Second International Conference on Multidisciplinary
Design Optimization and Applications,
2-5 September 2008, Gijon, Spain
www.asmdo.com/conference2008/

Multi-disciplinary Design Optimization for Human Well-Being and Overall System Performance

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Abstract

Human well-being and system performance is a multi-faceted field that often requires optimisation within the field of ergonomics. Simulation software such as the AnyBody Modelling System provides a unique tool for analysing the muscular-skeletal system of humans (and animals) that for given movements allows computing muscle forces, joint reactions, metabolism, mechanical work and efficiency. The use of this analysis tool permits to quantitatively analyse movement patterns, working positions and anthropometric data, which in turn enables automatic optimization to be carried out.

In this paper an integrated simulation process has been set up within the optimization software, modeFrontier, using AnyBody to calculate the muscular-skeletal forces for general movements using a full muscular-skeletal human mode to optimise ergonomic situations.

Some examples where the AnyBody calculations are used in modeFrontier to optimize certain general aspects in common life of the human body behaviour are presented. The optimisation examples included here are: a) determining the stiffness and position required for an accelerator pedal, and b) determining the seat position of a wheel chair to minimize the force required to move it.

1 Introduction

Nowadays Multidisciplinary Design Optimization (MDO) is becoming more and more a commonly used task in several engineering fields, such as the aeronautical and automotive Industry and as well in some fields of structural design. The application of optimization algorithms, such as gradient based or genetic algorithm and Pareto Frontier methods to optimize the trade-off, are gaining more recognition due to their efficiency and success to satisfy the intended requirements of complex engineering designs.

However, little, or no use at all, has been done in applying these techniques in the study of biomechanics or musculoskeletal dynamics. For instance in the case of the aeronautical industry, the physical modelling may be mathematical or experimental but the simulation of “human interaction” effects, in the use of flight simulators for example, has not been included to date.

Analysing the response of the human body to improve the comfort and performance when interacting within the environment and under several physical conditions requires a multi-disciplinary analysis since several assignments must be accomplished to achieve such an objective.

A musculoskeletal biomechanical analysis by itself is a complex task since it involves the interaction between several body parts. The AnyBody Modelling System provides a unique tool for analyzing the muscular-skeletal system of humans and animals. This software allows computing muscle forces, joint reactions, metabolism, mechanical work and efficiency for several types of movements. Based in this framework, therefore it is possible to quantitatively analyze movement patterns, working positions and anthropometric data which in turn enables automatic optimization to be carried out.

Now if an optimization of the interaction between human body and any object is desired, it will have to be performed under the frame of a Multidisciplinary Design Optimization in order to take into account all the factors that take part in this complex task. To achieve this type of analysis the multi-objective and multi-disciplinary design optimization program modeFRONTIER is used. modeFRONTIER basically is a design environment software that allows easy coupling to almost any computer-aided-engineering (CAE) tool that uses a variety of state-of-the-art optimization techniques, ranging from gradient-based methods to genetic algorithms, where users can optimize their process or design by specifying objectives and defining variables that affect factors such as geometric shape and operating conditions.

This paper briefly describes the modeFRONTIER optimization software and the AnyBody muscular-skeletal software systems used for carrying out the MDO relating to the human body. Some examples are described where this has been used very effectively in the design of components related to the automobile and medical/rehabilitation sectors.

2 modeFRONTIER multi-objective solutions

Optimization refers as the act, process, or methodology of making something, as a design, system, or decision, as fully perfect, functional, or effective as possible. From the mathematical point it is defined as a procedure to find the maximum (or the minimum) of a specific function, such as:

$$\max\left[f_1(x_1,\ldots,x_n), f_2(x_1,\ldots,x_n),\ldots, f_k(x_1,\ldots,x_n)\right]$$

$$\text{subject to}\begin{cases} \mathrm{g_i}(\bar{x}) \le 0 \\ \mathrm{g_j}(\bar{x}) \ge 0 \\ \mathrm{g_l}(\bar{x}) = 0 \\ \bar{x} \in S \end{cases} \tag{1}$$

In the case when $k>1$, and the functions are in contrast, the need to have a software program like modeFRONTIER emerges since the problem becomes a multi-objective optimization.

modeFRONTIER can be used as an integrated platform or a design environment for multi-objective (where the objectives are kept separate throughout the optimization process, rather than being collapsed into a single, weighted objective function from the beginning), and multi-disciplinary design optimisation allowing easy coupling to almost any computer-aided-engineering (CAE) tool that uses a variety of state-of-the-art optimization techniques, ranging from gradient-based methods to the increasingly popular genetic algorithms, where users can optimize their process or product by specifying objectives and defining variables that affect factors such as geometric shape and operating conditions.

The optimization process starts from an initial population of designs generated by means of the most efficient DOE (Design of Experiments) techniques then the design space exploration is conducted so as to determine the trade-off curve (Pareto Frontier) in the objectives space. A trade-off curve behaviour is typical of problems involving an optimization containing more than one, and often, conflicting objectives, where there is no fixed optimal solution, but rather a full set of optimal solutions. The whole process, from the DOE generation to the Pareto Frontier identification is carried out in an efficient and automated way by modeFRONTIER [1].

3 The AnyBody muscular-skeletal modelling system

The AnyBody Modeling System is designed for constructing complex models of the human body and for determining the environment's influence on the body, and it must consequently exhibit a computational efficiency that can only be obtained by inverse dynamics.

Kinematics is the initial stage that consequently plays a very important role in the process of muscular-skeletal analysis. While kinematics for mechanical analysis is a well-developed field, the modelling of the human body it still requires additional and quite special facilities to be considered. The analysis in the AnyBody Modelling System proceeds through a sequence of time steps defined by the user. A static problem has only one time step, and a dynamic problem has the time span of the analysis divided into steps of equal length. One of the advantages of inverse dynamic analysis is that time steps can be considered independent and without much bearing on the numerical convergence of the analysis. The purpose of the kinematic analysis is to identify each segment's position, velocity and acceleration in each time step. The AnyBody Modelling System uses the Cartesian formulation of the kinematic problem, in which each segment has six independent degrees of freedom, and constraints corresponding to joints are imposed on the full size system of equations. All segments of the mechanical system are modelled as rigid bodies, neglecting effects such as the wobbly masses of soft tissues.

The generality of the Cartesian method facilitates the implementation of useful features in the kinematic system. This is a major advantage in musculoskeletal modelling, where the complications of the human body kinematics and interfaces to the experimental techniques used in the field call for special considerations in the software architecture. The following two sections describe two such useful features, but more details can be found in the AnyBody Modelling System [2], Rasmussen et al [3] and Goldberg [4].

3.1 Kinematic measures

It is tempting to interpret the degrees of freedom of a human body model physiologically, for instance as the flexion of a knee or the twist of a forearm. However, binding the system to express the degrees of freedom in such physiological terms would seriously deplete the system's applicability for studies of humans in free movement and in connection with various types of equipment, and the general statement of the kinematic problem in fact allows for more flexible approaches.

In gait analysis, for instance, which is a major field of clinical diagnostics and research, movement is typically recorded by video tracking of optical markers attached to the body. The kinematics of the human body is sufficiently complex to make the conversion of marker positions to physiological joint angles a challenging task, and it would be desirable to be able to use the marker positions directly to drive the model. Another example is when the posture or movement of the human body is defined by its interaction with an artifact such as a bicycle, a hand tool, a chair, or a workplace. In the case of the bicycle, for instance, the movement of the feet is defined by the pedal cycle rather than the anatomical joint angles.

To enable definition of kinematics in terms of non-anatomical parameters, the AnyBody Modelling System has been equipped with an abstract concept named “kinematic measures”. A kinematic measure is just about any dimension that can be measured on the body model. Typical examples could be the distance between two points, the coordinates of a point (such as a video tracking marker) in space, the length of a muscle, or a joint angle. The concept of kinematic measures thereby encapsulates also the anatomical postural dimensions such as joint angles.

As an example of the generality of kinematic measures consider the problem of modelling a human body in an unsupported slow squatting movement (Figure 1). When performing such a task, care must be taken to maintain the position of the collective center of mass vertically above the contact line of the two feet on the ground, lest the model would fall over due to lack of forward/backward support. Since a squat involves individual movements of arms, trunk, thighs, shanks, and feet, it would be a very challenging task to specify a set of anatomical joint movements that would constrain the collective center of gravity. In the concept of kinematic measures, the collective center of mass is simply a point in the model, and it is consequently possible to drive it by inserting the specifications of its position into the position analysis. The consequence is that a driver on, for instance, the arm position can be neglected from the model, and the arms of the model will automatically attain the position necessary to balance the model in each stage of the movement, exactly as a test person would reach out in front of him during the squat to avoid falling backwards.

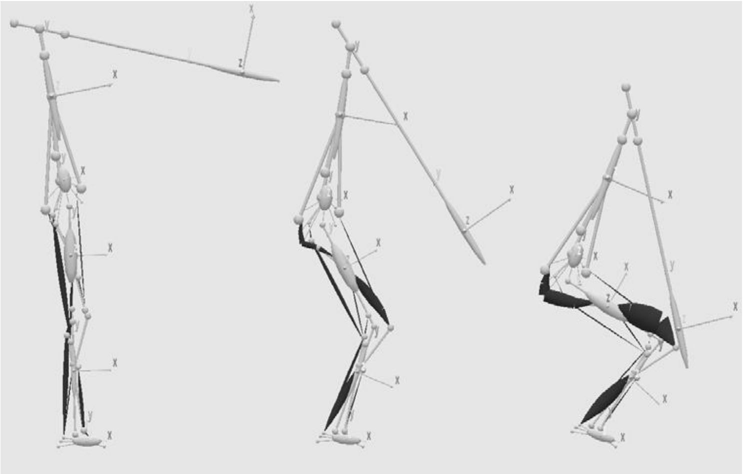

Figure 1. The control of arm positions in a squat model by means of the collective center of mass. The arm moves automatically to maintain the collective center of mass above the ball of the foot. The bulging of the muscles reflects the simulated muscle forces.

3.2 Muscle wrapping

One of the most complicated mechanical aspects of the human body is the fact that muscles wrap over bones and other tissues on their way from origin to insertion. When doing so, they exert forces to multiple parts of the segment surfaces, and as the model moves, the muscles slide over bones. Existing contact surfaces change or disappear, and new ones may arise.

The correct handling of this behaviour calls for algorithms of contact mechanics. An STL file is merely a collection of triangles, and almost any CAD system is capable of saving a surface representation on STL format. Thus, the CAD surfaces can be imported directly into the AnyBody model as shown in Figure 2. If the contact between the muscle and the bone is considered frictionless, then the identification of the muscle’s path over the bone essentially corresponds to an optimization problem: Minimization of the distance between origin and insertion with the bone surface as a territorial constraint on the path.

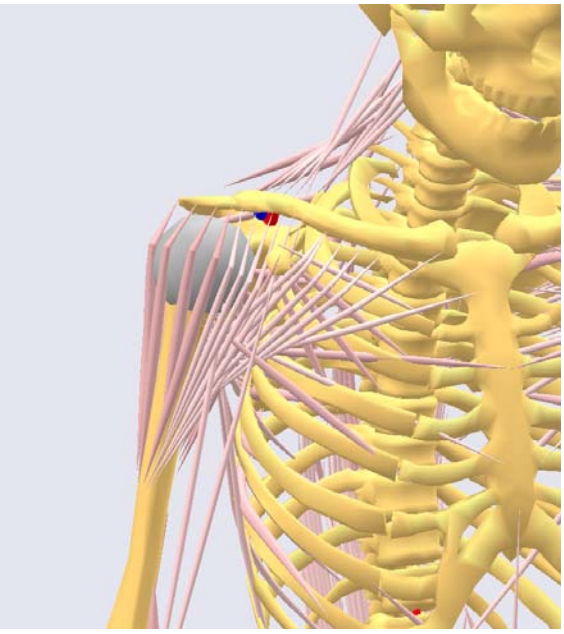

Figure 2. The deltoid muscle wrapping in the shoulder region.

This problem is modelled as a 3-D contact problem of an elastic string and a rigid obstacle representing the bone surface. The goal of this problem is to minimize the potential energy of the string. This way the shortest path of the string around the obstacle is obtained. The most important part in the formulation of this problem is to find the correct conditions for non-penetration of the analytical surfaces created by the system. The choice has been to use linearized contact conditions prescribing non-penetration of the surface by a point on the string in the direction of the outer normal vector to the surface. In the discrete case the method of prescribing the contact conditions of non-penetration is based on searching for contact pairs: point of string – closest surface in the normal direction - and collecting these conditions for all points of string discretization. Then the problem could be mathematically written into the usual form suitable for efficient solving in its dual form by fast algorithms.

4 Examples

To show the application of optimising designs that are based on human body movements we present some examples. Due to the relationship with the human species we use the Multi-Objective Genetic Algorithm (MOGA) even though we appreciate that the first version of these examples has only one objective (and other more efficient algorithms available in modeFRONTIER could be used) – future studies will include additional objectives.

4.1 Pedal design (automotive)

According to the automotive industry a good pedal design should provide an effortless and yet precise operation. This model example demonstrates how the pedal stiffness and the distance between the seat and the pedal influence the muscle effort of operating the pedal.

Consider a pedal hinged at one end and equipped with a torsion spring that stretches when the pedal is depressed. The dilemma is the following: if the spring is too weak, then the pedal will not provide much support for the leg, and the operator consequently has to extend the leg and hold it up against gravity, this will become very tiring. On the other hand, if the spring is too rigid, then the muscular effort of depressing it will become too large and repetitive operation of the pedal or static maintenance of a particular pedal position will cause fatigue. Similarly, different seat positions influence the muscular effort.

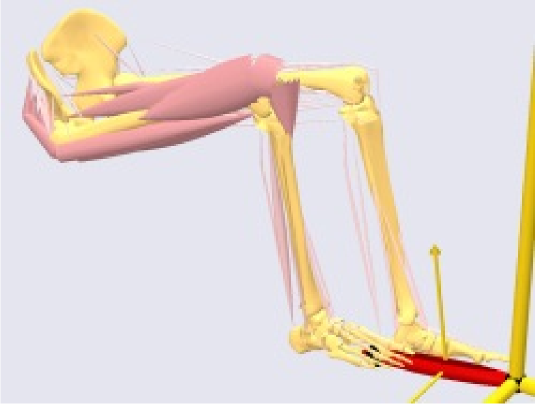

Figure 3: Model of legs and pedal

Even a simple model problem like this is too complicated to be thoroughly investigated by experimental methods. Coupling the muscular-skeletal modelling software inside the optimisation software it is possible to perform a systematic optimization to find the best solution of the spring stiffness and the seat position.

The problem was integrated into modeFrontier and an initial DOE of 9 designs was generated using the SOBOL algorithm to attempt to cover the parameter space as much as possible. Then the MOGA algorithm was used to find the Pareto frontier, submitting a total of 250 simulations.

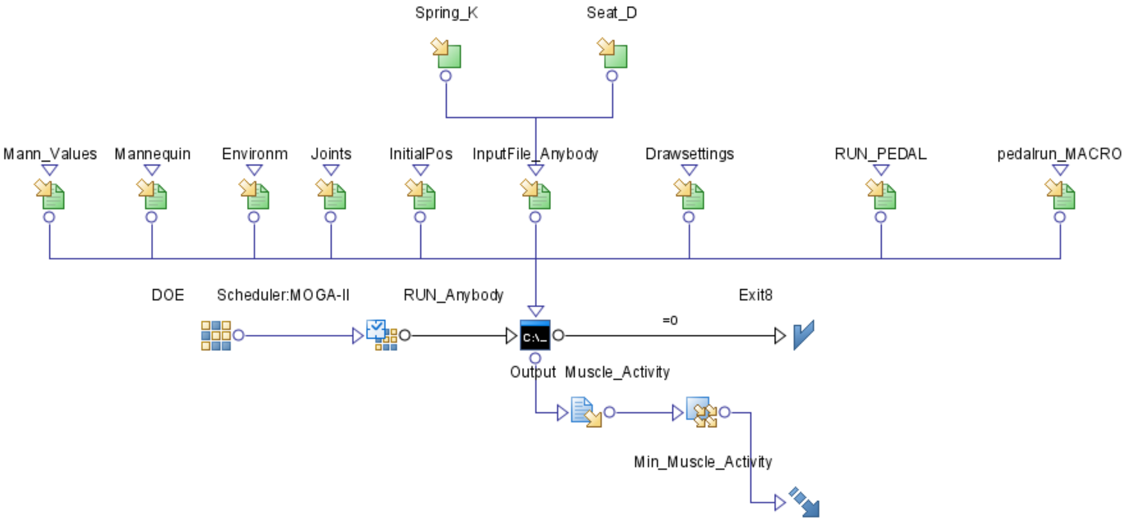

Figure 4: Integrated process within modeFRONTIER

In figure 5, the optimised results represented by the Pareto designs are shown in the red square. Figure 6 presents the history showing the spring stiffness progression. In figure 7 the correlation values, and the Probability Density Function between the muscle activity, the seat distance and the spring stiffness are shown.

Figure 5: The design chart showing the optimal designs marked in red square

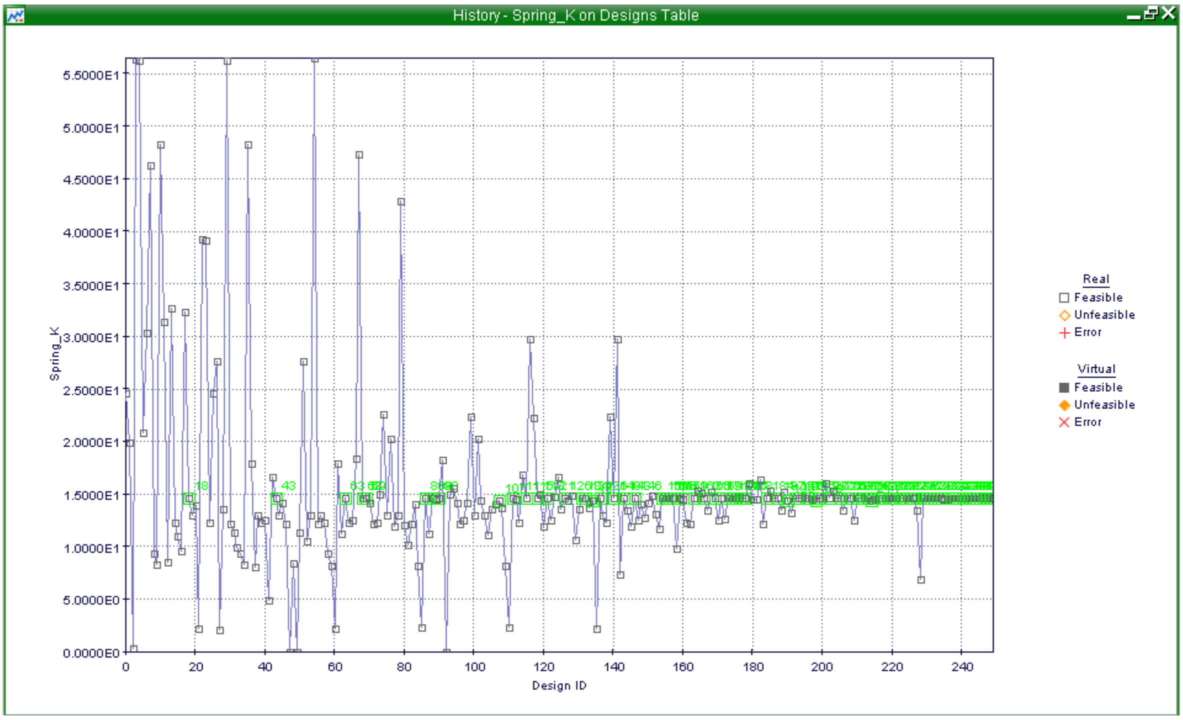

Figure 6: Optimization history showing spring stiffness progression

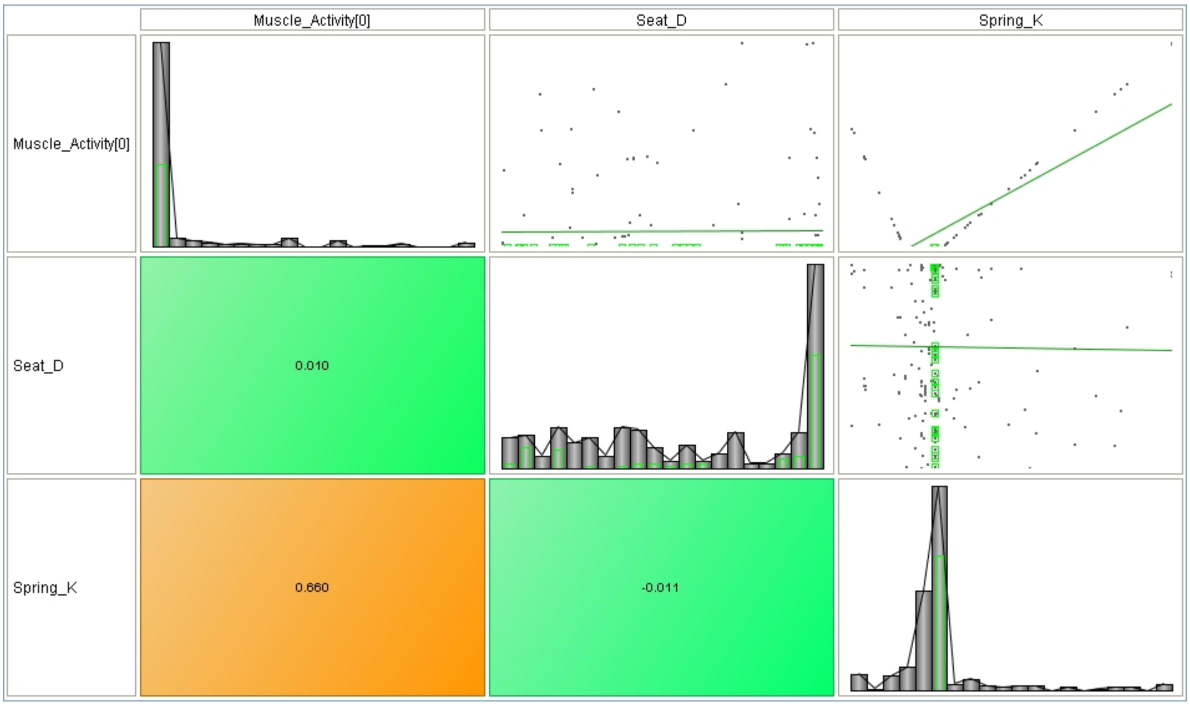

Figure 7: Scatter matrix of statistical results for the pedal design optimisation

Figure 7 indicates that the vital parameter is the pedal spring stiffness, almost irrespective of the distance of the seat from the pedal, since the correlation factor between muscle activity and the spring stiffness is 0.66, meanwhile for the case of the pedal distance is only 0.1. Figures 5 and 6 reveal that a spring stiffness of around 15 Nm/rad will result in a comfortable pedal operation with little influence from the seat position. The results presented here can be considered as an initial study that provides valuable information for designers.

4.2 Wheel chair (medical/rehabilitation)

A very large proportion of wheelchair users experience load-induced shoulder pain. This happens after several years of use, and it can be a very serious condition for an individual relying entirely on the arms for ambulation.

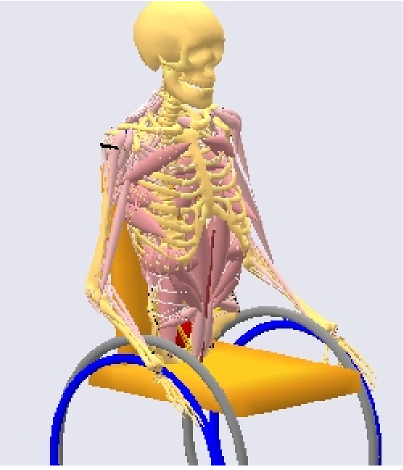

Figure 8: Model of upper body moving the wheelchair

The wheelchair parameters such as wheel diameter, push-rim position, axle position, and camber influence the shoulder forces during use. But precisely how?

This is a field where the consequences of a design change do not appear until several years of use. This alone makes experimentation impossible. But it is also ethically unacceptable to fit wheelchairs to humans in any other way than following best practice. In other words, computer simulation is the only way to gain knowledge about the influence of the wheelchair design on body loads. The depicted model investigates the gleno-humeral joint forces as a function of the axle position through a forward push on the push-rim. This is done via the model parameters: seat height relative to the axel, and seat position as the forward distance between the pelvis and axes. The initial design had a seat height of 196mm and a seat position of 191mm and these parameters were optimised in order to reduce the gleno-humeral forces as much as possible - this original design required a force of 759.5N.

The problem was integrated into modeFrontier (similar to that shown in Figure 4) and an initial DOE of 5 designs was generated using the RANDOM algorithm to cover the parameter space. Then the MOGA algorithm was used to find the optimum, submitting a total of 40 simulations, of which 12 produced incorrect models and were not run (this is detected and indicated by the software).

Figure 9 shows all the feasible designs in a 4D bubble chart. The original and optimal designs are pointed out to see the difference in the variables between the two designs. Figure 10 presents similar information to that in figure 7 for seat position, seat height and the gleno-humeral force. The parallel chart presented in figure 11 is useful to filter unwanted or un-useful designs. Figure 12 presents a RSM surface, which is used in design optimisations combining real and virtual simulations.

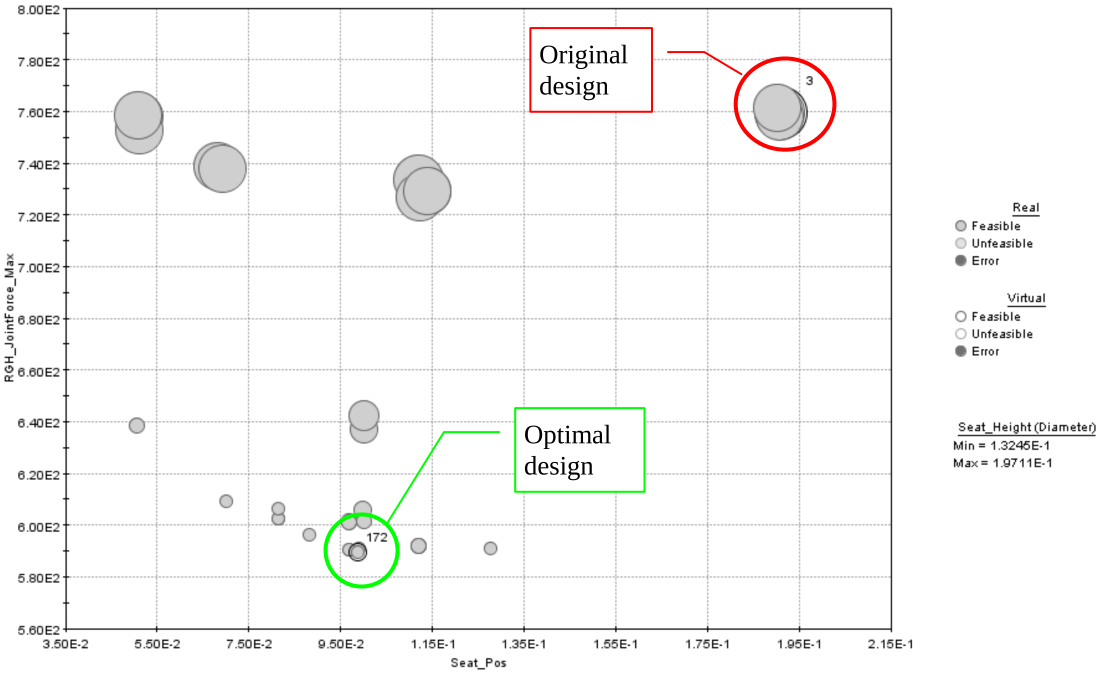

Figure 9: Bubble chart showing the original and the optimal designs

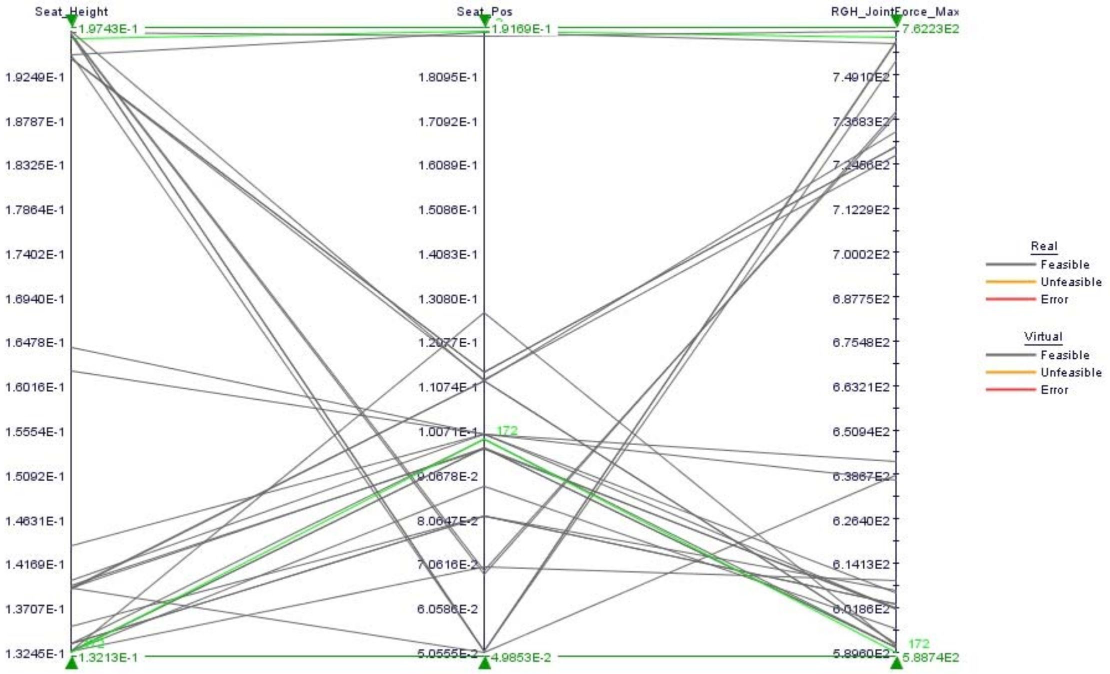

Figure 10: Parallel chart including all feasible designs

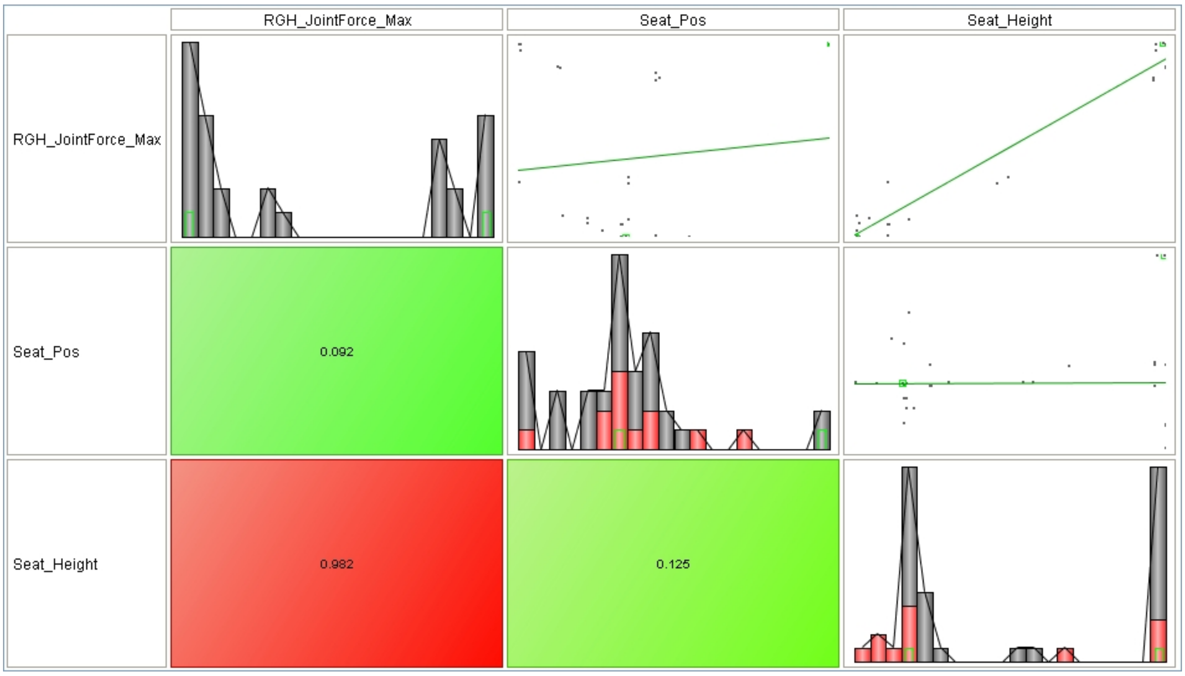

Figure 11: Scatter matrix of statistical results for the wheelchair design optimisation

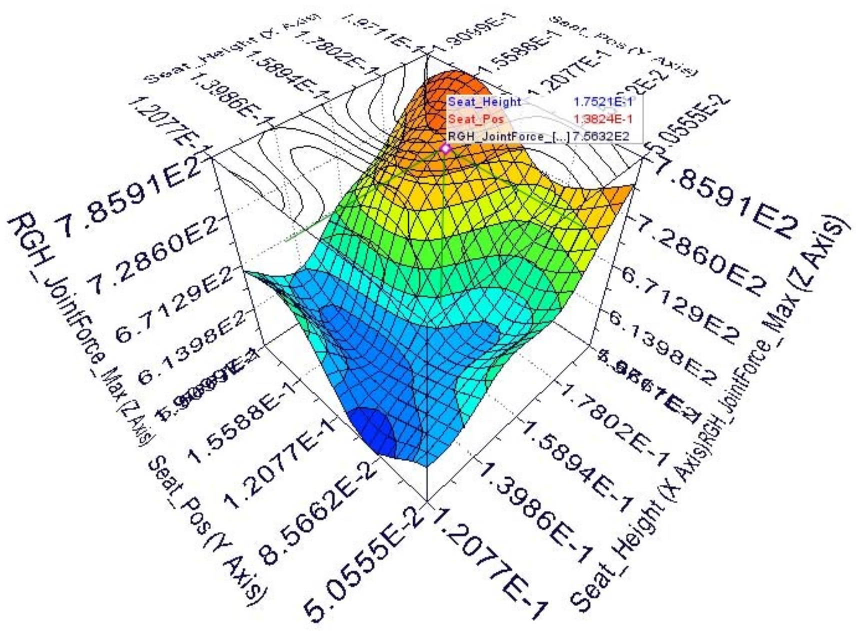

Figure 12: RSM surface

The optimised results presented in the preceding figures 9 and 10 indicate that even a slight movement of the seat can be important to the forces required to move the wheelchair. The optimal design indicates that with a seat height = 132mm and seat position = 98,6mm the gleno-humeral force is reduced to 589,6N. Comparing this with the original design, where seat height = 196mm and seat position = 191mm and the gleno-humeral force was equal to 759.5N, we have obtained a reduction of 22.4 % in the force required by lowering the seat height by 64mm and moving the seat position backwards by 92.4mm.

From figure 11 we can observe that the imperative parameter in the wheelchair design is the seat height. According to this information the effect of the seat position if almost negligible, since the correlation factor between the gleno-humeral force and the seat height account for most of the design response, therefore it may be thought that the reduction of the force could be obtained by just adjusting the seat height. However, it is observed that there is a correlation factor between the seat height and the seat position of 0.125 that may affect the results if the effect of the seat position is disregarded completely.

If the seat position factor is neglected and only the seat height parameter is modified (seat height = 132mm and seat position = 191mm) the reduction factor is reduced to 13.3 % (force equal to 658N), therefore this correlation may not be ignored.

This AnyBody simulation requires significant computer time and so it is possible to create a Response Surface Methodology to speed up the optimization process. The RSM presented in figure 12 is obtained implementing the Cartesian Anisotropic Kriging regression method using a Gaussian variogram. The RSM is useful for time consuming or computationally exhaustive processes, such as the one presented here for the wheelchair optimisation. The RSM chart is also useful in exploring solutions in areas where real analytical results have not been obtained.

5 Conclusions

It has been shown that the integration of the AnyBody software into the optimization environment of modeFRONTIER results in a very helpful tool to calculate and optimise the muscular-skeletal forces for general movements of the human body to optimise ergonomic situations.

Two examples were presented where optimisation was needed to determine the stiffness and position required for an accelerator pedal and to determine the seat position of a wheelchair to minimize the force required in moving it.

For the case of the accelerator pedal it was found that the fundamental parameter is the pedal spring stiffness, and that a value around 15 Nm/rad of the spring stiffness will result in a comfortable pedal operation with little influence from the seat position.

For the case of the wheelchair design the optimisation procedure gave an optimal design with a reduction factor of 22.4 % in the force required to move it.

It was observed as well that even if there is an imperative parameter in the direct response of the optimal design if there is a correlation factor between two of the input variables, as in the case between the seat position and the seat height, this correlation may effect the results considerably, so this type of result should be analysed carefully.

It was shown that when a simulation requires significant computer time it is convenient to create a Response Surface Methodology to speed up the optimisation process. The RSM is useful for time consuming or computationally exhaustive process, such as the one presented here for the wheelchair optimisation. The RSM chart is useful in exploring solutions in areas where analytical results have not been obtained or in the case when a combination of experimental and analytical data is needed.

References

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