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ON A HIP JOINT SIMULATOR ELECTRIC ACTUATORS INTEGRATED DESIGN AND OPTIMIZATION

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1. Introduction

In this paper the methodology and the solutions adopted during the design and development of a novel model of a multi axis hip joint simulator will be described.
The intensive use of last generation software tools, finally able to cooperate synergically executing complex analysis and simulations, showed interesting capabilities and new ways to solve the traditional design tasks.
Especially, for what concerns the electric actuators integrated design and development, it was showed that the strong integration of the 3D parametric CAD system with analysis and simulation software tools permits to quickly generate a precise numerical representation of the system that can then be processed easily on a common spreadsheet.
In fact, the definition of an optimised combination of the servomotors and reduction gears, to be selected from the available catalogues, can now be made using as input the numerical parameters obtained from the results of the accurate simulations performed on a virtual prototype based on the 3D CAD model, and its effectiveness finally verified on subsequent new simulations.

2. The hip joint simulator design and development

2.1 The problem

In a total hip joint replacement, the UHMW polyethylene acetabular cup wear has been widely implicated as an issue of primary importance since the wear debris accumulation can lead to an undesired loosening and inflammation in the local tissues and, ultimately, up to the total failure of the construct designed.
Thus, the interest in laboratory hip joint wear experiments has continuously increased. Many kind of hip joint wear test have been developed in order to examine and characterize the performance of the different bearing materials; it was finally realized that traditional employ apparatus are not really capable to totally reproduce the real wear mechanism involved in such a complicated bearing combination, where the complex relative motion and load cycles, varying continuously in magnitude and direction, generate complex paths [C. R. Bragdon, 1996] of preferred wear actions.
The typical hip joint relative movements, ordered in three rotational degree of freedom (flexion - extension in the sagittal plane, abduction - adduction in the frontal plane and internal and external rotation in the transverse plane), were described and calculated, as well as the magnitude and direction of the continuously varying resultant force acting between the femur head and the acetabulum (subdivided in vertical, antero - posterior and medio - lateral force components, parameterised as body weight percentage (%BW)) during a normal level walking [J. P. Paul, 1967]. (figure 1). At the same

time, even the thermo-chemical and biological environment has proved to deeply affect the wear mechanism. Thus, to really test a combination of biomaterials and prosthesis geometry, it is necessary to use complex mechanical simulators capable to reproduce as close as possible the real replacement in vivo physiological loading and motion environment.

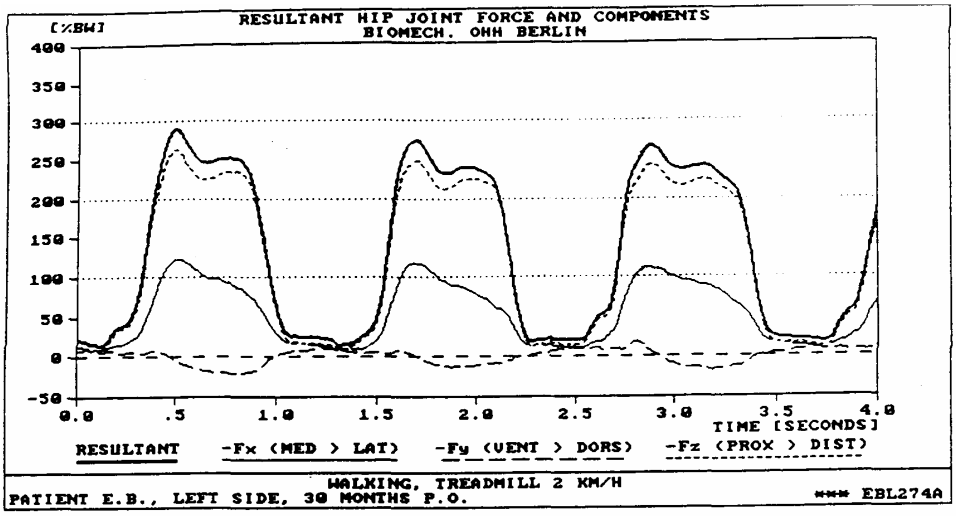

Figure 1. Hip joint forces (Load: %Body Weight, time: seconds)

2.2 The conceptual design

First, a "cost function", representing the whole error in reproducing a specific load cycle synchronized with a motion profile assigned [A. O. Andrisano 1995], was developed and finally an optimal spatial configuration for the load and motion apparatus, capable to minimize such a cost function (i.e.: maximize the total accuracy in reproducing the physiological condition of the time dependent loading and three dimensional mutually articulating bearing surfaces) despite the overall mechanical complexity was chosen. From the result of this analytical optimisation study, it was clear that the superposition of the errors committed by every single actuator's controller could lead to an overall accuracy error even superior than the one produced by a simplified system, then only 2 two load actuators were used.

These preliminary conceptual prescriptions were then developed in a complete design of a new model of hip joint simulator.

2.3 The hip joint simulator design

The whole simulator has been totally developed using a 3D parametric CAD (Solid Edge). All the geometries are based on layout parametrical sketches and their design variables interconnected. This permitted to quickly test multiple design variants, focusing only on few design target parameters. The whole design started from the test cell with the specimen. According to the requirements previously defined, it was immediately realized a position setting device in order to permit to simulate even non optimal surgical implant conditions that lead to misalign the prosthesis' cup and head during the in vivo working conditions. The test cell is designed to be filled with all the physiological fluid normally used in simulator studies, (i.e.: synovial fluid, distilled water…); more over, a temperature control and monitoring system assures a replication of the real physiological implant condition. Then, the theoretical study results imposed designers team even to physically separate the load apparatus from the motion apparatus one; the motion apparatus was the first developed.

Since the maximum stiffness and precision of movement was required, the three rotational axes have been realized adopting a three mutually perpendicular articulating swinging cradles architecture (fig.2); it was then decided to move each swinging cradle using closed loop feedback controlled high dynamics servo motor because of their ease of control, reduced overall dimensions and weight.

To dimension and optimize these electrical actuators were initially used the 3D CAD model properties

to obtain all the parameters values needed to solve the classical “inertia matching” theory algorithms [Hans Gross, 1990; H. Slocum, 1992]. Since the motion apparatus adopts a serial architecture, the design engineers realized immediately they were not able to calculate easily and quickly all the real values of the parameters (i.e.: moments of inertia…) that occur in the various complex configuration during the cradles mutual movements, but an initial approximated dimensioning activity was done.
Even the load apparatus was then designed. The extremely high dynamics and working frequencies to implement resulted particularly difficult to solve. Several different solutions were realized and validated, finally it was preferred to adopt again electric actuators controlled by a centralized unit.
The device designed for each load apparatus actuator is based on a spring load system: an electrical high dynamics servo motor loads through a screw a spring that finally delivers the calibrated forces; several position and force transducers are used for the feedback control (fig.3). A system of compensating forces, actuated via several reaction springs, permit to avoid axial play, especially during the inversion of the loading movements, assuring the necessary precision. During the 3D CAD design, the definition of the transducers that could best fit the working requirements an their positioning in the simulator, as well as the harness pathways, resulted difficult to solve.

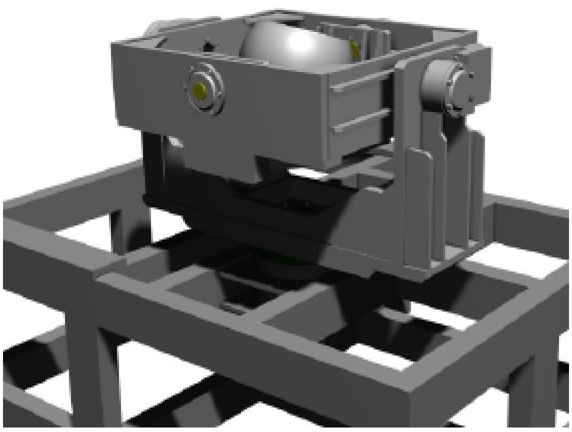

Figure 2. Motion apparatus

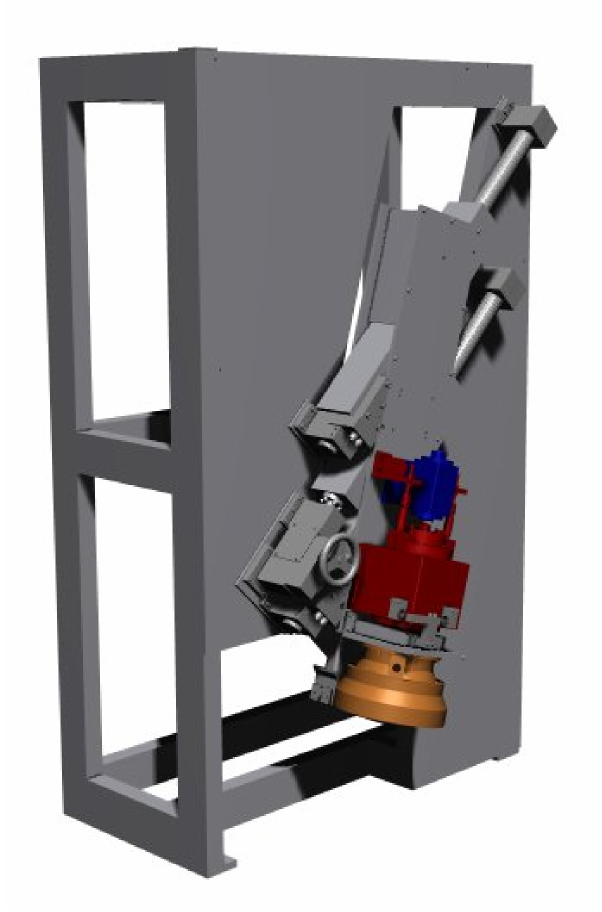

Figure 3. Load apparatus

Then the design of the hip joint simulator was almost completed, all the design variants were chosen but, in order to really assure the best performance reachable, an intense activity of further development was needed. To achieve a superior quality results in a fast and effective way, a specialized analysis software tool was needed.

3. The hip joint simulator electric actuators integrated design and optimization

3.1 The servomotors and gear reducer selection activity

The correct dimensioning and optimization of electric actuators is an intrinsically difficult task with lots of multidisciplinary implications in the whole design process.

In the case of a serial architecture, like the hip joint simulator developed by the authors, such a task becomes even more complicated: in fact, every choice of different combination of servomotors and gear reducers for a single actuating device strongly affects the parameters and conditions of the other actuators (for example: the moment of inertia).

The deep interaction between the mutual movements of the different mechanical subsystems, and, as already written, the varying of the moments of inertia and loads resistance depending on different configurations, makes this duty particularly difficult to solve accurately without the help of numerical solver.

The actual availability of analysis software tools, strictly integrated with the 3D CAD model, finally permits the design engineers to cooperate and to verify different solutions with a high level of accuracy in the reproduction of all the operating conditions; moreover, the parameters numerical values are referred to the true geometries and are not approximate.

In order to really succeed in developing all the different features involved, a proper “interface” agent on which the different specialists can communicate and share their knowledge and the evolving of their work is strongly needed.

A primary task in the electric actuators device selection activity is connected with the calculation of the optimal transmission ratio.

The classical inertia matching theories proved to be theoretically effective but difficult to implement in real operating conditions.

To solve such a task, several input parameters are needed, first of all the moments of inertia of the load, the gear reducer and the motor itself. The gear reducer (“gear”) and the motor moments of inertia have to be chosen from the catalogues where all their parameters are available, but, in fact, the first parameter needed, the load moment of inertia J_{load} , (referred to the motor axis), to be calculated from the geometry of the mechanism involved, has not necessarily a constant value, thus, even the “optimal” transmission ratio for a gear reducer becomes a set of values to choose from.

Moreover, the famous equation :

$$n_{opt} = \sqrt{\frac{J_{load}}{J_{motor} + J_{gear}}} \tag{1}$$

is basically only one equation with 2 variables to be chosen from a discrete set of values!

This means that it is absolutely necessary to adopt iterative numerical routines to find the combination that best match the load, but it is only an approximate solution.

Such selected combination must then satisfy several other strong constrains, as well as the dimensioning of the motor size (thermal verification), its control system design and programming, the electrical plant lay out or even the optimization of the total industrial economical cost, that are not specific competence of the mechanical design engineer that performed the previous tasks.

In order to really find the best solution it is then strongly recommended that all these different activities results and motivations are available to be compared in all their features in a easy to understand unique neutral format file for all the design engineers.

3.2 The integrated use of 3D parametric CAD with virtual prototyping software

In order to determine the optimal combinations of gear reducers and servomotors for every actuator of the hip joint simulator, a proper methodology was followed.

In fact, it was decided to import the Solid Edge CAD model (a fully parameterised assembly with more than 1600 components) in the Visual Nastran Desktop environment: thus it really became a

virtual prototype on which execute accurate simulation to test multiple design variants and obtain precise result and data of all the parameters involved.
The selection of the different kinematical constraint to implement in the model was the first real task to execute: several chance to solve the same joint showed interesting ways for further development.
Once the virtual prototype was realized, to the single end effectors it was immediately imposed to follow the loading and motion curves studying the joints reactions and efficiency.
Starting from the inner cradle of the motion apparatus, it was obtained the complete curve of the resistance torque, the angular velocity, acceleration and jerk.
Several kind of simulation were performed: on one hand in absence of external forces and perturbation to determine the fully inertial parameters, to be used to calculate the optimal transmission ratio, on the other hand with the presence of all the conservative forces and external stresses that was estimated to occur in operating conditions, to be used to find out the real efficiency of the mechanical devices and the total power consumption needed.
All the results were exported in a spreadsheet where it was possible to collect all the heterogeneous data, processing and composing their values that have been finally graphed and compared from all the design engineers under multiple point of views.
One of the first important result was the calculation and final graph of the time dependent curve of the load moment of inertia J_{load} , referred to the motor axis, to use for the determination of the optimal transmission ratio.
Then, using as input the maximum values of the final torque and angular velocity, increased by a convenient safety factor, the size of the reduction gear was determined. The kind of reduction gear, in this case Harmonic Drive, is usually chosen in order to satisfy the accuracy specifications and other few requirements.
This showed to help greatly the further calculations: in fact, since the Harmonic Drive reduction gears moment of inertia is almost the same for all the transmission ratio in the same size family, the equation (1) can be easily solved looking only for a proper motor.
The servomotor selection must initially satisfy primarily the thermal condition: firstly its power max value must exceed the system maximum total power peek needed by a convenient safety factor, then a model is chosen to be tested.
Since it is available even the trial motor's moment of inertia, it can be calculated the corresponding n_{opt} , and then chosen the closest available gear reduction factor n* that should be not superior of n_{opt}.
In determining such a parameter, the authors decided to follow 2 different ways: on one hand was used the load moment of inertia root mean square value (i.e.: rms value), on the other hand the load moment of inertia numerical value corresponding to the most critical zone in order to assure the best response in the worst case.
The trial combination of reduction gear and servomotor is then used to obtain another graph where is plotted the final torque and angular velocity curve reduced to the motor shaft and compared with the motor itself. If all the values do not exceed the motor maximum angular velocity and nominal torque the selection is validated and eventually it is suggested to test the other different combination available, especially if such torque values are much smaller than that limit.
Finally the CAD model of the reduction gears and servomotor, and their parameters, are inserted in the CAD assembly, the virtual prototype is then updated and new simulations executed in order to calculate the final performances reachable and to show which configuration best fit the desired operating target.
Once the electric actuators are defined, it can be possible to proceed to the selection of the servomotor-gear reducer for the subsequent actuator that must be simulated with the previous combination implemented (the servomotor and gear reducer previously chosen influence the system moment of inertia, i.e.: the load moment of inertia).
The chance to finally verify the final motus law obtained at the end effector with the input of the components chosen is a great tool for final validation.

4. Conclusions

In the present work the design and development of a novel hip joint simulator model was described.
Such a simulator was designed to reproduce with enhanced accuracy the physiological condition of the time dependent loading and three dimensional mutually articulating bearing surfaces; the high dynamics required to solve such a difficult task imposed the designers' team to deeply focus on the analysis of many different design variants for what concerns the architecture of the simulator and the final dimensioning and optimization of the electric actuators.
Several consideration on the integrated design and development of high dynamics mechanical devices moved by electric actuators were presented. The intensive employ of state of the art software tools, strongly integrated in their use, permitted to succeed in the correct dimensioning and optimization of the best combination of servomotors an gear reducers.
In fact, only using proper simulation tools, strongly integrated with the 3D CAD model, it was possible to realize a real virtual prototype, on which execute behavioural tests and finally obtain the complete set of accurate value needed to solve the inertia matching theories algorithms, otherwise of real difficult implementation.
The intensive use of a third party spreadsheet, permitted the design engineers to share their knowledge and to analyse and process all the simulation data obtained, mainly exposed in various composite graphs.
The methodology used is necessarily of complex implementation but, once realized, it permits to easily and quickly test multiple design variants in an extremely accurate way. Since inertia matching theory algorithm's number of variables exceed the equations available, it is absolutely necessary to adopt iterative calculations.

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