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ORIGINAL RESEARCH

Developing a Mechatronics-Twin Framework for Effective Exploration of Operational Behaviors of Prosthetic Sockets

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Abstract
A Stewart platform is a six-degree-of-freedom parallel manipulator widely used as the motion base for flight simulators and antenna positioning systems, among others. This work presents a novel mechatronics-twin framework that integrates such a manipulator with advanced biomechanical models and simulations for effective exploration of operational behaviors of prosthetic sockets with amputees. By means of the biomechanical models and simulations, the framework allows the users to first analyze the fundamental operational characteristics of individual amputees according to their specific body geometries, pelvis-femur structures, and sizes of transfemoral sockets. Such operational characteristics are then fed to one Stewart platform as the reference control signals for the generation of dynamic loads and behaviors of prosthetic sockets that are otherwise difficult to observe or realize with the real amputees. Experiments in form of integration testing show that the proposed control strategy is capable of generating expected dynamic operational conditions. Currently, the mechatronics-twin framework supports a wide range of biomechanical configurations and the quantification of the respective intra-socket load conditions for socket design optimization and anomaly detection.

Keywords Mechatronics-Twin · Stewart manipulator · Transfemoral amputee · Prosthetics · Human-in-the-loop · Cyber-physical system · Biomechanical modeling · Force-control

Introduction

Limb amputations cause serious physical disabilities that compromise the quality of life of many people around the globe. Limb prostheses offer a solution to reduce the negative impact of such disabilities, attempting to restore a normal functionality and amputee autonomy, as much as possible. It is estimated that 90% of amputees will wear a prosthetic limb for the rest of their lives. On the other hand, despite some important recent advances in prosthetics, around 40–60% of prosthesis wearers still report rather low satisfaction with the comfort of their prostheses [1].

As a critical interface between the amputee (natural) stump and the prosthetic (artificial) device, a prosthetic socket must ensure efficient fitting, appropriate load transmission, stability and control of the human-prosthesis interactions. A poorly designed or sub-optimal socket could result in a set of problems, ranging from reduced bio-mechanical fitness, hampered dynamic control, to poor comfort and medical complications (e.g., skin lesions). The actual performance of socket constitutes therefore a key factor for the success or failure of entire prosthesis. The optimization of

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prosthetic sockets is however a difficult task as each solution is inherently individual, while suffering from the fact that a wide range of actual operational conditions are difficult to observe and quantify. Such operational conditions are typically related to the dynamic load distribution, stump volume fluctuation and tissue evolvement, etc. In current practices, the load bearing capability of the stump can only be checked by prosthetists using "touch and feel" technique.

This paper presents a novel *mechatronics-twin* framework that addresses the above-mentioned challenge by serving as an analytical replica for revealing the complex operational interplay of prosthesis wearer, prosthetic device and prosthetic socket. The overall approach is characterized by an integration of (a) virtual behaviors based on a combination of advanced biomechanical modelling, simulation, and FEA (Finite Element Analysis); and (2) physical behaviors based on well-controlled motions of a six-degree-of-freedom parallel manipulator referred to as *Stewart platform*. In particular, while the virtual behaviors are useful for establishing basic understanding of fundamental bio-mechanical operational conditions and interactions of individual amputees, the physical behaviors allow a refined investigation of related operational conditions and interactions that are beyond the support of virtual behaviors and difficult to observe with the real amputees. The framework also aims to constitute an important basis for dynamic testing and calibration of novel sensors to be deployed inside prosthetic sockets [6]. Such sensors, if not properly managed, could exhibit performance concerns relating to measurement sensitivity, inaccuracy and drift. For the design of sensor functions, the operational data based on such virtual and physical behaviors constitute a basis for effective training of data-driven algorithms. Clearly, any approaches that rely on repeated experimentation on actual prosthesis wearers for such dynamic testing and calibration tasks will not be preferable. This would potentially cause further trauma to the wearers.

Currently, the mechatronics-twin framework supports different bio-mechanical configurations and dynamic operational conditions through the following steps: (1) *biomechanical modelling and simulation* of overall gait dynamics; (2) *FEA* for basic analysis and virtualization of possible intra-socket load conditions; (3) *3-D printing and prototyping* specific test stumps and sockets configurations for physical tests; (4) *physical testing by Stewart platform* with the test stumps and sockets. An overview of this mechatronic-twin framework can be seen in Fig. 1.

The rest of this paper elaborates these steps with the following sections: "Related Work" discusses related concepts and technologies in the domains of prosthetic design, operation perception and analysis. "Biomechanical Modelling and Simulation", "Finite Element Analysis", "3D Printing and Prototyping", and "Physical Testing by Stewart Platform" elaborate the support for modelling, simulation, prototyping and testing. The results by a case study are presented in "Case Study and Results". Finally, the conclusion is given in "Conclusion".

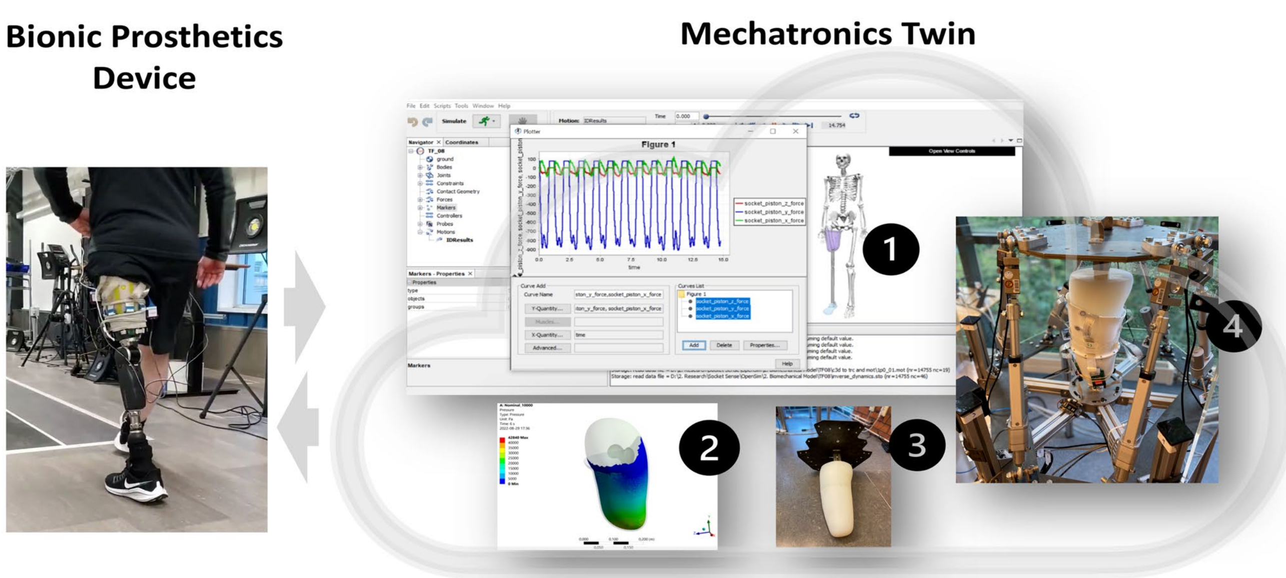


Fig. 1 Overview of the mechatronics-twin that allows both virtual and physical replications of prosthetic device. The virtual replication is supported by (1) biomechanical modelling and simulation; (2) FEA; The physical replication is supported by (3) 3-D printing and prototyping; (4) physical testing by Stewart platform

Related Work

Transfemoral (above knee) amputation is a surgical procedure performed to remove the lower limb above the knee joint when that limb has been severely damaged via trauma, disease, or congenital defect. Essentially, the usage of prosthetic device aims to restore the ambulation and self-esteem of amputee to the maximum extent. The major components of a transfemoral prosthesis include *socket*, *suspension*, *knee joint*, *pylon* and *feet* [10]. Among these prosthetic components, the socket serves as the interface between the residual limb and the prosthesis. It protects the residual limb and transmits the forces associated with standing and ambulation.

For the design and optimization of prosthetic sockets, an understanding of the actual intra-socket pressure load conditions becomes necessary. The state of the art approaches to modern limb prosthesis are therefore searching for mechanical, electronic, and computing technologies to support novel sensory and data analytic capabilities. On the other hand, the sensing of intra-socket load conditions is always a challenging task due to the inherent complexity of socket design as well as the variability of related biomechanical conditions and operational dynamics. For example, all modern pressure sensor technologies, including resistive transducer, piezoelectric transducer, optical pressure transducer, and capacitive transducer [2], have their respective challenges in regard to the deployment and effectiveness. For successful usage of such technologies, sensor testing and calibration become also especially important. To this end, it is necessary to take the specific conditions of each individual socket in relation to the unique curvatures and surface hardness of stump, as well as related operational behaviors into consideration [14]. Such conditions, if improperly treated, may affect sensing range and performance negatively. For instance, the dynamic load conditions may interfere with sensor drift, hysteresis, and other frequency response characteristics [5].

The overall objective of the mechatronics-twin framework is to support the replication of a physical target system on the basis of measurements, similar to the objectives of *digital-twin* [3]. The approach addresses however in particular the challenges arising from complex human-prosthesis interactions for which a pure virtual replication becomes ineffective or costly. The additional physical replication for a further refinement of virtual behaviors is achieved by a six-degree-of-freedom parallel manipulator referred to as SP (Stewart Platform). Since being firstly introduced in 1949, various SP based solutions are widely used as the motion base for antenna positioning systems, machine tool technology, flight simulators, etc. Today, there are over 1400 research articles about manipulators analysis and design. See e.g., [4, 8, 9, 11, 19]. Our approach adopts a PID (Proportional-Integral-Derivative) strategy to the motion control of SP, with the control reference generated by biomechanical simulation and real-time feedback from the operation. Similar approaches can be found in [16, 18].

Biomechanical Modelling and Simulation

This technical step aims at eliciting the most fundamental operational characteristics of a prosthetic device as an integral part of amputee. Within the mechatronics-twin framework, it provides the support for estimating the piston-forces and moments within the amputee stump-socket assembly during walking. Knowledge of such physical interactions is essential for more detailed analysis of stump and prosthesis dynamics. All tasks are based on *OpenSim*, which is an open source tool for the modeling, simulating and analyzing of neuromusculoskeletal systems [7].

The work starts with a quantification of amputee body geometries, sizes of the pelvis-femur structure and prosthetic socket based on a combination of measurement and estimation. These geometries are not only essential for visual representation of the bodies, but are also important in the estimation of piston-forces with *inverse dynamics* when combined with a configuration of associated body masses. To achieve a good scaling in biomechanical models, proper measurement of the limbs are required to determine the joints connecting the various bodies. The masses of the residual limb are initially approximated by equating the volumetric density of the default healthy limb to the residual limb. The *Static Optimisation Tool* of *OpenSim* is then used for a further adjustment of these masses regarding the kinematics and ground reaction forces of test-subject. A similar approach is used to develop a transfemoral biomechanical model in OpenSim to estimate joint torques [15].

A biomechanical model for identifying the piston-forces of transfemoral or transtibial prosthesis within dynamic gait cycles is then constructed with *OpenSim* as shown in Fig. 2. This model includes detailed stump and socket models as shown in Fig. 3. The current modeling of transfemoral prosthesis is based on a refinement of a well defined transtibial model [20]. In particular, numerous adaptations are enabled to match the requirement of estimating specific piston-forces from a transfemoral amputee. This includes replacing the transtibial socket, tibia pylon, remaining tibia, and with specific transfemoral socket and femur configurations.

During gait cycles, the piston-forces and moments are related to the contact forces between stump and socket as shown in Fig. 4a. The conjunction of all force vectors F_C over the discrete regions of stump surface t at each specific

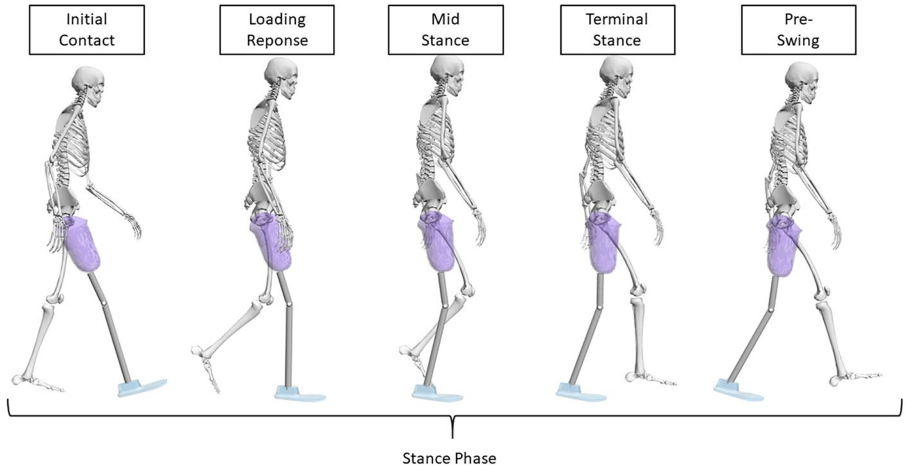


Fig. 2 A snapshot of biomechanical model and related gait phases

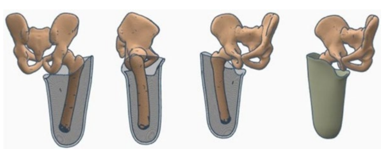


Fig. 3 Different views on positioning one femur in a transfemoral socket model

gait phase is equivalent to the piston force F_P and moments of the same stump. The contact force F_C at each region is a composition of normal force experienced from the pressure F_N and shear force F_S of the same region. For the mechatronics-twin framework, an amputee leg model, shown in Fig. 4b, is used to stipulate the related multi-body parameters of particular concern. These include:

- *Interface_r*: representing the imaginary rigid joint between the femur and the socket located at the *COM* (Center of Mass) of the stump.
- *Interface_SP*: representing the joint between the socket (*S*) and the femur pylon (*P*).

The corresponding piston-forces and moments at these interfaces are calculated according to the simulated ground reaction forces during gait cycles and the corresponding multi-body transformation through the *Inverse Dynamics Tool* of *OpenSim*. In Figs. 5 and 6, one example of the piston forces and moments over 7 gait cycles is shown. They are represented in terms of percentage of gait cycle. The sampling frequency for the simulation is 100Hz. These internal joint reaction data are then exported for the

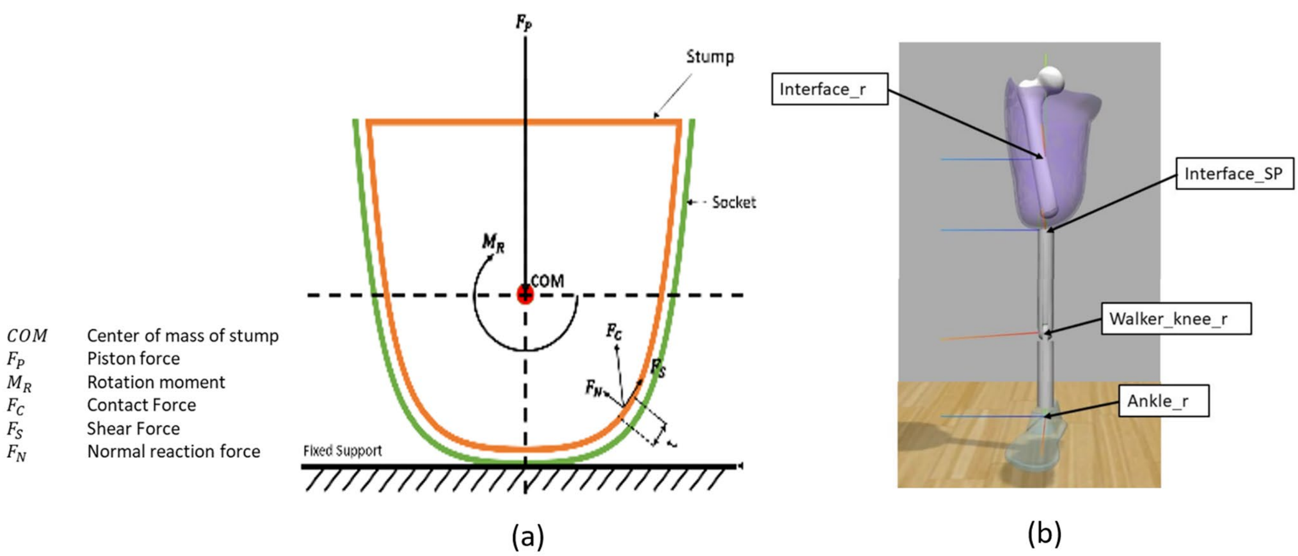


Fig. 4 **a** Basic force tensors determining the intra-socket loads condition; **b** basic configuration of an amputee leg model integrating transfemoral socket and stump (right leg)

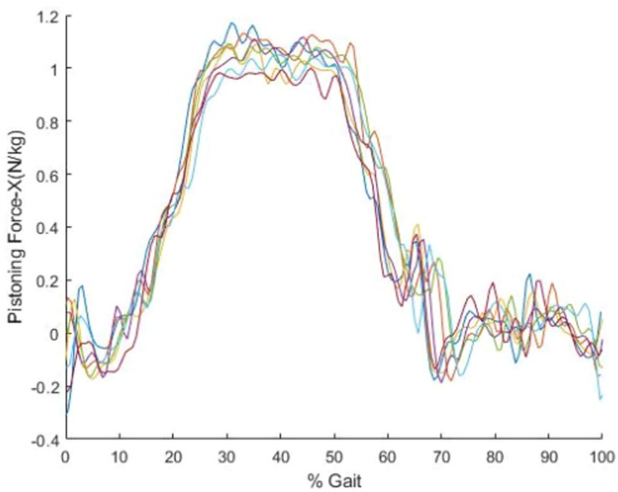


Fig. 5 One example of piston force along *X*-axis (lateral-medial axis) of 7 consecutive gait cycles

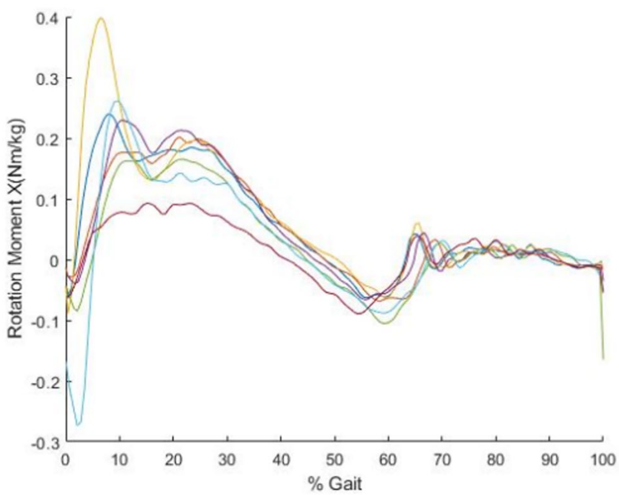


Fig. 6 One example of rotation moment around *X*-axis (lateral-medial axis) of 7 consecutive gait cycles

analysis of socket-stump interface conditions (see "Finite Element Analysis" below).

Finite Element Analysis

The goal of this technical step is to provide an effective characterization of possible intra-socket load conditions of concern before any further physical tests. Within the mechatronics-twin framework, it provides the support for establishing the virtual behaviors relating to the contact forces on stump surface, based on the internal joint reaction data from the biomechanical modelling and simulation. This joint reaction can be normalized as seen in Fig. 5 in an effort to identify relationships in the gait by comparing metrics such as standard deviation between various test subjects [15]. In addition, the FEA also provides useful insights about contact forces and displacement on the interface of stump and socket. The analysis is based on *ANSYS workbench*, which is a commercial software tool providing support for advanced FEA. Due to the complex fine-grained interplay of related surface conditions, modeling with conventional software such as *MATLAB Simscape multibody* would be a less preferred option. The work begins with a setup of the FEA model by importing the geometries of the stump, socket and femur to the *DesignModeler* of *ANSYS workbench*. The simulation setup also includes defining the material properties of the various bodies such as *density*, *Young's modulus* and *Poisson's ratio*. The calculated internal joint reaction data by *OpenSim* are thereafter used as the inputs to the FEA software. See Fig. 7 for one example of the derived pressure load conditions by FEA.

3D Printing and Prototyping

This technical step is responsible for producing and prototyping the femur-stump assemblies and sockets. Within the mechatronics-twin framework, it provides the physical replica of femur-stump assemblies and prosthetic sockets for further physical testing by the test-rig. 3D printing is used mainly due to the excellent lead times. The approach also

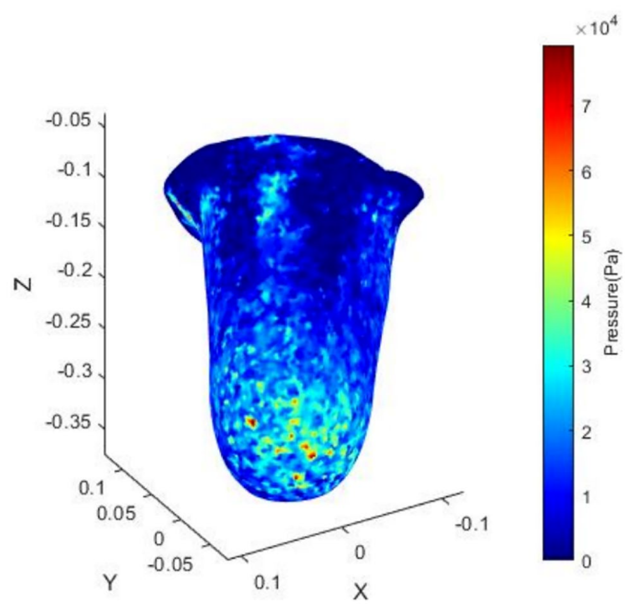


Fig. 7 One example of average pressure load of 7 consecutive gait cycles (medial posterior view)

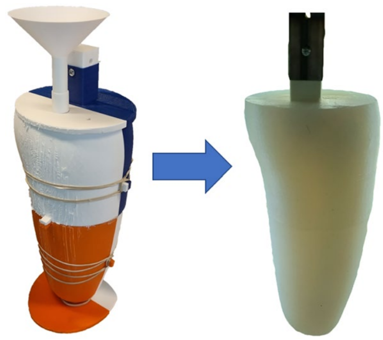


Fig. 8 The shell mold casting process of silicone stump

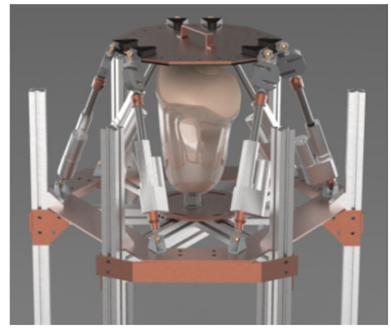


Fig. 9 The configuration of physical test-rig with femur-stump assembly, prosthetic socket, and Stewart platform

allows a geographical distribution of activities, e.g. having the patient measurement in one region and the testing in another region.

The printing and prototyping of physical replicas use the measurements of related femurs, stump assemblies and sockets. In particular, a physical replica of socket could be dimensioned by evenly extruding the geometry of target stump by 3 mms according to a widely used socket thickness [13]. The design could also be based on the scanning of a socket being used. The stump replicas are produced by a *shell mold casting* process, for which the shell is first created based on the geometry of stump as seen in Fig. 8. Similarly, a femur prototype is also generated by printing and integrated within the stump. The related design tasks are supported by *Meshmixer* [17], which is a composition tool for arbitrary surface meshes.

In practices, the sizes of these physical replicas are often larger than the maximum printing volumes of commercially available 3D printers. Under the circumstances, the parts are printed separately and assembled together thereafter. By diving the process into multiple sections, the lead time could also be also reduced significantly.

Physical Testing by Stewart Platform

Within the mechatronics-twin framework, the physical testing by Stewart platform allows a more detailed investigation of operational behaviors of prosthetic devices as an integral part of amputee. The goal is also to refine, verify and validate the corresponding virtual behaviors using the physical prototypes of femur-stump assembly and prosthetic socket. The physical test-rig consists of the prototypes of femur-stump assembly and prosthetic socket, and a Stewart platform, as shown in Fig. 9. Each leg of the Stewart platform is mounted with a load cell and a linear actuator for the motion control.

A schematic representation of the Stewart platform is shown in Fig. 10a. The platform has two coordinate systems, located at the geometry center of the *moving-platform*, $P(X_p, Y_p, Z_p)$, and the geometry center at the *base-platform* (i.e., the fixed platform), $B(X, Y, Z)$. Points b_i and p_i are the connecting joints to the base and moving platforms be the leg i, respectively. The key control parameters are shown in Fig. 10b, c. The big (R-radius) and small (r-radius) circles represent the base- and moving-platform respectively. The leg joints are denoted by the b_1 and p_1. The figures also show the the length of a leg and the relating angle to Z-plane.

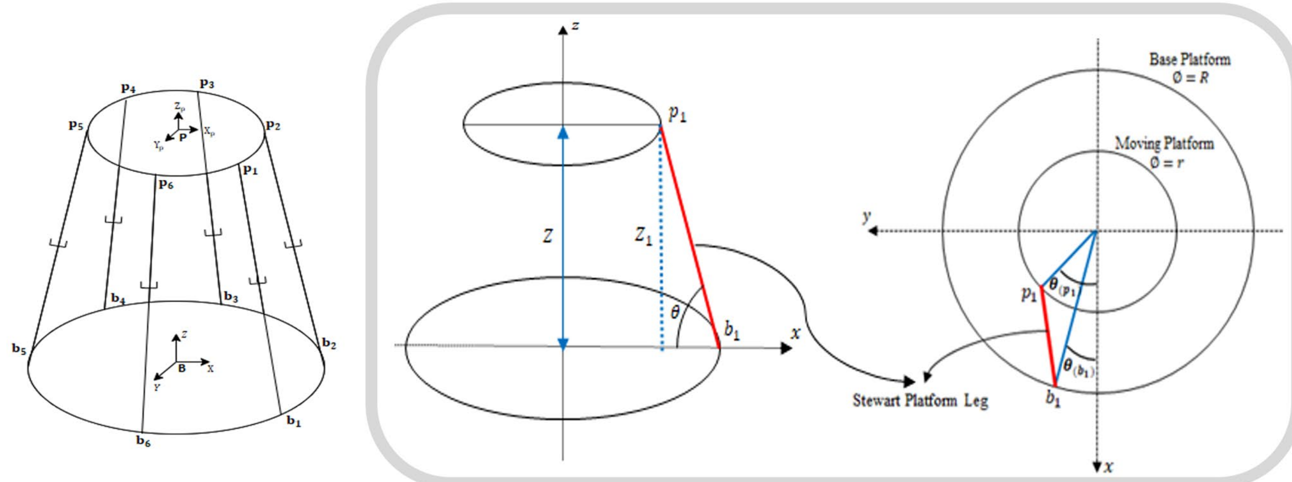
As one key step in the process of motion control, a *lumped-parameter model* is used to specify the target plant given by femur-stump assembly and socket. This method allows the complex operational behaviors of prosthetic devices to be captured by parameterized *spring-mass-damper* models. Especially, the joint movement along each DoF (Degree of Freedom) will be expressed as follows:

$$F = k \times x + d \times \dot{x} + m \times \ddot{x} \tag{1}$$

where k is the spring stiffness, d is the damping coefficient, m is the mass, and x is the displacement. The preferred values for these parameters are estimated according to the *MSE* (Mean Square Error) between the estimated forces in Eq. (1) and the estimated forces from the simulations introduced in "Biomechanical Modelling and Simulation" and "Finite Element Analysis". The performance of a lumped-parameter model identified with a pattern search algorithm [22] is shown in Fig. 11. Currently, our framework supports the estimation of lumped parameters for each DoF including polar coordinates.

For the motion control of testing, the current framework adopts a *cascaded force-position control* approach, as shown in Fig. 12. The design consists of the following major function blocks:

- **Force control**: This is a PID control function for deriving the desired displacements of the central moving plate of platform.
- **Position control**: This is a PID control function associated to each leg of the platform for deriving the required



(a) (b) (c)

Fig. 10 **a** A schematic view of Stewart Platform [18]; the key leg parameters with **b** side view, and **c** upper view

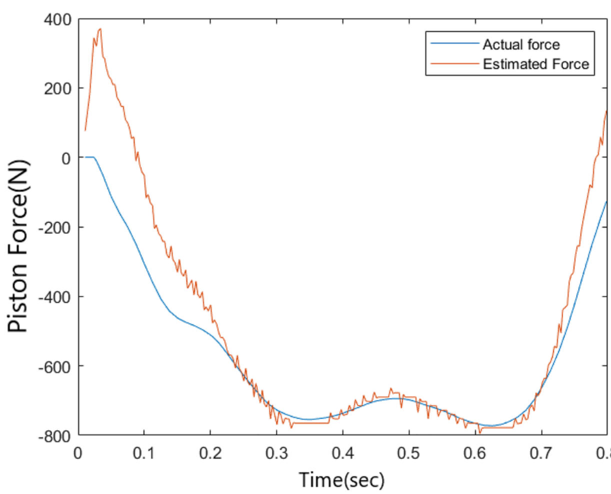


Fig. 11 The comparison of estimated force by a lumped parameter model vs. actual force given a fixed displacement in a simulation model

force for the linear actuator based on the discrepancy between the desired and measured leg conditions.

- **Inverse kinematics** : This is an analysis function for generating the reference length of each leg of the platform based on desired position of the central moving plate of platform.
- **Forward kinematic**: This is an analysis function for deriving the kinematic conditions of the geometry center of the *moving-platform* based on the measured leg lengths.

As shown in Fig. 12, the control starts with a specific *force reference* (i.e., a trajectory of desired reference forces F_{ref} to be implemented), derived from the biomechanical modeling and simulation. The controller first calculates the differences between such reference forces with the *force feedback* (i.e., a trajectory of actual measured forces F_{feedback} by the Stewart manipulator) as follows:

$$e_f = F_{\text{ref}} - F_{\text{feedback}} \tag{2}$$

where the *force feedback* is given as the sum of measured force feedback of each individual leg f_i, as defined below:

$$F_{\text{feedback}} = \sum_{i=1}^{6} f_i * \sin\theta_i \quad (i = 1, 2, \ldots, 6) \tag{3}$$

where the force feedback of each leg, f_i, is measured by the load cell mounted on each leg. The angle θ_i denotes the angle of each leg with respect to the *XY* plane on the base platform coordinate system as shown in Fig. 11. The value is calculated with the position sensor feedback.

The *Force Control* function derives the desired displacements of the moving-platform dis_Z for the actuation of the desired trajectory as follows:

$$\text{dis}_Z = (K_{pF})e_f + (K_{iF})\int_0^t e_f(\tau)\text{d}(\tau) + (K_{dF})\frac{e_f(\tau)}{\text{d}t} \tag{4}$$

This desired displacement is then combined with the *observed Z-position* for defining newly desired *Z-position*. The *Inverse Kinematics* function takes then the desired *Z-position* as inputs and derives the corresponding reference length of each leg.

The observation of operational conditions is supported by the *Forward Kinematics* function, which derives the current kinematics conditions regarding the current positions of

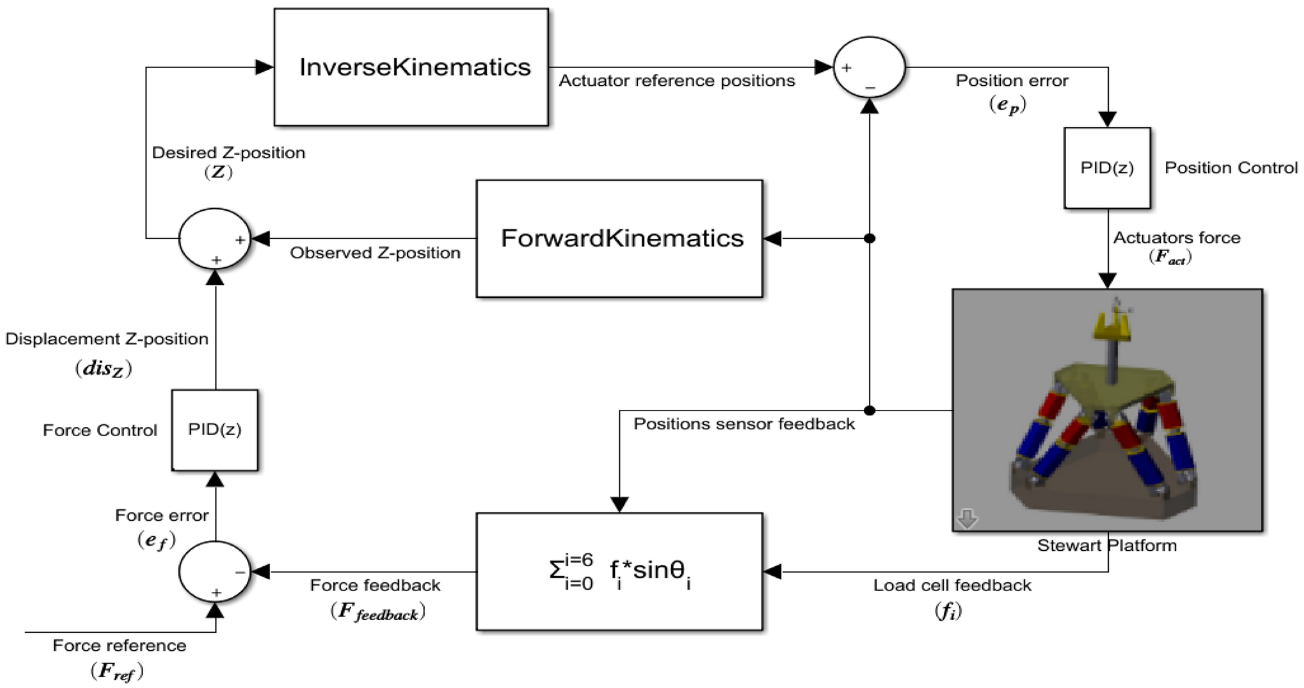


Fig. 12 Overview of the cascaded force-position control

each leg. The design follows the concept presented in [12]. With this approach, the *moving-platform* position after each iteration is given based on a *Jacobian* matrices. To quickly find a good approximation, a numerical solution based on *Newton–Raphson* method [21] is used.

The *Position Control* function takes the desired leg length references as well as the actual measured leg positions by the load cell as the input signal. Similar to force control strategy, the computed errors are multiplied by PID constants, which have been estimated by trial and error, at each time step. The needed forces (actuator efforts), F_{act}, for each leg are the output of this PID controller which are used to generate the needed length of each leg to perform the desired movements of the moving platform of Stewart platform.

$$F_{act} = (K_{pP})e_p + (K_{iP}) \int_0^t e_p(\tau)d(\tau) + (K_{dP})\frac{e_p(\tau)}{dt} \tag{5}$$

Case Study and Results

In order to validate the proposed approach, a case study is carried out using a stump replica casted according to the configuration of an amputee. The geometry and additional data such as weight and height are identified from a test led by Ossur Inc. as shown in Table 1.

Table 1 Test-subject information

Patient info.	Value
Age	42 years
Body mass	80 Kg
Height	180 cm

A scan of the amputee's residual limb, shown in Fig. 13a, is performed to generate the 3D geometry data for the 3D printing and prototyping of the stump and socket replicas. For the case study, a cyclic gait load is applied to the stump as a well-defined gait behavior. Through the biomechanical modeling and simulation ("Biomechanical Modelling and Simulation"), the corresponding normalized piston forces are identified, shown in Fig. 13b.

The entire assembly is 3D printed and casted within 72 h by using six *Ultimaker* 3D Printers, and thereafter integrated with the Stewart Platform. The Stewart Platform takes the normalised piston forces as the control references and conducts the testing. Within the Stewart Platform, the load cells of leg are *Vetek VZ-101BH*, whereas the actuators are *Transmotec DLA* series linear actuators rated for 250 *N* of nominal dynamic load. The position control function is implemented with an embedded computer node based on *Arduino Mega Microcontroller*. A custom package is developed in *ROS* (*Robot Operating System*) to support the control of overall behaviors. The feedback signals from the position sensors and load cells are collected with this computer node and

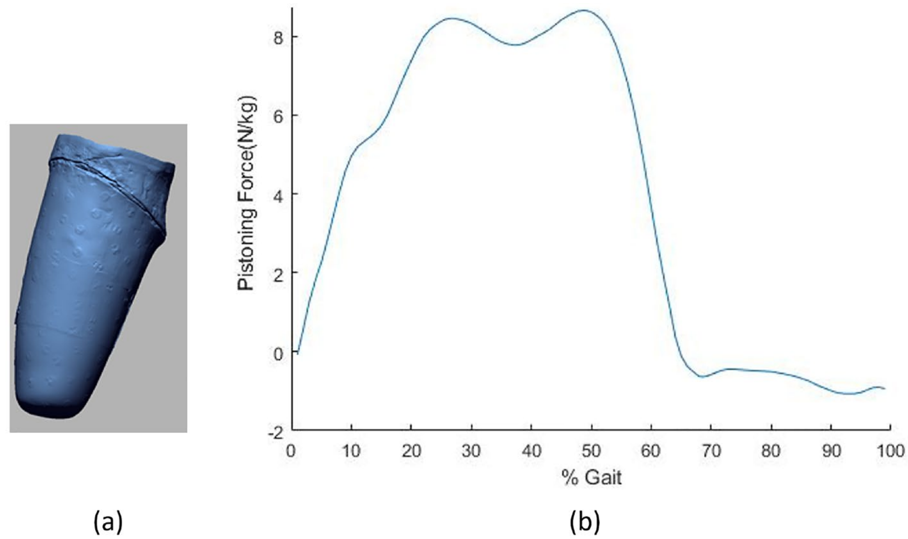


Fig. 13 **a** Scanned residual limb of test-subject; **b** the related piston force during operation

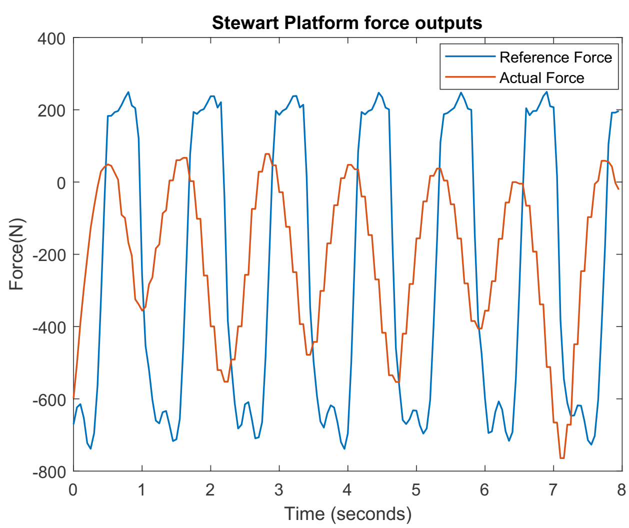


Fig. 14 A result of the force control of Stewart platform

passed to other control functions located at a host PC (running with Linux, a Ryzen 9 mobile processor and 32GB RAM).

A comparison of the resulting force trajectory from the test is compared with the reference trajectory as shown in Fig. 14. In the test, the weight of the platform, femur and stump assembly are subtracted from the net force vector to effectively apply the gait piston force load. The result shows that the proposed control strategy is capable of achieving the required magnitude and wave form of the dynamic load cycle. Although a phase shift is observed, mainly due to the computation delay, it would not affect the overall quality of test regarding the the replication of targeted mechanical process. The damping of the output can be attributed to a combination of high inertia of the platform and insufficiently performing linear actuators. The inertia of the actuator gearbox can also cause a damping of the system thus preventing a faster response. Further tuning and development of the PID controllers may alleviate these issues.

Based on the results derived from the output of the Stewart platform, a lumped parameter model relating the end effector position and dynamic loads can be quantified. This not only assists in simplifying the complex interactions in the socket-stump interface. The estimation also may assist in improving the controller performance. Due to the large variation of these dynamic interactions between different amputees due to differences in composition of amputated limb, socket geometry and stump geometry, it may be necessary to estimate the lumped parameters in real-time and tune the controller accordingly.

To store the experimental results ROSbag is used. Upon storing the results, they are exported to MATLAB. The position of the end-effector is used to estimate velocity and acceleration to aid in the lumped parameter estimation as seen in Eq. (1). For example, the velocity and acceleration are estimated as shown in Fig. 15.

To estimate the lumped parameters, a pattern search algorithm is used. However, to ensure that the force estimation can be done using a transfer function for further usage in a real-time controller, the force-position relation must be linearized at two points. These points are the equilibrium position for the lumped spring c_d and residual force due to the weight of the platform and stump assembly c_F. Therefore equation 1 can be rewritten as seen in Eq. 6.

$$F = k \times (x - c_d) + d \times \dot{x} + m \times \ddot{x} + c_F \tag{6}$$

The objective function of the pattern search algorithm calculates the RMSE (Root mean square error) between the estimated force and actual force for various values of k, m, d, c_d and c_f. Based on the case study outputs shown in Figs. 14 and 15, a pattern search algorithm is executed and the lumped parameters are successfully estimated as shown

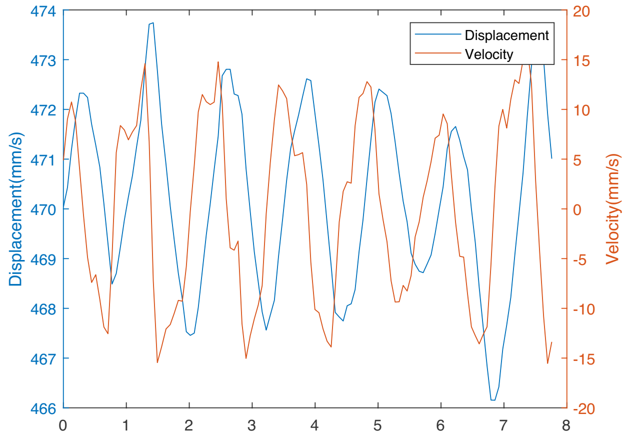


Fig. 15 Velocity estimation from displacement

in Table 2. A low RMSE of 4244.78 N^2/s is achieved. The resultant comparison of Estimated force from the lumped parameter model and Actual force is seen in Fig. 16.

Conclusion

In this paper, a novel simulation and testing framework for effective exploration of complex operational behaviors of prosthetic devices in terms of a mechatronics-twin was presented. It serves as the analytical replica of prosthetic devices with both virtual and physical behaviors for effective data-driven analysis and sensor calculation. The approach provides also a platform for effective optimization of prosthetic devices by revealing undesired load conditions without real tests by amputees. This would for example avoid unnecessary trauma to the amputees.

The results by case study show that the proposed solutions can fulfill the expected goals. Additionally, the current design of this framework opens up many perspectives for future research. In further studies, the modeling support can be enhanced with a mixture of heterogeneous friction coefficients as well as more complex hyper-elastic material models for the stump. The simulation and testing cases can also be automated for different load or gait conditions. A refinement of the controller design based on for example optimal control would also improve the control performance. For example. the case study demonstrates that a more effective controller performance may be required. By developing an adaptive controller to accept lumped parameters when performing control operations it may be possible to achieve significantly better control performance. Various software and hardware technologies would also need be explored to support the implantation of the proposed framework in industrial scale.

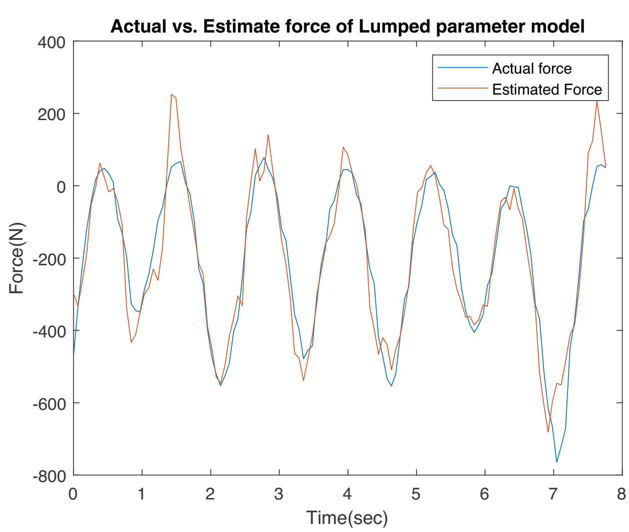


Fig. 16 A comparison of force estimated from lumped parameter model vs. actual force from test-rig given a displacement curve

Table 2 Estimated lumped parameters

Lumped parameter	Value
Mass (m)	0.2 Kg
Damping coefficient (d)	14.1208 Ns/mm
Stiffness coefficient (k)	87.6325 N/mm
Stiffness equilibrium position (c_d)	−470.0352 mm
Residual forces (c_F)	221.1362 N

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Data availability The datasets used and analyzed during the current study are available via the repository. https://zenodo.org/records/7714890.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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