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Biomechatronic System Engineering

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Abstract—**Development of active systems in the field of prostheses and orthotics is currently one of the main topics in medical rehab research. As in this field different researcher from different disciplines, not only from technical areas like informatics, mechanical engineering and electrical engineering, but also from medical and biological research do have to work together, there is a strong need for an integrative development procedure. In this paper a systematic and methodical approach for the development of active systems in the field of Prosthetics and Orthotics is presented. Two examples of active powered devices in this field are shown. One is an active powered knee prosthesis. The other one is an active powered arm orthosis. The presented procedure starts with the definition of the boundary conditions, which are derived from the application, and ends with a graphical description of the important parameters for the power train in powered P&O devices.**

Powered prosthesis; development procedure; methodic approach; biomechatronic engineering

I. INTRODUCTION

Active powered prostheses and orthoses are expected to improve the energy efficiency and the suitability for daily use of artificial body parts. In the past powered prostheses were developed for highly active persons (mobility class 3 or even higher). But during the last decade it turned out that such prostheses are highly suitable for older persons, who are not that active (e.g. mobility class 2). The reason for this is, that active powered systems can give certain stability and therefore older people feel more secure when using these systems.

Developing a system which meets the requirements of the specific application is the overall aim in research and development. The transfer of the application into technical requirements is here a sophisticated challenge. It is absolutely necessary to convert data of medical measurements into technical parameters to enable a good and well defined development procedure. An efficient system design starts with an accurate definition and calculation of parameters taken from biomedical measurements. In this paper we show two examples of our research and development work of the last 10 years in biomechatronic systems engineering. We focused on the following core technologies:

1.) Sensor-system, development and integration: Mainly the development of motion sensors like IMU (Inertial Measurement Unit)-sensors is the key. Getting the right gait parameters in a real time system is one of our main research topics in this area.

2.) Electronic motors and electromechanical drive train development: We started some years ago using of the shelf electronic motors. We are now working on our own motor developments and help companies and research institutes in motor testing and development.

3.) Development procedure: One of our main goals is to improve the way such complex mechatronic devices are developed. We try to get a general methodic for developing such systems in a short time and with a high quality.

Figure 1 shows the active powered knee prosthesis. This prosthesis was developed in a national research project.*

Figure 1: Active powered knee prosthesis.

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II. DERIVATION OF TECHNICAL SYSTEM PARAMETERS

A. *Field of Application*

The basic parameters for dimensioning active supporting systems for humans are always data that are collected for one certain application. For dimensioning an active artificial limb, data taken from gait analysis have to be used. In this paper the dimensioning of the active powered knee is described. For the following dimensioning of the drive system it is important to structure and document all relevant boundary conditions. Typical applications for the development of an artificial limb are applications like walking on a plane or climbing staircases. For each of those applications different boundary conditions occur and therefore a different set of parameters has to be defined. In literature the design of many different artificial joints is described. The design of a foot prosthesis based on medical raw data is well discussed [1]. In [4] the effect of walking speed is analyzed using biomedical data and mathematical methods. The design of an active knee prosthesis using medical motion data can be found in [2]. The scientific process of gathering motion data by using gait analysis is described accurately in [6]. As can be seen in literature, the usage of medical data is an often used approach for the development of biomechatronic systems. The following model describes a development procedure of biomechatronic systems, in which technical parameters are derived from biomedical data. With the resulting technical parameters the requirements for the powertrain in P&O devices can be defined.

B. *Graphical overview*

A schematic overview of the theoretical model is shown in "Fig.2".

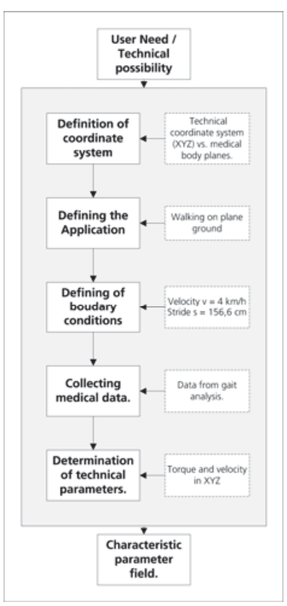

Figure 2: Schematic overview

At the start of the development procedure the user needs and the technical possibilities have to be collected. Raw data is only usable, if the boundary conditions, by which the measurement was conducted, are documented accurately. The first step during the development process is the definition of a general coordinate system. With this coordinate system the technical parameters can be described. The boundary conditions are the technical frame in which a functionality of the prosthetic system is expected. Based on mathematical definitions and the relating boundary conditions, the appearing torque and angular velocities at the considered joint are determined. The determined kinetic quantities are defined as the requirement of the prosthetic system. To gather the requirements for the power train the mechanical properties of the prosthesis have to be considered. The result is a characteristic speed-torque curve, which is the basis for the dimensioning of the power train.

III. IMPLEMENTATION OF THE DEVELOPMENT MODELL

A. *Raw Data*

In our case Raw data contain medical acquired motion data. In the special application of an artificial knee, data of gait analyses are used. With a camera based motion capturing system and with force plates the cycle of movement of the knee joint and the acting torques are recorded. Apart from the accurate data recording it is important to document the boundary conditions. Typical boundary conditions for the knee joint can be the ground on which the patient walks, the weight of the patient or the walking speed. If there are several boundary conditions that cannot be valid at the same time, one of them has to be chosen. This chosen condition is the application for which the design process is applied. For the design of a drive system for several applications, the process must be applied separately for each application.

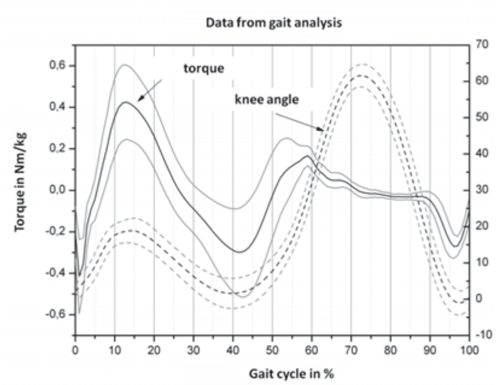

Figure 3: Data from gait analysis

"Fig.3" shows the angular position of the knee and the acting torques during the gait cycle for one stride. The application is walking on a plane.

B. Mathematical definitions

For further consideration some mathematical definitions are necessary. First of all a general coordinate system is defined. This coordinate system is assigned to the considered system. Every mathematical quantity has to be defined according to that coordinate system.

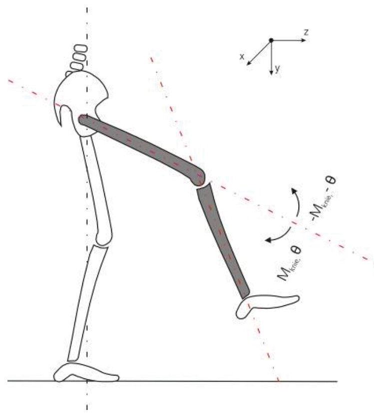

Figure 4: Definition of coordinate system

In “Fig.4” the definition of the torque M_{kbod} and the knee ankle θ is shown. With the coordinate system on the top right corner the motion and the construction of the technical system can be described exactly. The following quantities are defined within and relative to the coordinate system:

- Torque at the knee joint M_{kbod}
- Position of the knee angle θ

C. Boundary Conditions

Based on the application, for which raw data was acquired, the boundary conditions have to be defined. For the active powered knee the following boundary conditions were chosen:

- Weight of the patient: m = 100kg
- length of stride s = 156.5 cm (according to [5])
- Walking velocity: v = 4 km/h

The definition of boundary conditions is important, because it has to be defined in which circumstances the technical system has to serve the purpose, for which it will be made. For other limb joints boundary conditions have to be defined knowing the use case and the range of motion.

IV. Characteristic parameter field

Positions of the operating points on a characteristic parameter field diagram of torque and speed are important for the design of a power train in technical systems.

A. Knee joint behaviour

A characteristic angular velocity at the knee joint can be calculated using the following parameters:

- Knee angle curve θ
- Length of one stride s
- Walking speed v

In “Fig.5” the acting torque of the knee joint M_{kbod} over angular velocity ω is shown. Thanks to this representation the kinematic requirements for the technical prosthetic system are determined.

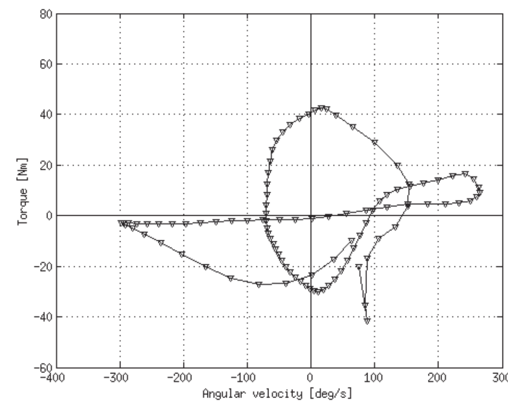

Figure 5: Chracteristic parameter field at the knee joint

The described processing model does not contain other requirements like size or design. It does only handle the kinematic requirements. If there are special requirements for other parameters, they can be handled with the boundary conditions.

B. Considering of mechanical properties

For further development the characteristics of the mechanical prosthesis system has to be considered. In this example a lever arm principle [7] was used to show the influence of the kinematic systems on the characteristic curve and on the design of the power train. “Fig.6” shows the mechanical system which was used as a test “build up”/ test frame.

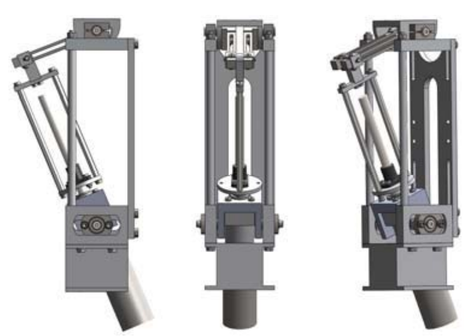

Figure 6: Used mechanical build up

The mechanical efficiency of the prosthesis depends on several parameters which modifies the kinematic requirements.

In the special case of a mechanical knee joint, whose principle is based on the mechanical structure in [3], there are several gear units, and several mechanical efficiencies. The gear units reduce the required torque by raising the needed speed. The mechanical efficiency partially depends on the actual knee angle. Through the consideration of the mechanical properties the characteristics of torque and speed is show in "Fig.7".

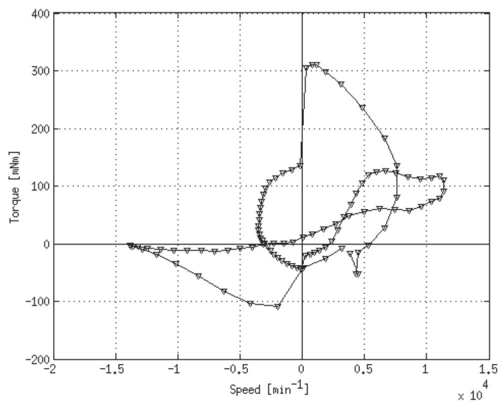

Figure 7: Characteristic parameter field at the motor

C. *Design of the power train*

With the characterization of the dependency of torque and speed on the motor shaft, every possible operating point is specified. Based on that fact the design of the drive system can be progressed in the same way like the design of drive systems for industrial machines and devices. The characteristics of the drive have to include every operating point and thermal limits have to be kept. For the development of a prosthetic system for several applications, the results of the design process are several characteristics of torque and speed. To design the drive system it has to be possible for the drive to reach every operating point of every application.

V. PROJECT EXAMPLES

During the last 10 years we used the described development procedure in different product development projects. Mainly in the field of prosthetics, but also in the field of active powered orthotic devices. The most impressive ones are: an active powered knee prosthesis and an active powered arm orthosis. These Systems were developed in collaboration with industrial partners and partners from University.

A. *Active powered knee prosthesis*

The development of active powered leg prosthesis was originally initiated by the outcome of the C-Leg by Otto Bock. C-Leg was the first system which showed the general benefit of an active controlled knee system. Still C-Leg is the most popular and also the most sold active controlled knee in the world. The first active powered system in this field was the power knee by company Össur. In the first version this system was quite heavy and huge. But the second version was improved a lot and opened a complete new field of research: active powered device for nearly every mobility class but also for elderly people. That these active powered devices help people with a low mobility class was somehow a surprising outcome. This however led us and many other research groups around the globe to also start doing research in this field.

B. *Concept of an low cost active powered device*

At the very beginning of our research work we defined the boundary condition for our project. In this case boundary conditions means:

1.) Low cost version.

2.) Simple to use.

3.) High benefit when using the system.

To meet the requirements of "low cost" system, we used for example a plastic-housing. The whole mechanical frame was designed using a fiber-reinforced plastic mechanical build up. This means that not only the design parts are made of plastic, but also the parts which are responsible for the force transmission.

C. *Testing of mechanical properties*

At the beginning of the project we investigated different composition of fibrereinforced plastic. Figure 8 shows two different examples of plastic housings. One with a higher percentage of fiber and the other with a lower percentage of fibre compared to the finally used mechanical frame.

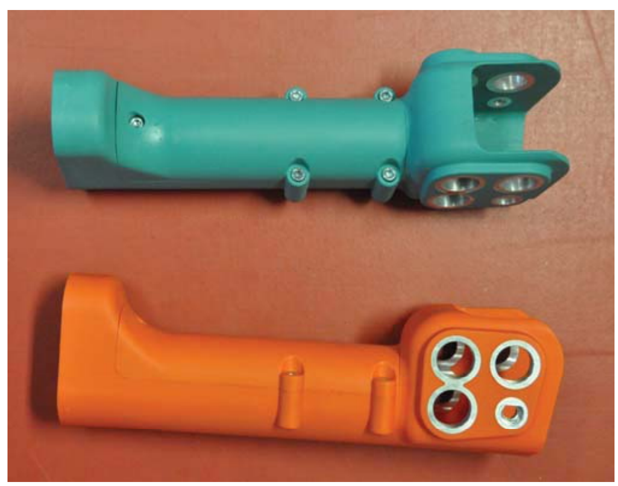

Figure 7: Plastic build up with different percentage of fibre

D. *Project outcome and next steps*

The final project was conducted together with companies from the supplying industries and University Stuttgart. We were finally successful in developing a first prototype of an active powered knee with the following features:

- Fibre-reinforced plastic housing
- Usage of an electronic motor with a novel stator technology to improve energy efficiency.
- Maximum torque output at the knee axis of more then 64 Nm.
- Usage of low cost manufacturing technologies.

Figure 9 shows the first prototype of this active powered device while testing on a treadmill. The next steps will mainly include the development of an embedded control system and the testing with patients.

Figure 9: Testing on a treadmill

VI. DEVELOPMENT OF AN ACTIVE POWERED ARM ORHTOSIS

A. *Introduction*

A very close field of research is the development of orthotic devices for people with paralysis. There are many ways of losing the ability of active moving and active controlling a limb. People suffering from stroke or people with brachial plexus injury still have the limb, but don’t have the possibility of active controlling it. New systems in the field of rehabilitation use motors in combination with mechanical frame to active move the limb.

B. *Research for active controlling a limb*

In the last 10 years we focused in this area of research very much on the control strategy, on possible sensor systems and also on the realization of electromechanical drive systems. New developments in the field of small and lightweight gearboxes supported our research work.

C. *Active powered arm elbow orthosis*

Figure 10 shows a picture of our active powered elbow orthosis. We used a bevel gearbox in combination with an electronic motor. As mechanical frame a passive arm orthosis was applied.

Figure 10: Active powered arm orthosis

D. *Results*

The final design of the drive system within the arm orthosis consists of an electronic motor and a directly mounted planetary gearbox which enabled the required velocity and torque characteristics. The motion of this rotary drive system was then transmitted via bevel gearbox to the elbow axis. In figure 11 a test with the active powered arm orthosis is shown.

Figure 11: Weightlifting with the arm orthosis.

With the described system it is possible to apply a maximum torque of about 13 Nm at the elbow axis using a 40 W motor. The motor efficiency is about 90%, the maximum needed angular velocity at the elbow axis is 72°/s.

The next steps in the development will be the integration of an accurate control system meeting the requirements of patient safety. The focus of our next research project is the integration of arbitrary control using EMG-Sensors (Electromyography).

VII. CONCLUSION

In this paper a general approach for the development of active powered prostheses and orthoses is presented. A model for the development process is described and two examples of newly developed active systems are given. The most important process step when developing such active devices is the accurate transfer of medical requirements into technical parameters. Core of the suggested procedure is the definition of a general coordinate system in which the technical parameters of the biomechanical systems are described in a mathematical form and the derivation of the technical system requirements. During the course of the projects we focused on the implementation and integration of the active electromechanical power train. We saw that there is still a lot of potential to lower the energy consumption by using highly efficient motors and gearboxes.

VIII. OUTLOOK

In the next 10 years several "Biomechatronic" systems will enter the market. The reason is on the one side the technological developments in the area of motors and gearboxes. On the other side the benefit of such active powered devices is very high and will even be higher when systems become lighter, smaller and easier to use.

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