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A CAD-BASED SYSTEM FOR THE AUTOMATIC DESIGN OF LOWER PROSTHETIC LIMBS

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Abstract: Even today, many people around the world, that need artificial limbs, do not have access to them. This is mainly because of the high cost associated with the design and production of artificial limbs. One critical key factor that contributes to the cost of the production of artificial limbs is the complete customization of shapes and proportions to each individual patient. Automating this process could substantially reduce the cost of producing artificial limbs. In this paper we utilize the API (Application Programming Interface) of a commercial CAD-based system to automate the three-dimensional design of prosthetic lower limbs. First, the essential design parameters for the automation process are defined. These parameters are mainly based on human physiology and the traditional design and fabrication techniques of artificial lower limbs. Then, the system, based on the values assigned to the input parameters, automatically creates customized prosthetic lower limbs. In addition, the system offers various design alternatives based on the intended use of the artificial limb. The CAD-based System presented in this paper highlights the feasibility of comprehensive parameterization in the prosthetic limb design process, which harbors significant potential for shaping future developments in prosthetic limb design. Beyond technical considerations, it also holds promise for positively influencing cost dynamics and improving accessibility within this critical domain.

Key words: CAD, API, design automation, prosthetic lower limbs, artificial limbs.

1. INTRODUCTION

Artificial limbs are devices, either mechanical, electronic, or robotic in nature, designed to replicate or substitute a human limb that has been amputated or lost. These prosthetic limbs are typically created to restore mobility and functionality to individuals who have experienced limb loss because of accidents or medical conditions. The manufacturing process of artificial limbs primarily involves the utilization of materials such as metals, plastics, ceramics, or rubber. Once constructed, they are attached to the user's body using implant or fixation systems. The widespread use of artificial limbs has significantly impacted the lives of amputees, enabling them to regain their independence, engage in daily activities, and enhance their overall quality of life.

The pricing of prosthetic limbs is contingent upon their type and intended application. Generally, artificial limbs incur considerable costs, ranging from several thousand to tens of thousands of euros, contingent on the specific type, intricate design, and materials employed. Additionally, one must factor in regular maintenance expenses, repair costs, as well as the need for periodic adjustments and replacements over time. Regarding design, it represents a multifaceted and time-intensive endeavor necessitating specialized expertise. Furthermore, achieving optimal conformity of shapes and proportions to the individual user contributes significantly to the escalation of expenses. Consequently, the automation of this process holds the potential to substantially diminish the temporal and financial burdens associated with the design of artificial limbs.

The investigation of prosthetic limb design and manufacturing has primarily focused on the selection and manufacturing processes of limb materials [1,13,30]. In addition, many researchers have been focused on the construction of the prosthetic limb socket [5,19,31]. Curtze et al. [9] explored the radius of curvature and center of pressure of artificial feet in relation to different footwear types, while Hansen et al. [17] investigated the natural foot effective length ratio as a measurement tool for prosthetic limb design. Colombo et al. [8] conducted research on designing prosthetic limbs based on magnetic resonance imaging (MRI) data. Review articles discussing various techniques for designing and manufacturing prosthetic limbs can be found in [2,28,43]. To the best of our knowledge, there is a limited number of studies with respect to artificial limbs for sports usage. Dyer [11] investigated the stability of prosthetic limbs in cyclists and Mitu et al. [30] studied the proportions and dimensions of artificial sports limbs. An important contribution to the field of prosthetic limbs is the work of Porten [34], which analyzes the natural proportions of the human body.

Tang et al. [37] explored the design of prosthetic upper limb components in their research. Their study aimed to improve the design and functionality of prosthetic devices for the upper limb, potentially enhancing the quality of life for individuals in need of such devices.

Many studies have examined automation in CAD/CAM/CAE Systems. For example, Badan et al. [3] developed a tool for automated hole creation, Pescaru et al. [33] focused on automating footwear design, Zbiciak et al. [44] explored gear and helical gear design, Tsagaris et al. [39] developed a system for dynamic simulation of the human hand.

Several studies have focused on the automation of manufacturing, measurement, and assembly of mechanical components [6,16,18,22,27,35,38,40,41,42]. These studies explore various aspects of automation in mechanical component production processes. Additionally, research has been conducted on the simulation of robotic mechanisms using the SolidWorks API [4,10,29,25,] focused on punching simulation. CAD based systems for the automatic design of high-profile products have been presented in [21,23,26]. Killian [20] explored the general principles of parametric design, while Kyratsis et al. [24] investigated parametric design through Rhino Grasshopper.

Porten's research [34] suggests that the physical proportions of the human body can be represented through mathematical equations. These proportions have been historically influential in the creation of artistic works such as paintings and sculptures. Additionally, they played a role in the mass production of prosthetic limbs in Germany following World War I. In our research, we focus on proportions related to an individual's height, foot length, distance from the floor to the knee joint, and distance from the ankle joint to the floor. In the following section we will provide detailed discussions on the mathematical equations representing the proportions of these four elements.

It is important to note that the anatomy and mechanical functioning of artificial limbs differ from natural limbs, necessitating a study of proportions specific to artificial limbs. Campbell et al. [5] conducted research illustrating the proportions between two artificial components, namely the artificial tibia (shank) and the socket, which is designed to accommodate the existing natural part of the limb.

According to Campbell et al. [5], Hsu et al. [19], and Nurhanisah et al. [31], the socket that connects the natural limb to the prosthetic tibia is custom-made to ensure a perfect fit. This can be achieved through techniques such as 3D scanning or mold making. The design of the socket is of great importance in the fabrication of prosthetic limbs, as its proper adaptation to the natural limb is crucial for the correct functioning of the artificial limb.

The artificial tibia typically consists of a cylindrical skeleton with a uniform thickness. It is connected to the artificial foot through a joint. Aumüller et al. [2] depicts the natural joints of the human body as mechanical joints, categorized based on their degrees of freedom (Figure 1). The ankle joint belongs to the second category of joints, allowing movement of the foot in a specific range. Specifically, the ankle joint permits dorsiflexion of up to 20 degrees and plantar flexion of up to 30 degrees. To control the range of motion and prevent it from exceeding these limits, a stop mechanism is employed.

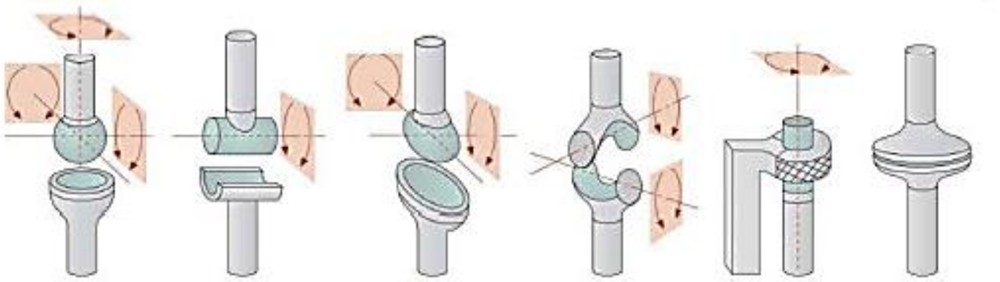


Fig 1. Various joints of the human body depicted as mechanical joints [2]

When designing an artificial foot, various factors are taken into consideration. These include the natural foot's movement and structure, the required strength to support the individual's weight and movement, and the impact on the person's balance and freedom of movement. The design of a prosthetic foot also considers additional technological features, such as pressure sensors or electronic systems, which can aid in controlling the wearer's movement.

The shape of an artificial foot varies depending on its intended use. For instance, an artificial foot designed for sports, specifically running, will have a different shape compared to one used for daily walking. Sports insoles are typically designed to provide maximum support to the areas experiencing the most stress during running. The curvature of these insoles is tailored to meet the specific needs of the individual runner. A typical artificial running foot consists of three primary sections. The rear section contributes to shock absorption, the front section enhances ground contact and acceleration, and the intermediate section provides stability and weight support. Artificial running insoles often incorporate specially designed shock-absorbing zones to reduce pressure on the joints and minimize the risk of injuries.

2. MATERIAL AND METHODS

To automate the design process, we need to identify the essential parameters that define the shape of the artificial lower limbs. These parameters are mainly based on human physiology and the traditional design and fabrication techniques of limbs.

First each part of a prosthetic limb for walking and running is identified. Then, the design parameters are defined based on Porten's research [34], which provides general proportions of the human body (Figure 2). The parameters are defined as follows:

- *H_Person*: Represents the height of the person.
- *L_KneeToFloor*: Represents the distance from the center of the knee joint to the floor.
- *L_AnkleToFloor*: Represents the distance from the center of the ankle joint to the floor.
- *L_Foot*: Represents the length of the foot.

The relationships between the above parameters are defined as follows [34]:

- H_Person = 4 * L_KneeToFloor - 2 * L_AnkleToFloor
- L_Foot = H_Person / 6.6

Next, we define the following parameters based on the work Campbell et al. [5]:

- *L_Socket*: Represents the length of the socket that fits the existing limb section.
- *L_Shank*: Represents the length of the artificial tibia.
- *D1_Socket and D2_Socket*: Represent the start and end diameters of the socket.
- *D_Shank*: Represents the diameter of the artificial tibia.
- *T_Socket*: Represents the thickness of the socket.

Additionally, based on average physical foot measurements, we define the following parameters:

- *W_Foot*: Represents the width of the foot.
- *C_Foot*: Represents the center of gravity of the foot along the axis of the tibia.

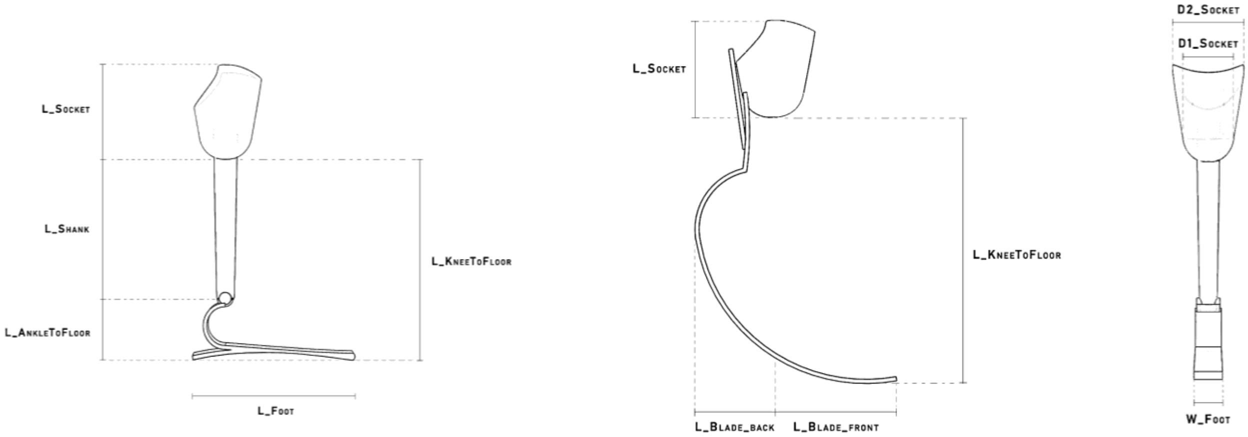


Fig. 2. Walking and running prosthetics

Afterwards, we establish the relationships between the parameters as follows:

- *L_Shank* = L_KneeToFloor - L_AnkleToFloor - L_Socket
- *D1_Socket* = L_Socket / 1.2
- *D2_Socket* = 1.15 * L_Socket
- *T_Socket* = D2_Socket - D1_Socket
- *D_Shank* = D1_Socket / 2.2
- *W_Foot* = L_Foot / 3
- *C_Foot* = L_Foot / 5

These equations define the interdependencies between the parameters and allow for the calculation of each parameter based on the given inputs.

When formulating the design of an artificial limb specifically for running, we introduced two additional parameters [30]:

- *L_Blade_front*: Represents the distance from the center of gravity of the artificial limb to the front edge of the blade.
- *L_Blade_back*: Indicates the distance from the center of gravity of the artificial limb to the rear limit of the blade.

According to the ratios based on drawings by Mitu et al. [30], we establish the relationships for the new parameters as follows:

- L_Blade_front = L_KneeToFloor / 2
- L_Blade_back = 0.6 * L_Blade_front

These relationships are necessary to optimize the design of the running prosthetics, ensuring suitable balance and performance during running activities.

Next, we present a software prototype for the design of artificial limbs.

2.1. A software prototype

The main idea of the software prototype is to provide a simple procedure to automate the design of prosthetic limbs. First, the user inputs the necessary parameters through an easy-to-use interface. Figure 3 shows the main window of the software prototype in which the user inserts the parameters. These parameters are used to establish proportions between the different components of a limb. Then, the design process involves the solid modeling of a prosthetic limb below the knee joint. It consists of three components: the *socket*, the *tibia,* and the *foot*. Finally, the software prototype enables the assembly module for the individually designed 3D components in order to assemble the prosthetic limb.

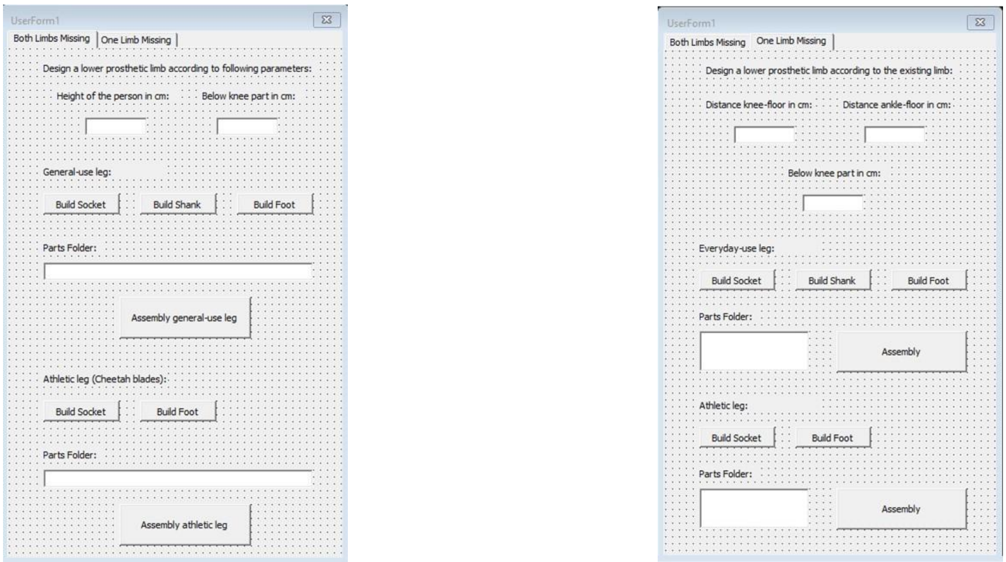


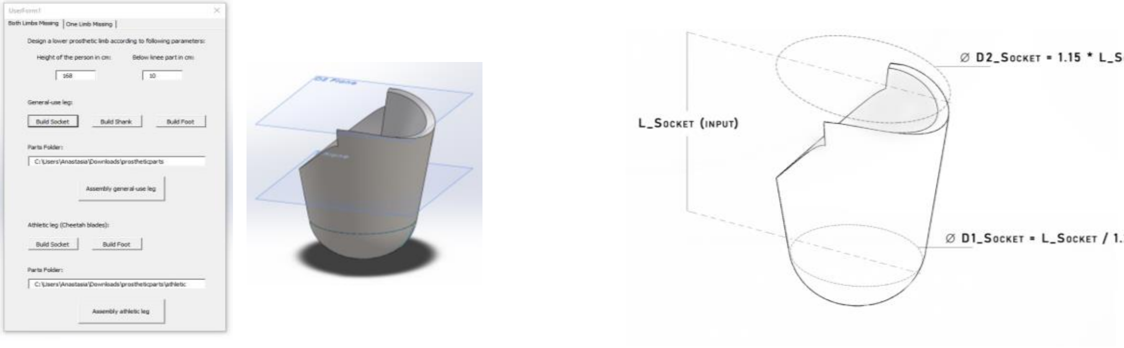
Fig. 3. The main window

To automate the design process, the Application Programming Interface (API) of a commercially used CAD (Computer Aided Design) system was utilized. The selected software is SolidWorks™ which makes use of Visual Basic™ event driven programming language.

First, in the main window of the software prototype the user has two options: (i) design two prosthetic limbs for cases where both lower limbs are amputated, and (ii) design one prosthetic limb for cases where only one lower limb is amputated. For the first case, the design is based on the person’s height. For the second case, the design is based on the person's height and the length of the existing natural part below the knee joint. Furthermore, the user inputs the following measurements:

- The distance from the center of the knee joint to the floor (L_KneeToFloor).
- The distance from the center of the ankle joint to the floor (L_AnkleToFloor).
- The length of the existing physical segment below the knee joint (L_Socket).

The shape of the *socket* is determined by two circles with diameters D2_Socket and D1_Socket. The distance between these circles is determined by the value specified by the user for the L_Socket variable. The variables D1_Socket and D2_Socket are computed as follows: D1_Socket = L_Socket / 1.2 and D2_Socket = 1.15 * L_Socket, respectively. Consequently, these variables are entirely dependent on the value entered in the main window, allowing for a customizable socket design tailored to the individual's specific requirements and anatomical dimensions. The design of the prosthetic socket aimed to mimic the natural shape of the body, ensuring a better fit. The back rim of the socket is positioned lower than the front to avoid interfering with the knee joint's movement. Once the data has been entered by the user, the "Build Socket" button is selected to initiate the socket design process. Figure 4 depicts the design result achieved in the SolidWorks software once the input values have been entered.



Height of the person in cm: 168

Below knee part in cm: 10

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Parts Folder: C:\Users\Anastasia\Downloads\prostheticparts\athletic

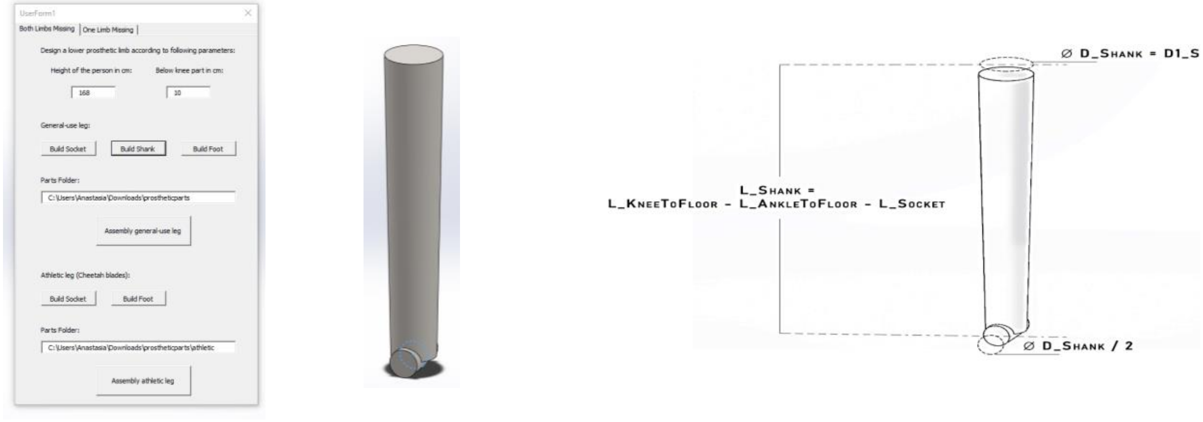
Fig. 4. Socket design

Next, the user has the option to design a foot suitable for walking or running.

Walking foot design

For the design of a foot for walking the user must design two components: (i) tibia and (ii) foot.

The shape of the artificial *tibia* is achieved by extruding a circle with a diameter D_Shank. This extrusion process imparts a draft to the 3D shape, resulting in the diameter of the lower part of the tibia being smaller than that of the upper part. The variable D_Shank is calculated relative to the lower diameter of the socket, given by D_Shank = D1_Socket / 2.2. The length of the shank, denoted by L_Shank, is determined based on both input data: L_Shank = L_KneeToFloor - L_AnkleToFloor - L_Socket. The prosthetic shank is designed by inputting the respective values for the H_Person and L_Socket variables, and subsequently selecting the "Build Shank" button (Figure 5).



Height of the person in cm: 168

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Fig. 5. Artificial tibia design

To depict the part of the ankle joint connected to the artificial tibia, a vertical circle with a diameter of D_Shank/2 is drawn. This circle is then extended to a width equal to D_Shank. The design of the ankle joint draws inspiration from the anatomy volume by Aumüller et al. [2], which delves into the mechanics of joints in the human body. By incorporating anatomical considerations, the design ensures a functional and biomechanically appropriate connection between the artificial tibia and the ankle joint, promoting enhanced mobility and stability for the user.

Due to the intricate shape of the prosthetic foot, a set of three points, for the creation of an arc, is defined to assist in the design process. These points are determined by the variables C_Foot, L_AnkleToFloor, and L_Foot as follows:

- C_Foot = L_Foot / 5
- L_AnkleToFloor= 2 * L_KneeToFloor - 3 * L_Foot
- L_Foot = H_Person / 6.6

The shape obtained from the set of the three points is extruded with the variable W_Foot serving as the width for the extrusion. The value of W_Foot is calculated as W_Foot = L_Foot / 3. This ensures that the extrusion has the desired width, proportionate to the length of the foot. Furthermore, in the upper part of the artificial foot, the complementary section of the ankle joint is incorporated, which forms the base for the cylinder of the artificial ankle joint. Finally, the "Build Foot" button is selected to complete the design of the artificial foot (Figure 6).

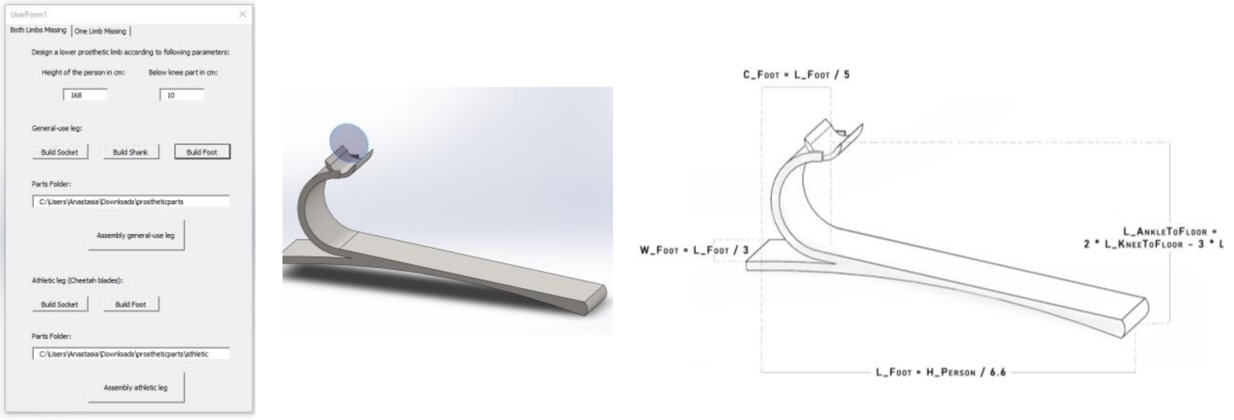
Design a lower prosthetic limb according to following parameters:
Height of the person in cm: 168
Below knee part in cm: 10
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Fig. 6. Artificial walking foot design

Athletic foot design

For the design of an athletic foot (Figure 7), which is intended for athletic use, the user inputs the height of the person (H_Person) and the length of the natural part below the knee joint (L_Socket). Then, a set of points is calculated, based on the variables L_Blade_front, L_KneeToFloor, and L_Blade_back, as follows:

- L_Blade_front = L_KneeToFloor / 2
- L_KneeToFloor = (H_Person + L_AnkleToFloor * 2) / 4
- L_Blade_back = 0.6 * L_Blade_front

The shape resulting from the set of points is extruded with a width W_Foot = L_Foot / 3. To achieve the desired elasticity of the foot, the thickness of the blade is set to W_Foot / 15. The additional element in the upper part of the blade serves the purpose of securing the tread onto the socket. Finally, the "Build Foot" button is selected to complete the design of the artificial foot.

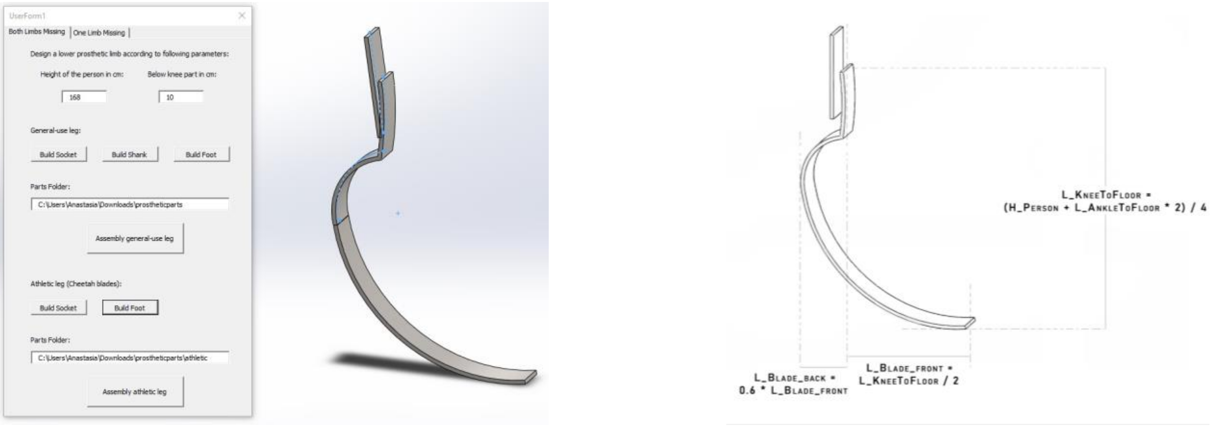
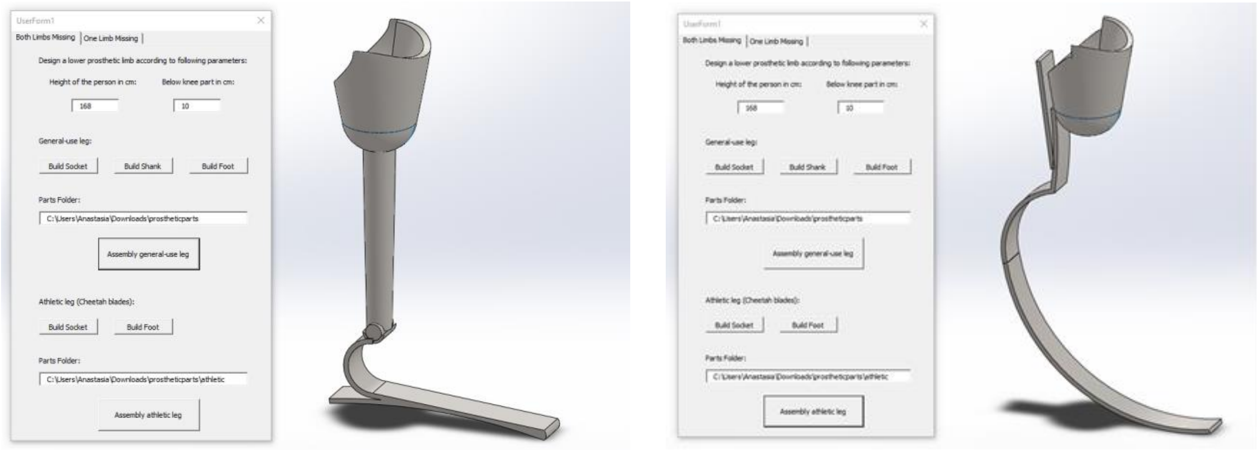

Design a lower prosthetic limb according to following parameters:
Height of the person in cm: 168
Below knee part in cm: 10
Parts Folder: C:\Users\Anastasia\Downloads\prostheticparts
Parts Folder: C:\Users\Anastasia\Downloads\prostheticparts\athletic

Fig. 7. Athletic foot design

Assembly of the prosthetic limbs

The assembly of the different components is accomplished by selecting the "Assembly" button (Figure 8). To facilitate the automatic selection and assembly process, the main window includes an input field where the user can enter the location of the files for the three elements (socket, shank, and foot). By providing the file locations, the system can seamlessly access and integrate the designed components. Upon entering the file locations, the system automatically fetches the designed elements from the specified locations and proceeds to assemble the prosthesis, using geometric constraints among the already defined variables. This automated process streamlines the design and assembly of the prosthesis, saving time and ensuring a consistent and efficient workflow.



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Height of the person in cm: 168

Below knee part in cm: 10

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Design a lower prosthetic limb according to following parameters:

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Below knee part in cm: 10

Parts Folder: C:\Users\Anastasia\Downloads\prostheticparts

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Fig. 8. Assembly of the prosthetic limbs

3. RESULTS AND DISCUSSION

The automation of CAD design for artificial limbs offers significant advantages in terms of reducing both design and production time, as well as associated costs. By automating the design process, especially when employing repetitive design commands, efficiency is greatly improved. Modifications to the design models can be easily implemented through the adaptation of the programming code, eliminating the need to start the design process from scratch due to errors or weaknesses in the initial design results. This flexibility allows for rapid creation of different versions of the model within a short timeframe, thereby streamlining the design iterations. Moreover, design automation ensures accuracy and consistency in the final design, enhancing the overall quality of the prosthetic limbs produced.

Designing prosthetic limbs is a complex and time-consuming process that requires specialized knowledge and meticulous customization of shapes and proportions to suit each individual user's needs. This level of personalization contributes significantly to the overall cost of artificial limbs. However, implementing automation in the design process has the potential to substantially reduce both time and costs associated with creating these prosthetics. The automation of the design phase using CAD technology enables the generation of precise models through 3D printing technologies, thereby bolstering production efficacy. Moreover, leveraging this technology for the design of artificial limbs empowers users to preview outcomes prior to production. This attribute furnishes users with direct engagement in the design process, affording them the opportunity to articulate feedback and preferences, thereby substantially contributing to the refinement and optimal customization of the prosthetic limb.

4. CONCLUSIONS

The use of a CAD system API provides access to the functionality of a general-purpose CAD system. Many time-consuming tasks can be automated, whereas a large set of CAD features can get organized in an easy-to-use application. Furthermore, it is possible to supplement the developed applications with a user-friendly interface. In this paper we present a software system for the automation of the design of prosthetic lower limbs, which is incorporated into a commercial CAD system, through the Application Programming Interface (API). First, the necessary parameters, which are based on human physiology and the traditional design and fabrication techniques of artificial lower limbs, are defined. Then, the system, based on the values assigned to the input parameters, automatically creates customized prosthetic lower limbs. The presented software system highlights the feasibility of comprehensive parameterization in the prosthetic limb design process, which harbors significant potential for shaping future developments in prosthetic limb design.

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