefore, the order of multiplying the different matrices. For our study, the recommendations of the International Society in Biomechanics (ISB) have been followed which does not only recommend a specific sequence of rotations but also how to set the local anatomical reference systems [6].

2.2. Kinetic analysis

Kinetics describe the forces and moments that cause movement. An inverse dynamic approach is followed to estimate the forces and moments of the joints. It considers the limb and joint kinematics, the external forces and moments exerted on the limbs, and the geometric and inertial characteristics of the limbs.

Both internal and external forces need to be considered. In the case of studying the forces and moments present during wheelchair propulsion, internal forces are the ones coming from the muscle activities, joints, ligaments or friction between the different parts of the body and external forces are the ones coming from the wheels of the wheelchair (active forces) or the wind resistance (passive forces). Therefore, a variety of kinetics analysis could be done.

The following considerations are taken into account in this analysis:

• The kinematic analysis needs to be performed previously, to know the location of the components of the limbs and joints that form the kinematic chain.

• The anthropometric model that supports the modeling of the upper limb needs to be set; that is the geometric and inertial characteristics.

• A model has to be selected to make the calculations according to the study performed.

3. Technologies used

Motion capture techniques are used quite broadly nowadays thanks to the different technologies available and for a very broad field of applications. In this section the technologies used for this biomechanical analysis are described.

3.1. Kinescan system

This is a photogrammetry system provided by the IBV (Instituto de Biomecánica de Valencia) based on passive markers that are detected thanks to an infrared light which is coupled to a digital camera [7]. This technology obtains positions in space by the intersection of two or more photogramms. Reflective markers are placed on the patient's bony landmarks to track them in 3D and obtain their positions.

Furthermore, this system allows the synchronization with the device that acquires kinetic data on the hand-handrim contact point.

3.2. Smartwheels

Smartwheels are used to acquire forces and moments of the hand-handrim contact point [8]. These wheels gather information about forces during the interaction between the hand and the ring of the wheel while propelling. Smartwheels are designed in a way that the size of the wheel is the regular size for a wheelchair and there is an instrumented ring that collects the force information thanks to the strain gauge and encoder integrated into the wheel.

The Smartwheels can be attached to any wheelchair so that the tests could be done with the wheelchair that the patient normally uses or with a different one if needed.

4. Clinical Application

The information obtained from both, the Kinescan and the Smartwheels, is processed through a custom-made software interface in which the inverse dynamic and post-processing algorithms are embedded, being transparent to the user. Different scripts are created to process all the data and the general process followed is shown in Figure 1.

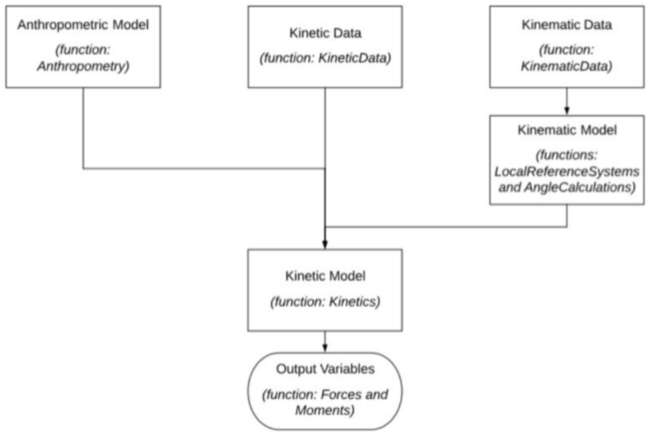

Figure 1. *General approach of the process data processing*

The aim of all these functions is to obtain the forces and moments in all joints taking into account the positions of the markers in different local reference systems, the anthropometry of the upper limb (see Figure 2), the Euler angle calculations and, of course, the filtering of the data obtained by both, Kinescan and Smarthwheels. This data processing is the one that would feed the application to develop.

Therefore, a clinical application which allows the clinical staff to obtain all biomechanical results without the need for having a deep technical knowledge and without having to deal with any programming software has been developed. Moreover, a report functionality is incorporated into the solution based on the interaction with the processed data creating a comprehensive solution.

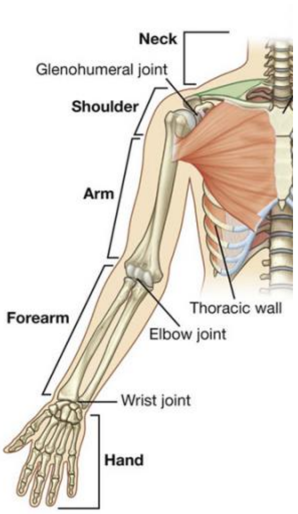

Figure 2. *Upper limb structure*

To start with the design of the clinical application, the indications from the clinical team of the Biomechanics and Assistive Technology Unit of the Hospital Nacional de Parapléjicos were followed. Also, similar applications such as the one used in gait analysis with the CODA system have been studied [9].

The interface created is clear, focused and supporting the user through the logic of a propulsion test. This interface is organized in four different tabs as shown in Figure 3 and the language is Spanish as it has been designed for a Spanish hospital.

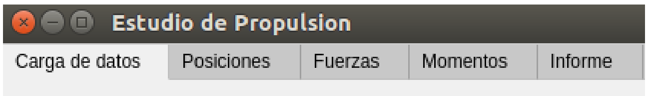

Figure 3. *Tabs generated for the clinical application*

The first tab of the interface ("Carga de datos", meaning "data load") loads the data needed for the analysis and perform the calculations. It has two buttons: one to load the data from the Smartwheels and another to load the data from the Kinescan software. Once this information is gathered, a calculation option needs to be included so that the program can start running.

The interface has to call the needed information from the MATLAB scripts through .mat files to be able to show the information to the clinician. In the second, third and fourth tabs, information about the positions, forces and moments of the different joints are shown. At the beginning, each of the tabs would be empty giving the option to the user to select any or all of the joints in case this is needed. A small legend is provided to the clinicians so that they are guided in understanding the graphs. Some guidance is needed to know what the positive and negative values means and this is included in each of the them.

Figure 4 shows an example of the graphs plotted in the interface. The mean (black) and the standard deviations (red and blue) are shown in all graphs. The interface allows to zoom in and zoom out for visualizing specific details.

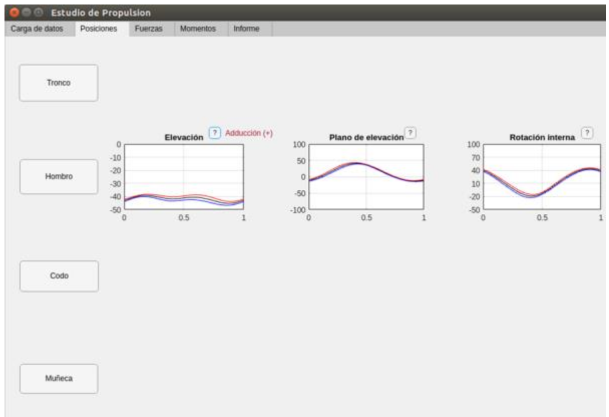

Figure 4. *Positions tab with legend*

In the case of forces and moments, graphs are shown for the different joints on the different axes: x, y and z axis.

The last tab includes a report generator. In this tab the clinicians would fulfill the information required for the report generation and, once the Report Generation button is clicked, a document is generated with the relevant information extracted from the graphs, as well as the graphs themselves.

Once the application was created, a validation test has been done together with clinicians at the Hospital. Personal interviews with the clinicians, a questionnaire about the tool developed as well as an experimental test were performed in order to properly validate the tool.

5. Experimental Test and Results

This experimental procedure focuses on validating the application performing a kinetic and kinematic analysis of the propulsion of two similar wheelchairs with a small difference in weight. Moreover, a protocol for the clinician which sets the steps to take in order to accomplish such an analysis is developed. This protocol provides details about how and where to locate the reflective markers, how to record and export the data for data processing and, finally, how to analyze it with the developed clinical application.

The two models of wheelchairs used to perform this experimental test are:

- Invacare Action 3: it has a seat surface of 43 cm x 40 cm (width x depth) and a weight of 13.5 kg.
- Quickie Life: it has a seat surface 43 cm x 38 cm (width x depth) and a weight of 12 kg.

The invacare model is the one available at the Hospital Nacional de Parapléjicos de Toledo and the quicke model has been provided by an orthopedics to perform this test.
Taking into account these characteristics, the objective was to perform a pilot study to verify that such a difference on weight of the wheelchair does not have a direct impact on the positions, forces and moments on the different joints of the arm. This pilot study has been accomplished with five able-bodied subjects that propelled both wheelchairs randomly at a speed of 3 kilometers per hour during 30 seconds in a treadmill. According to the developed program, the mean values and the standard deviations of all the positions, forces and moments are obtained as well as the values from the different cycles during wheelchair propulsion. At the end of the experimental session, an usability test is conducted in

order to gather detailed feedback of the end-users, the clinicians. To accomplish this usability test, personal interviews and a non presential questionnaire were given to get appropriate feedback.

5.1. Results

Once all the variables are obtained, a statistical analysis is done to check that no differences exist between the two models of wheelchairs previously presented. As the sample for this pilot test is limited, a Wilcoxon non-parametric test for two related samples is conducted [10] which shows no significance. Then, a boxplot is used to analyze the data obtained as seen in Figure 5. In this figure the information from the wrist position is analyzed: the first two values correspond to the alpha value (ulnar-radial deviation), the second pair of values to the beta one (internal rotation) and, finally, the last values correspond to the gamma value (flexion-extension movement) [11]. In the case of the alpha and gamma values, there is a higher difference in the mean values but the statistical analysis does not show difference due to the quartiles. This boxplot also shows that the data distribution seems symmetric except for the gamma values when using the invacare action 3 wheelchair.

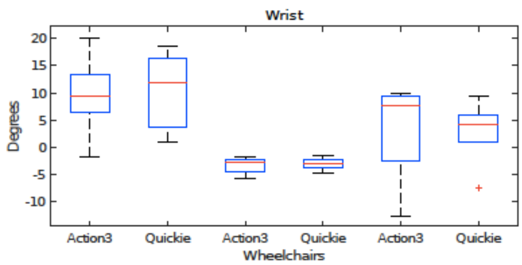

Figure 5. *Wrist position analysis with both wheelchairs*

This boxplot study is performed for all the joints' positions, forces and moments showing no statistical difference between the values obtained using the wheelchairs. Taking into account these results, it can be said that no difference appears by using the two wheelchairs analyzed in this pilot test and that the application developed has perfectly worked in the accomplishment of these tests, showing robustness and efficiency during the process.

From the usability test conducted, a positive feedback from the clinicians was obtained finding the tool useful. Also, improvements were suggested in order to make the application more clinically oriented such as including interactive messages in the screens and resizing the graphs given the option to the user to decide on upon this.

6. Conclusions

The main objective of this work was to transfer results from a research and development project based on the biomechanical analysis of the upper limb to a clinical application. With this transference, the clinicians could easily perform a propulsion study through a clinically-oriented, friendly application and a standard protocol that guides them through the analysis in a really fast and easy manner. To do so, a pilot study has been performed using this application. The realization of this test has been successful as well as the results. This development has been done taking into account the input from the clinicians.

This work opens the possibility to perform biomechanical studies that could support the wheelchair selection by providing objective data. Therefore, a further analysis should be done in this respect. Part of this analysis would be accomplished with the pilot study that is being performed during July 2018 using different wheelchairs with more difference in the configuration used by two group of patients: paraplegics and tetraplegics. This way, the impact on the kinematic and kinetics variables will be studied.

Acknowledgements

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References

[1] Nógrádi, A. Transplantation of Neural Tissue into the Spinal Cord, Second Edition. Springer, Szeged, Hungary, 2006 (ISBN: 0387263551).

[2] Cardenas, M. D. D. and Gerard, B. Upper extremity pain after spinal cord injury. *Spinal Cord,* vol 37, sup 3, 1999, pp 1-23 (ISSN: 1362-4393).

[3] Hingtgen, B., McGuire, J. R.,Wang, M., and Harris, G. F. An upper extremity kinematic model for evaluation of hemiparetic stroke. *Journal of Biomechanics,* vol 39, sup 4, 2006, pp 681-688 (ISSN: 0021-9290).

[4] Tolani, D., Goswami, A., and Badler, N. I. Real-time inverse kinematics techniques for anthropomorphic limbs. *Graphical Models*, vol 62, sup 5, 2000, pp 353-388 (ISSN: 1524-0703).

[5] Wu, G., Van Der Helm, F. C., Veeger, H. E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., and Buchholz, B. Isb recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part ii: shoulder, elbow, wrist and hand. *Journal of Biomechanics,* vol 38, sup 5, 2005, pp 981-992 (ISSN: 0021-9290).

[6] Mitchell, H. L. and Newton, I. Medical photogrammetric measurement: Overview and prospects. *ISPRS Journal of Photogrammetry and Remote Sensing*, vol 56, sup 5, 2002, pp 286-294 (ISSN: 0924-2716)

[7] Instituto de Biomecánica de Valencia. Kinescan/ibv v2014. http://analisisbiomecanico.ibv.org/productos/tecnicas-de-registro/kinescan-ibv.html. [Online; accessed 2018-06-10].

[8] University of Pittsburgh. Smartwheel — human engineering research laboratories — university of pittsburgh. http://www.herl.pitt.edu/smartwheel. [Online; accessed 2018-06-28].

[9] Codamotion. Movement analysis for clinical services - codamotion. https: //codamotion.com/movement-analysis-for-clinical-services/. [Online; accessed 2018-06-28].

[10] Landau, S. and Everitt, B. A handbook of statistical analyses using SPSS. Chapman & Hall/CRC Press LLC, Florida, USA, 2004 (ISBN: 1584883693).

[11] Hall, S. J. (2012). Basic Biomechanics, Sixth Edition. McGraw-Hill Companies, New York, USA, 2012 (ISBN: 978-0-07-337644-8).