OPTIMAL PROSTHESES, ORTHOSES AND EXOSKELETONS FOR PHYSICAL ACTIVITY

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Wearable physical assistive devices, such as prostheses, orthoses and exoskeletons are great inventions to enable a large range of subjects with very different disabilities, injuries or diseases to perform physical activity who would not be able to do so otherwise. The purpose of this paper is to present the benefits of model-based optimization methods to analyze and improve these devices such that they are best adapted to address the need of different pathologies or even individual subjects. Using detailed multibody system models of the human and the wearable devices, it is possible to tune parameters related to the kinematics, dynamics and control of the devices or even test completely new design ideas or setups. Optimization problems are formulated and solved in order to fit simulated motions of the combined system of human and wearable device to desired behaviour e.g. coming from motion recordings of healthy subjects or to generate motions that optimize particular performance criteria. The presented approach also allows to study the frequently asked question if certain prosthetic devices create and advantage of the wearer over able-bodies subjects.

KEY WORDS: Wearable robotics, multibody system modelling, optimization

INTRODUCTION:

Wearable robots or wearable physical assistive devices, such as prostheses, orthoses and exoskeletons, have made a lot of technological progress in recent years (see e.g. [1] for an overview of recent developments). They do not only allow patients with diseases or disabilities to perform motions of daily activities, but also to engage in different types of sports. While the goal in general lower limb prosthetics for everyday motions is to come as close as possible to the performance of able-bodied subjects, the special prostheses developed for different types of sports sometimes allow the athletes to be so successful that it is even assumed that thy might have an advantage over able-bodies athletes, such that they are sometimes not allowed to compete [2][3]. Exoskeletons and orthoses have a wide range of current and future applications from enhancing the body strength of able-bodied subjects, such as soldiers or specific workers to carry heavy loads or walk long distances, to fully powering the motions of parallelized limbs of patients. In the future, we can also envision applications of active exoskeletons or orthoses for different parts of the body for a much wider class of subjects, e.g. able-bodied athletes that suffer from some injury, but want to continue their training anyway, so loads would have to be taken actively from the concerned parts of the body by suitable active devices. Exoskeletons and orthoses could also help elderly people to continue physical activity until a very high age, e.g. by contributing the required extra power to still let them climb or walk up high mountains - in the same way as electronic bikes, which became extremely popular in recent years, allow elderly to go up steep hills that they would not be able to surmount without this support. The development of such novel devices poses challenges on the control as well as the design side. The purpose of the paper is to show that model-based optimization and simulation can play an important role in this context to analyze the effect of each device on the particular motions and to develop the best possible devices for given tasks. We present our general modelling approach and the numerical tools underlying our studies. As examples, we mention results from the analysis of prostheses in sports as well as from design studies for lower leg exoskeletons. All computations presented are based on efficient multi-body system models of the human body which can be personalized to a particular athlete as well as parameterized to suit the respective device. We then solve multi-phase optimal control problems to either perform model-based movement predictions or to fit the model to

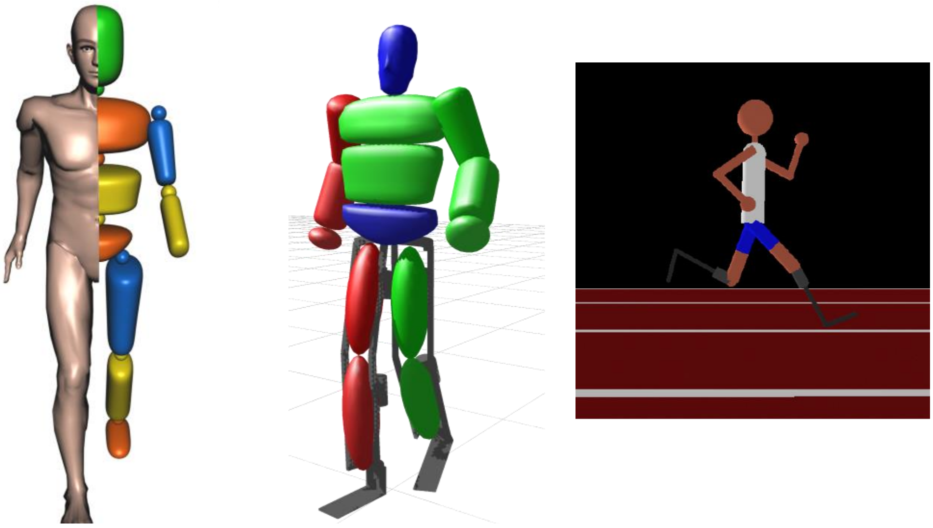

Figure 1: (a) Abstraction of the human body as rigid multibody system, (b) Human model with lower limb exoskeleton and (c) Human model with running prostheses

given data.

METHODS:

The studies discussed in this paper rely on advanced computational methods for motion analysis and prediction, in particular efficient multibody system models of humans and robotic devices and state of the art optimal control techniques.

The first pillar of our methods are efficient multibody system modelling tools. For whole-body motions in sports, such as walking, running, jumping, cycling, rowing, to name just a few, the human body can be represented as a system of roughly 15 – 20 segments (pelvis, different torso segments, head, neck, thighs, shanks, feet, upper and lower arms, hands, etc.) with 35 – 40 degrees of freedom in total. Very fine details of the human body such the degrees of freedom as all finger or toe segments are usually not required for whole-body motion studies. We can assume that the internal degrees of freedom of the human are powered by joint torques. While for some questions it is also interesting to replace these joint torques by models of all corresponding muscle torques, this is not necessary in our case. The multibody system models depend on kinematic and dynamic data of the humans, e.g. lengths, mass centers, masses and inertias etc. of all segments. Tabular anthropomorphic data is available depending on the overall height and mass of a subject (see e.g. [4]). However, our previous research has shown that this data varies a lot between subjects, and that any detailed model-based analysis of a particular subject's motion requires at first a careful personalization of the multibody system model adjusting the model parameters [5]. Robotics devices can also be formulated as mechanical systems that have their own inputs (such as motor torques) but that can also take state information of the human as control input. The model of the device typically also includes free model parameters (to be determined by optimization) and can be combined with the human model either by a fixed (constraint based) coupling or a looser coupling (e.g. by springs).

Models of humans performing motions in sports are typically characterized by multiple phases of motion defined by different sets of contacts with the environment. At phase

changes, when new contacts occur, there are often discontinuities of the system states, in particular the velocities. The same is also true for the combined models of humans and exoskeletons, orthoses and prostheses. The general form of these models is given in the top part of figure 2. In our research group, efficient tools for setting up equations of motion of human motions have been developed, namely RBDL [6, 5] and DYAMOD [7].
The second pillar of our methods for studying combined motions of humans and robotic devices is the formulation and solution of an optimal control problem. Optimal control problems are helpful in this context to achieve different tasks, such as

- Fitting the motions of the model to some desired reference motion from motion capture (e.g. to make the motion of the human with assistive device follow that of an able-bodied subject);
- Optimizing a performance criterion, such as minimum energy, minimum load, minimum torques etc.

The general form of the multiphase optimal control problem is given in the bottom part of figure 2. It contains all different types of objective functions and uses the multi-phase mechanical model as constraints. In addition, all kinematic and dynamic constraints of the human and the device, such as torque limits, joint angle limits etc. are considered as constraints in the optimal control problem. Optimal control problems of this form can be solved by a direct multiple shooting method, as implemented in the code MUSCOD [8,9].

Multiphase mechanical model with discontinuities

Description of each phase:

$$\dot{q} = v$$
$$\dot{v} = a$$
$$\begin{pmatrix} M(q,p) & G(q,p)^T \\ G(q,p) & 0 \end{pmatrix} \begin{pmatrix} a \\ \lambda \end{pmatrix} = \begin{pmatrix} -N(q,v) + F(q,v,p,u) \\ \gamma(q,v,p) \end{pmatrix}$$
$$g_{pos} = g(q(t),p) = 0$$
$$g_{vel} = G(q(t),p) \cdot \dot{q}(t) = 0.$$

Phase switching function:

$$s(q(\tau_s), v(\tau_s), p) = 0$$

Discontinuity between phases:

$$\begin{pmatrix} M(q,p) & G(q,p)^T \\ G(q,p) & 0 \end{pmatrix} \begin{pmatrix} v_+ \\ \Lambda \end{pmatrix} = \begin{pmatrix} M(q)v_- \\ 0 \end{pmatrix}$$

Optimal control problem formulation

$$\min_{x(\cdot),u(\cdot),\tau} \sum_{j=1}^{n_{ph}} \left(\int_{\tau_{j-1}}^{\tau_j} \phi_j(x(t),u(t))\, dt + \Phi_j(\tau_j, x(\tau_j)) \right)$$

$$\begin{aligned} \text{s. t.} \quad & \text{multiphase mechanical model} \\ & g_j(t,x(t),u(t)) \geq 0 \qquad \text{for} \quad t \in [\tau_{j-1}, \tau_j] \\ & r_{eq}(x(0),..,x(T)) = 0 \\ & r_{ineq}(x(0),..,x(T)) \geq 0 \end{aligned}$$

Figure 2: General form of model equations (top) and of optimal control problem formulation (bottom) used for our studies.

RESULTS & DISCUSSION:
The presented methods can be applied to a variety of problems studying the common motion of humans with technical devices. We will briefly present results for two examples.
In the first case, we considered the use of special prostheses in sports at the example of the famous case of Oscar Pistorius [2]. He was competing in 400 m running competitions with the aid of two passive spring-like Carbon fiber prostheses which were assumed to give him an unfair advantage over able-bodies athletes since they are much lighter than regular

human lower legs and thus might save a lot of effort when swinging the legs forward. Simple models consisting on of point masses and springs only as they are often used in biomechanics can not answer this question, and the approach presented here based on detailed multibody system model provides a very interesting alternative. We have performed this study in [10] and shown that with a proper tuning of the passive springs, it is indeed possible to perform running motions with quite small torques and very little knee flexion, when compared to able-bodied sprinters (see figure 3). However, to fully answer the question of advantage and disadvantage, it also would be necessary to not only consider steady state running, to use even more detailed models, e.g. of the stump-shaft interaction, and to first answer the question about the fair performance and comparison criterion for 400 m sprints. Also including information about further athletes in running or jumping might improve the model.

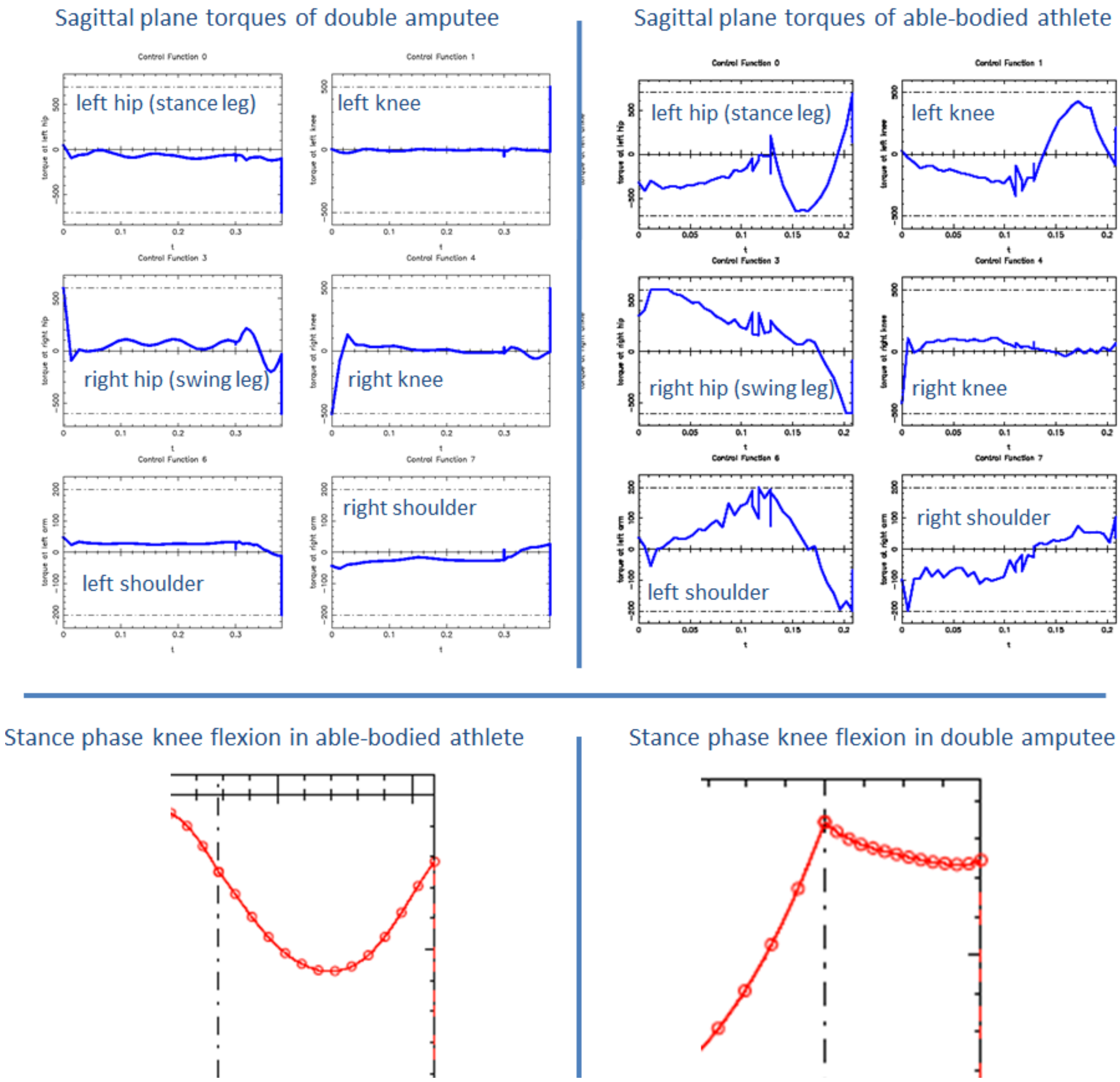

Figure 3: Example results for running motions with artificial legs: Comparison of sagittal plane torques (top) and stance phase knee flexion (bottom) for double amputee and able-bodied athlete [10]

In the second case, we have studied the question, which design requirements a lower limb exoskeleton would have to satisfy, as a function of its mass and the interial properties of the patient, in order to be able to support walking motions of paraplegic patients in different walking situations (level ground, slope up, slope down), which motors would be required, which loads the structure would have to support and which joints could be actuated by simple passive devices as linear springs (see [11] for more details). This was achieved by fitting the modeled motion to data of healthy human subjects. When applying these results to the example of elderly people walking uphill requiring only partly support it would be possible to repeat this study for their individual parameters and their individual torque limits and determine the required remaining torques to be produced by the exoskeleton. The study could also be performed in exactly the same way for any other type of motion in sports. It would of course also be possible to perform this type of study for more local orthoses designed to take loads off just one particular joint.

CONCLUSION:

In this paper we have briefly introduced model-based optimization as a tool to analyze and improve wearable robot devices for physical activity in handicapped, injured or elderly subjects. While the brevity of the paper did not allow to present any of our projects in this context in detail, we gave a brief summary of two of the projects, namely the study of prostheses for sports, and of a lower limb exoskeleton for walking on different terrains. The methods could also be used for more general motion studies in sports for humans with and without technical equipment or for studies on different impairment levels in disability sports.

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