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Prosthesis-User-in-the-Loop: A User-Specific Biomechanical Modeling and Simulation Environment

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***Abstract*— In this paper, a novel biomechanical modeling and simulation environment with an emphasis on user-specific customization is presented. A modular modeling approach for multi-body systems allows a flexible extension by specific biomechanical modeling elements and enables an efficient application in dynamic simulation and optimization problems. A functional distribution of model description and model parameter data in combination with standardized interfaces enables a simple and reliable replacement or modification of specific functional components. The user-specific customization comprises the identification of anthropometric model parameters as well as the generation of a virtual three-dimensional character. The modeling and simulation environment is associated with Prosthesis-User-in-the-Loop, a hardware simulator concept for the design and optimization of lower limb prosthetic devices based on user experience and assessment. For a demonstration of the flexibility and capability of the modeling and simulation environment, an exemplary application in context of the hardware simulator is given.**

I. INTRODUCTION

Human locomotion is the result of a complex functional interplay of the brain, spinal cord, peripheral nerves, muscles, bones and joints. The human locomotor system is able to adapt to various gait scenarios such as climbing stairs or fulfilling evasion movements as well as different gait velocities like walking or running [1]. In the design of lower limb prostheses, the performance and variability of human motion is the point of reference. Current prosthetic devices are able to provide either a semi-active support by adjusting mechanical parameters like stiffness and damping or an active support by applying mechanical energy for specific joints. These features improve biomechanic performance and reduce physical effort for the users, but still exhibit weaknesses in flexibility and operation. There is a demand for further development in technical functionality and in order to increase user satisfaction [2]–[4].

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A novel design approach based on user experience and assessment is introduced by Prosthesis-User-in-the-Loop, a hardware simulator for the design and optimization of lower limb prostheses. The primary objective of the approach is to establish a user-centered development of transfemoral prosthetic devices by providing a mechanical and visual simulation of human gait with different prosthetic concepts. The hardware simulator applies user-specific biomechanical models of the human locomotor system as well as dynamic models of prosthetic concepts for the generation of a holistic illusion.

In biomechanical simulation of human gait, two different types of dynamic models can be distinguished: templates and anchors [5]. Template models represent simplified models that define the general behavior of a leg in varying gait scenarios without providing information on detailed neural and musculoskeletal mechanisms, e.g., [6], [7]. Anchor models are based on detailed morphologic and physiological models that consider joint forces and torques as well as muscle activities of participating muscle groups. For the simulation of dynamic and time-dependent human motion, high-dimensional models of multi-body systems consisting of various sub-models for bones, muscles, tendons and wobbling masses are applied, e.g., [8], [9]. The combination of template and anchor models or anchor models with dynamic models of prosthetic devices is only marginally investigated.

For modeling and simulation of general or biodynamic multi-body systems, there are several methods and programs of various structure. These systems, e.g., ADAMS, SIMPACK or OPENSIM are applicable to the dynamic modeling of human locomotion or prosthetic concepts in principle, but usually do not allow to exploit structural properties of multi-body systems. In many cases an exploitation allows to transform a possibly large system of differential algebraic equations into a reduced system of ordinary differential equations with a minimum number of state variables. This reduced problem can numerically be solved in a more robust and efficient manner [9], [10].

The modeling and simulation environment presented in this paper provides an efficient and flexible modeling approach for general and biodynamic multi-body systems. The fundamental concept is introduced in Section II. Details are given on biomechanical modeling and simulation approaches, data management as well as user-specific customization. In Section III, an exemplary application in the context of Prosthesis-User-in-the-Loop is described. The application addresses an inverse dynamics simulation of human gait for estimating design parameters. A concluding discussion of the modeling and simulation environment as well as a brief outlook on future works are given in Section IV.

II. CONCEPT

The operation of Prosthesis-User-in-the-Loop is based on user-specific biomechanical models of the human locomotor system for the generation of individual gait patterns as well as dynamic models of different prosthetic concepts. For establishing a holistic sensorial illusion of walking with the simulated prosthesis, a visual simulation with a custom virtual three-dimensional character is required. The regular replacement or modification of prosthetic concepts makes a simple and fast reconfiguration of the applied dynamic models necessary. Design parameters need to be identified by the application of biodynamic simulation and optimization approaches. These requirements are met by a flexible and efficient biomechanical modeling and simulation environment with a focus on user-specific customization.

A. Biomechanical Modeling and Simulation

The modeling of biomechanical multi-body systems is based on the novel object-oriented class library MBSLIB. The structure of a modeled system is stored in a hierarchical model tree and consists of primitive modeling elements. Standard modeling elements include fixed or floating bases, rotatory or translational joints, fixed translations and rotations, rigid bodies, model forks and model endpoints. Each branch of the model can consist of multiple modeling elements, but must be terminated by an endpoint. External forces are assigned to endpoints or joints. The modular approach of the class library allows to extend the list by specific modeling elements like the human knee joint with specialized geometry or different muscle models.

For the dynamic simulation of a modeled system or the evaluation of optimization problems, MBSLIB provides an efficient implementation of established computational procedures. The dynamics of a multi-body system are given by

$$\boldsymbol{\tau} = \mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) + \mathbf{G}(\mathbf{q}) + \mathbf{F}_{ext} \ ,$$

with $\mathbf{q}$ being the vector of the joint positions, $\boldsymbol{\tau}$ being the forces or torques acting in the joints and $\mathbf{M}$ being the mass matrix. $\mathbf{F}_{ext}$, $\mathbf{G}$ and $\mathbf{C}$ are torque or forces in the joints resulting from external forces, gravitation and Coriolis forces. Solving the equation for $\boldsymbol{\tau}$, given $\ddot{\mathbf{q}}$, $\dot{\mathbf{q}}$ and $\mathbf{q}$, is known as inverse dynamic problem. MBSLIB applies the recursive Newton-Euler algorithm (RNEA) to compute inverse dynamics. The determination of $\ddot{\mathbf{q}}$, $\dot{\mathbf{q}}$ and $\mathbf{q}$ from a given $\boldsymbol{\tau}$ is known as forward dynamic problem. MBSLIB offers two methods for solving forward dynamics: the composit-rigid-body algorithm (CRBA) and articulated-body algorithm (ABA). Depending on the size of the modeled system, the appropriate method with regard to performance and computational time can be chosen. MBSLIB allows a transparent exchange of the computational procedure. The numerical solution of optimal control problems is significantly facilitated by the computation of the sensitivity matrix with respect to the control variables and model parameters. In combination with approved optimal control methods, the numerical forward dynamics optimization of human motion can be solved in principle [11]–[13].

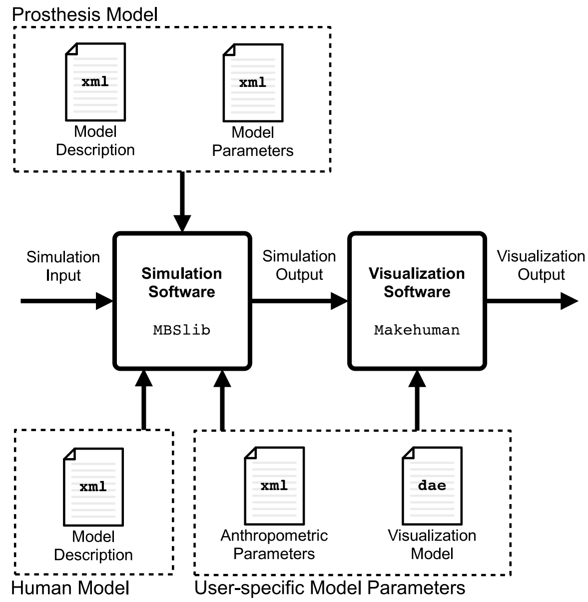

Fig. 1. Management of model description and model parameter data.

B. Distributed Data Management

Dynamic modeling in context of Prosthesis-User-in-the-Loop comprises biomechanical models of the human locomotor system, dynamic models of various prosthetic concepts as well as associated model parameters. In order to ensure a simple and fast replacement or modification of the applied dynamic models, a flexible management of modeling data and the introduction of standardized interfaces is required.

By separating model description and model parameter data, changes in the model structure become independent of the definition of model parameters. A further distinction can be made between human model data including the human model description, prosthesis model data containing prosthetic model description and parameters and user-specific parameters consisting of anthropometric parameters and data of the three-dimensional visual character used in visual simulation. The definition of standard interfaces between functional components such as mechanic interactions at the user-simulator interface assure consistency and interchangeability. This functional distribution of modeling data results in three different data modules that can be combined arbitrarily to form a valid simulation environment. Figure 1 illustrates the described management of model description and model parameter data.

C. User-Specific Customization

The dynamic simulation of individual gait patterns and the generation of a custom virtual three-dimensional character necessitates the identification of user-specific biomechanical and anthropometric parameters. For dynamic modeling, these

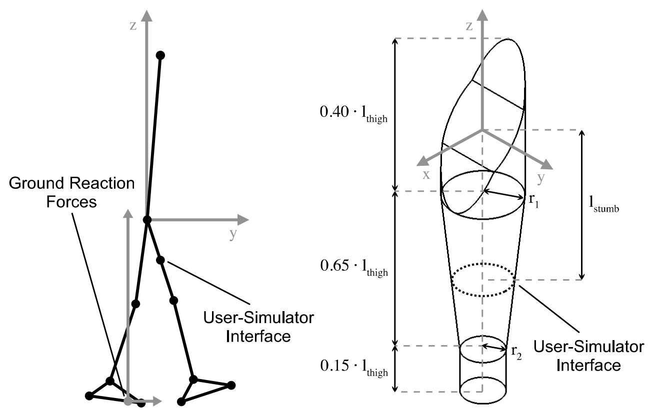

Fig. 2. Dynamic model and geometry of the human thigh model [15].

parameters include length, mass and moment of inertia of the modeled body segments. The specific values are difficult to measure and vary in age, weight, height, gender and ethnic group of the user. Historical studies on body segment parameters mostly applied invasive methods to estimate the specific values, while modern studies are grounded on non-invasive X-ray screening and magnetic resonance imaging. An overview of existing studies on this subject can be found in [14], [15]. The determined data is used to derive regression equations for the desired body parameters dependent on individual characteristics of the user. The most comprehensive collection of measured data and regression equations is based on a survey on man-machine interfaces in spacecraft design [16], [17]. The software CALCMAN implements the found regression equations and allows to estimate body segment parameters for two-dimensional modeling dependent on weight, height and gender of the user [8].

In reference to positive influences from illusions in mirror therapy and didactic benefits resulting from visual simulation, a holistic illusion might enable a manipulation of the user's body image and a proprioceptive recalibration towards the prosthetic device [18]. In order to provide a sensorial illusion of walking with the simulated prosthesis, the customization is extended to the generation of a user-specific virtual three-dimensional character. The software MAKEHUMAN is able to generate a custom three-dimensional character with a structural skeleton and skinned mesh. Modifiers for basic body parameters like age, gender, tone, height and weight are provided for macro modeling. Individual body parameters such as asymmetries or facial characteristics allow detailed micro modeling [19]. The generated character is actuated by joint trajectories obtained from a biomechanical forward kinematic simulation of human gait.

III. APPLICATION

The mechanical simulation unit of Prothesis-User-in-the-Loop needs to apply the mechanical interactions to the residual limb of the user. These interactions have to reproduce typical torque and force characteristics at the transfemoral user-simulator interface resulting from dynamic reactions and ground reaction forces occurring during human gait. For a first estimation of the required actuator performance, an inverse dynamic simulation for different gait velocities and lengths of the residual limb is performed.

The applied dynamic model of the human leg consists of three rigid bodies for the thigh, shank and foot as well as three rotatory joints with a single degree of freedom for the hip, knee and ankle joints. In addition, a rigid body for the trunk including arms and head and a rotatory joint for the sacroiliac joint are integrated. All elements are standard modeling elements of MBSLIB. With this configuration the dynamic model is able to reproduce fundamental human locomotion in sagittal plane.

The applied joint trajectories and ground reaction forces for the inverse dynamic simulation are the arithmetical average from eleven female and ten male participants with a mean height of $1.73\,\mathrm{m}$ and a mean weight of $70.9\,\mathrm{kg}$ performing walking and running [20]. Body segment parameters are estimated with CALCMAN and averaged according to the given gender ratio. A detailed geometric model of the human thigh is applied for the identification of the residual limb parameters [15]. The dynamic model and the geometry of the human thigh model are illustrated in Figure 2. The unknown radii r_1 and r_2 of the thigh model are determined by solving a constrained optimization problem to match mass and moment of inertia. For the inverse dynamic simulation, joint trajectories and ground reaction forces for walking at $1.6\,\frac{\mathrm{m}}{\mathrm{s}}$ and running at $2.6\,\frac{\mathrm{m}}{\mathrm{s}}$ are used. The length of the residual limb is varied from $25\,\%$ to $75\,\%$ of the estimated thigh length. A validation of the simulation results with reference data from literature showed reasonable characteristics for hip, knee and ankle torques in walking [1].

The normalized simulation results for normal force, torque and rotatory power at the user-simulator interface are presented in Figure 3. The characteristics of normal force describe the typical double force-peak for walking and single force-peak for running and do not differ significantly for a varied length of the residual limb [6]. The characteristics of torque show length-dependent deviations. Under load in the first half of the gait cycle, a longer residual limb results in a longer lever arm and induces higher torque. Without load in the second half of the gait cycle, the indicated effect is reversed and a longer residual limb induces less torque. The same results can be observed for the characteristics of rotatory power. The maximum normal force is given by $10.8\,\frac{\mathrm{N}}{\mathrm{kg}}$ for walking and $20.4\,\frac{\mathrm{N}}{\mathrm{kg}}$ for running. The peak torque reaches $1.4\,\frac{\mathrm{Nm}}{\mathrm{kg}}$ for walking and $3.0\,\frac{\mathrm{Nm}}{\mathrm{kg}}$ for running.

IV. CONCLUSIONS AND FUTURE WORKS

The concept and structure of the presented modeling and simulation environment is aligned to the requirements specified by the concept of Prosthesis-User-in-the-Loop. The applied modeling approach enables a modular and intuitive development of dynamic biomechanical models in combination with an efficient implementation of established computational procedures for the simulation of multi-body systems. By introducing a functional distribution of model

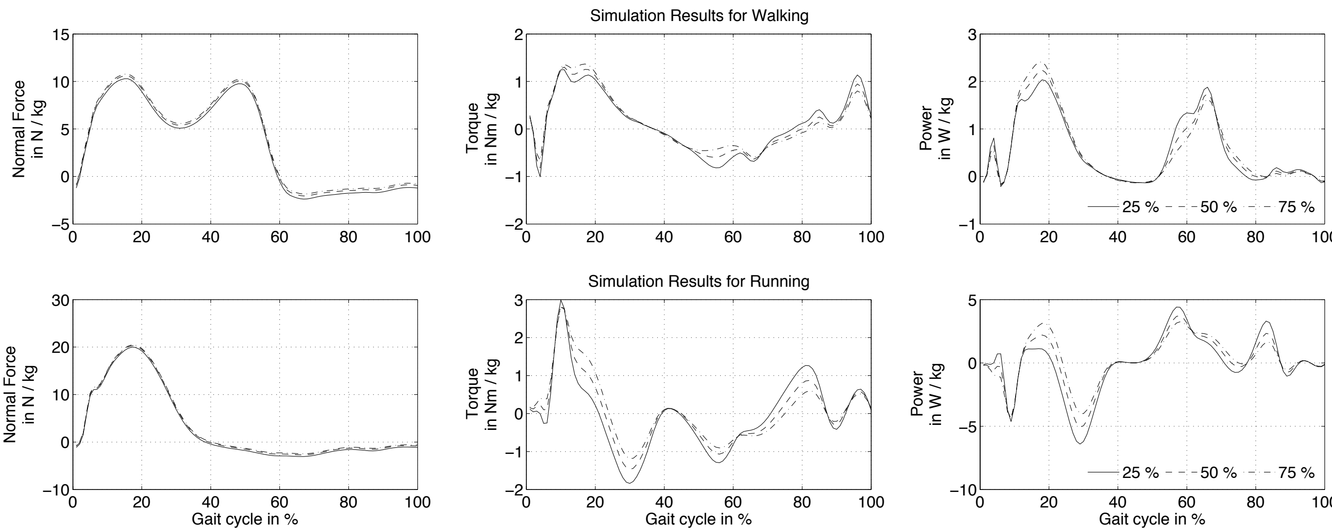

Fig. 3. Normalized simulation results for normal force, torque and power for a walking and running motion with different lengths of the residual limb.

description and model parameter data as well as standardized interfaces between specific functional components, a simple and reliable replacement or modification of dynamic models for human locomotion or prosthetic concepts is assured. The user-specific identification of biomechanical model parameters and the generation of a characteristic virtual three-dimensional character allow to implement custom dynamic simulations and visual illusions for individual users. With these capabilities, the modeling and simulation environment forms the foundation for user-centered development and evaluation of sophisticated and enhanced prosthetic devices and basic technologies. The given exemplary application demonstrates a selection of the presented features.

Future works will concentrate on the extension to three-dimensional modeling and simulation of human motion. Appropriate models for biodynamic characteristics like wobbling masses and muscle-tendon complexes need to be included into the set of modeling elements. In order to exploit the redundancy of the human locomotor system, the application of optimization approaches and the identification of specific objective functions has to be further advanced.

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