A Mechatronics-twin Framework based on Stewart Platform for Effective Exploration of Operational Behaviors of Prosthetic Sockets with Amputees

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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, antenna positioning systems, machine tool technology, etc. 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, sizes of transfemoral sockets, etc. 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.

1 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. At present, despite some important recent advances in prosthetics, 40 to 60% of amputees exhibit a rather low satisfaction level due to comfort issues (Baars et al., 2018).

As a critical interface between the amputee (natural) stump and the prosthetic (artificial) device, a suitable prosthetic socket must ensure efficient fitting, appropriate load transmission, stability, and control. The performance often constitutes a key factor for the success or failure of the prosthesis itself. The optimization of prosthetic sockets is however a difficult task as each solution is inherently individual, while suffering from the fact that a wide range of operational conditions can only be partially observable or quantifiable. Such conditions are typically related to the dynamic load distribution, stump volume fluctuation and tissue evolvement, etc. For example, in current practices, the load bearing capability of the stump can only be checked by prosthetists using “touch and feel” technique. The socket-related issues that are of concern range from reduced bio-mechanical fitness, hampered dynamic control, to poor comfort and medical complications (e.g. skin lesions).

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 amputee, 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*.

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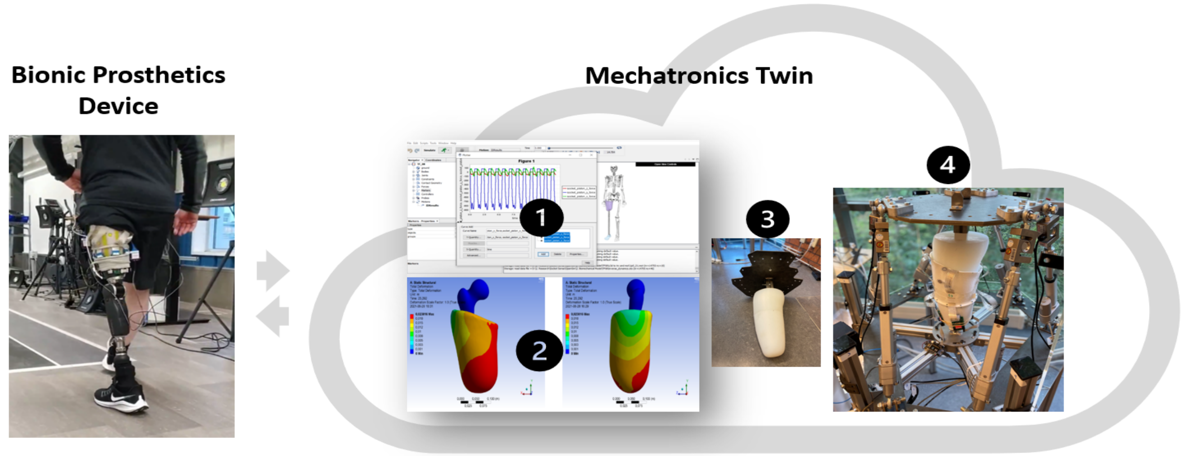


Figure 1: Overview of the mechatronics-twin that allows both virtual and physical replications of prosthetic device. The virtual replication is supported by (1) biomechanical modelling and simulation; (2) FEA; The physical replication is supported by (3) 3-D printing and integrating; (4) physical testing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

In particular, while the virtual behaviors are useful for establishing basic understanding of fundamental biomechanical operational conditions and interactions of individual amputees, the physical behaviors allow a refined investigation of such operational conditions and interactions that are otherwise difficult to observe or realize with the real amputees. Moreover, the framework also aims to constitute an important basis for successful deployment of next generation flexible wearable sensors inside bionic prosthetic sockets for real-time monitoring of dynamic load conditions. Due to their inherent physical flexibility, such sensors could suffer from some performance concerns, relating typically to the measurement sensitivity, inaccuracy and drift (Dejke et al., 2021). By generating operational data with well defined fidelity, such virtual and physical behaviors allow the training and testing of data-driven algorithms for the sensor functions.

Currently, the mechatronics-twin framework supports a wide range of bio-mechanical configurations and the quantification of respective dynamic operational situations including the intra-socket load conditions. This is done by the following technical 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 Figure 1. The rest of this paper elaborates these technical steps. It is structured into the following sections: Section 2 discusses related concepts and technologies in the domains of prosthetic design, operation perception and analysis. Section 3, 4, 5, and 6 elaborate the support for modelling, simulation, prototyping and testing. The results from a case study is presented in Section 7. Finally, the conclusion is given in Section 8.

2 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* (Geng et al., 2012). Among these prosthetic components, the socket serves as the interface between the residual limb and the prosthesis. It must protect the residual limb and appropriately transmit the forces associated with standing and ambulation.

A perception of the intra-socket load conditions would help the prosthetists optimize the design of prosthetic devices for improved operational fitness and comfort. Due to the inherent complexity and variability of human body and prosthesis operation, such a perception would also constitute the most important basis for enabling data-driven analyses where machine-learning and artificial intelligence methods are employed for the modeling and exploration of complex operational conditions. The state of the art approaches to modern limb prosthesis are therefore searching for an integration of mechanical, electronic, and computing technologies to support novel sensory and data analytic capabilities. This is, however, always a challenging task. Normally, direct sensing of the pressure conditions is restricted by specific requirements on sensor deployment and performance. For example, all modern pressure sensor technologies, including *resistive transducer*, *piezoelectric transducer*, *optical pressure transducer*, and *capacitive transducer* (Bao., 2000), have their respective disadvantages. For successful usage of such technologies, sensor testing and calibration become therefore important. For the calibration of sensors, it is always important to take the actual operational condition into the consideration. One reason for this is that the specific structural conditions of each individual prosthetic socket, relating for example to the curvature and surface hardness, could lead to the problems of sensor performance (Khodasevych et al., 2017). Different bio-mechanical conditions and operational behaviors also lead to varying dynamic conditions that in turn may interfere negatively with the sensor drift and hysteresis, as well as other frequency response characteristics (Buis and Convery, 1997). Moreover, sensor re-calibration could also be necessary in order to compensate for the drift over life cycle.

This paper presents an approach to a novel mechatronics-twin framework for prosthetic devices is similar to the notion of *digital-twin* in regard to the replication of a physical target system on the basis of measurements (Boschert and Rosen, 2016). The approach addresses however in particular the challenge of complex biomechanical dynamics of prosthesis operation as well as the need of physical replica for data generation and sensor calibration. Clearly, any approaches that rely on repeated experimentation on the amputees will not be preferable. This would in the worst case cause further trauma to the amputees. Therefore, in the mechatronics-twin framework, a six-degree-of-freedom parallel manipulator referred to as SP (Stewart Platform) has been adopted for a refinement of the digital virtual replication given by modeling and simulation.

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. (Furqan et al., 2017), (Wapler et al., 2003), (Grace et al., 1993), (Brandt et al., 1999) and (Fichter et al., 2008). 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 of SP. Similar approaches to SP control can be found in (Şumnu et al., 2017) and (Rossell et al., 2015).

3 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 (Delp et al., 2007).

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

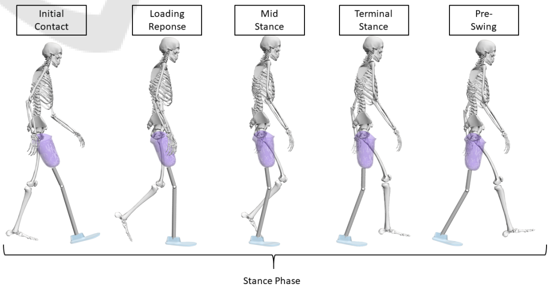


Figure 2: A snapshot of biomechanical model and related gait phases.

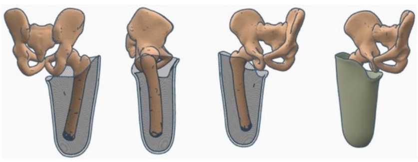
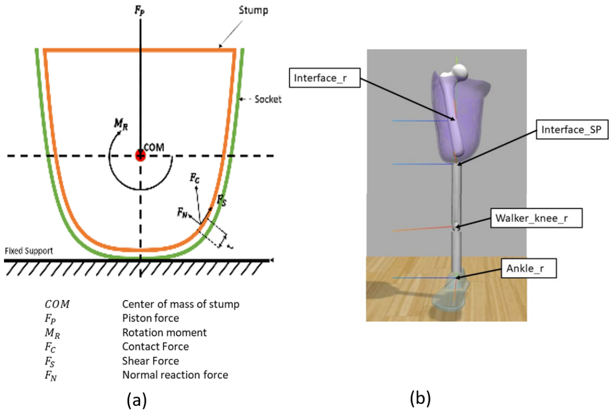


Figure 3: Positioning femur in a transfemoral socket model.



(a) (b)

Figure 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).

OpenSim to estimate joint torques (Mohamed, 2018).

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 Figure 2. This model includes detailed stump and socket models as shown in Figure 3. The current modeling of transfemoral prosthesis is based on a refinement of a well defined transtibial model(Willson, 2017). 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 Figure 4 (a). The conjunction of all force vectors F_C over the discrete regions of stump surface t at each specific 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 Figure 4 (b), 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 Figure 5 and Figure 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 analysis of socket-stump interface conditions (see Section 4 below).

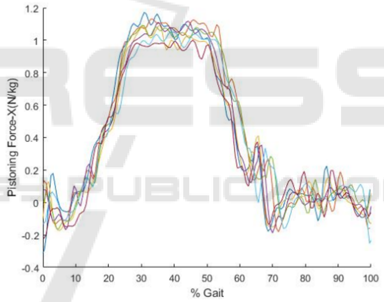


Figure 5: One example of piston force along X-Axis (lateral-medial axis) of 7 consecutive gait cycles.

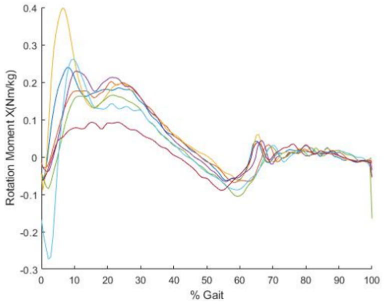


Figure 6: One example of rotation moment around X-Axis (lateral-medial axis) of 7 consecutive gait cycles.

4 FINITE ELEMENT ANALYSIS OF LOAD CONDITIONS

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 Figure 5 in an effort to identify relationships in the gait by comparing metrics such as standard deviation between various test subjects (Mohamed, 2018). 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 Figure 7 for one example of the derived pressure load conditions by FEA.

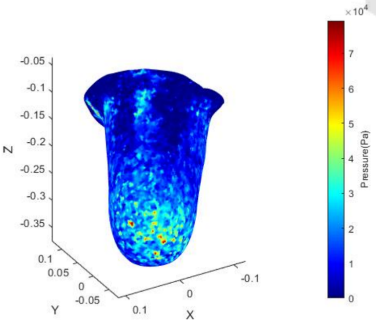


Figure 7: One example of average pressure load of 7 consecutive gait cycles (medial posterior view).

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

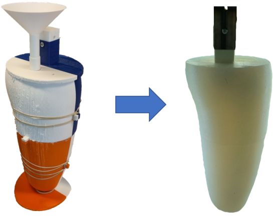


Figure 8: The shell mold casting process of silicone stump.

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 millimetres according to a widely used socket thickness (Jamaludin et al., 2018). 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 Figure 8. Similarly, a femur prototype is also generated by printing and integrated within the stump. The related design tasks are supported by *Meshmixer* (Schmidt and Singh, 2010), 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.

6 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

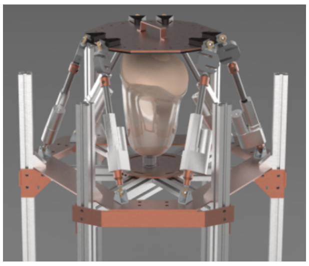


Figure 9: The configuration of physical test-rig with femur-stump assembly, prosthetic socket, and Stewart platform.

platform, as shown in Figure 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 Figure 11 (a). 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 Figure 11 (b) and (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 Equation 1 and the estimated forces from the simulations introduced in Section 3 and 4. The performance of a lumped-parameter model identified with a pattern search algorithm (Zanetti, 2021) is shown in Figure 10. Currently, our framework supports the estimation of lumped parameters for each DoF including polar coordinates.

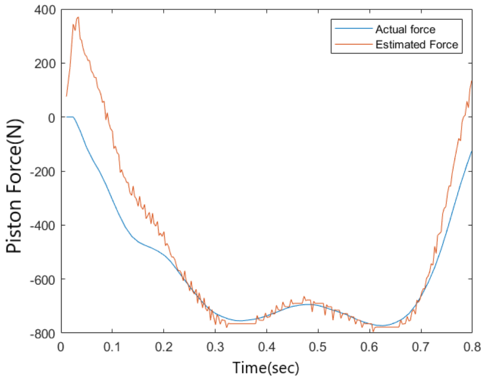


Figure 10: The comparison of estimated force by a lumped parameter model vs. actual force given a fixed displacement.

For the motion control of testing, the current framework adopts a *cascaded force-position control* approach, as shown in Figure 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 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.

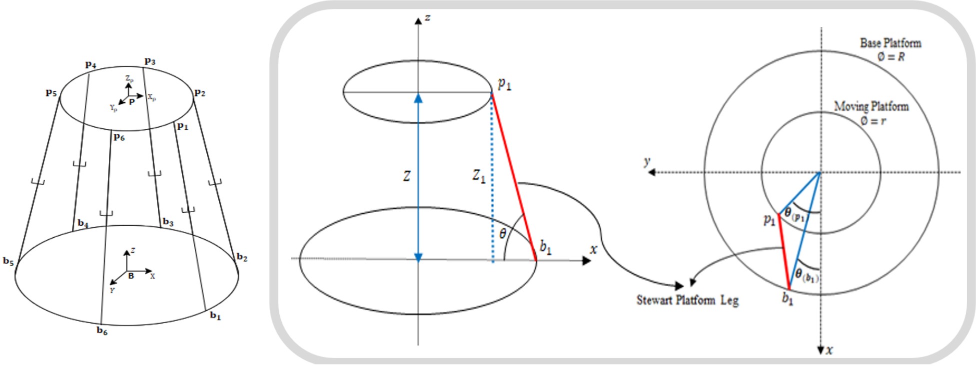
As shown in Figure 12, the control starts with a specific *force reference* (i.e. a trajectory of desired reference forces F_{ref} to be implemented), derived from the biomechanical modeling and simulation. The controller first calculates the differences between such reference forces with the *force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

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

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

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

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 Figure 11. The value is calculated with the position sensor feedback.



(a) (b) (c)

Figure 11: (a) A schematic view of Stewart Platform(Şumnu et al., 2017) ; The key leg parameters with (b) side view, and (c) upper view.

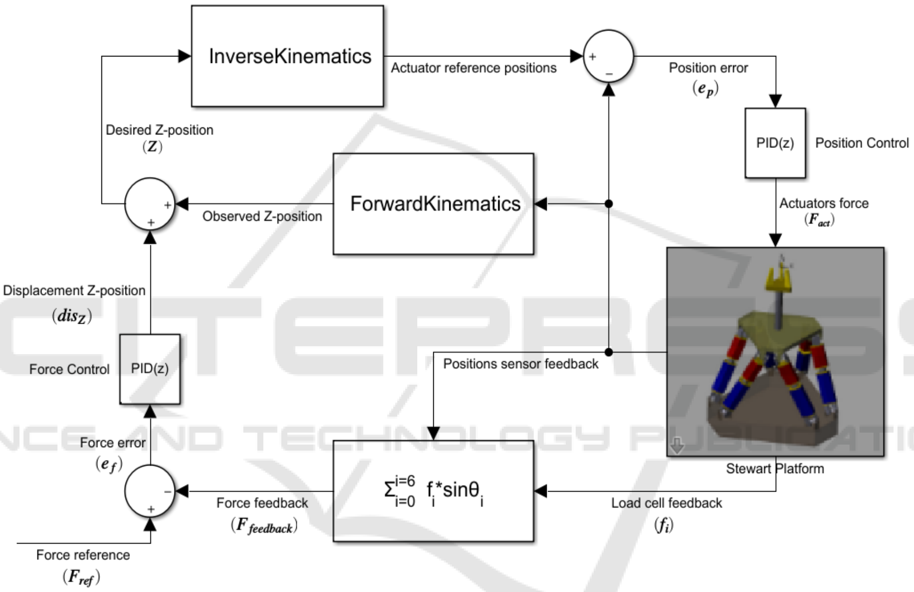


Figure 12: Overview of cascaded force-position control.

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

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

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 each leg. The design follows the concept presented in (Harib and SrinivasanHood, 2003). 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 (Wilson and Sadler, 1993) 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.

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

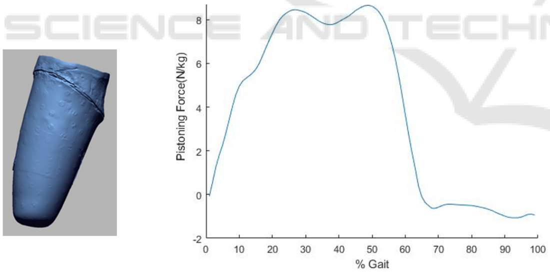
7 CASE STUDY AND RESULTS

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	80Kg
Height	180cm

A scan of the amputee's residual limb, shown in Figure 13 (a), 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 (Section 3), the corresponding normalized piston forces are identified, shown in Figure 13 (b).



(a) (b)

Figure 13: (a) Scanned residual limb of test-subject; (b) The related piston force during operation.

The entire assembly is 3D printed and casted within 72 hours 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 embedded computer node and passed the 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 Figure 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 signal can be attributed to the weak of knowledge of the linear actuators. The inertia of the 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.

8 CONCLUSION AND FUTURE WORK

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 hyperelastic 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. Various software and hardware technologies would also need be explored to support the implantation of the proposed framework in industrial scale.

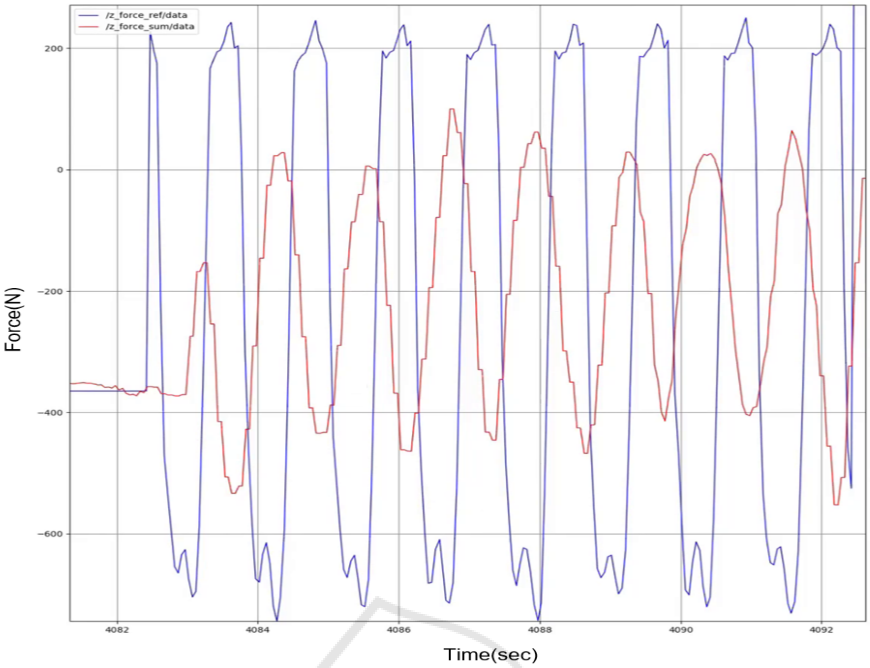


Figure 14: A result of the force control of Stewart Platform.

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Test-subject data such as residual limb geometry, weight, height and age were provided by Össur (https://www.ossur.com) based on a pilot study.

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