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Modular CAD Design and Engineering Documentation of a Hydraulically Damped Lower Limb Prosthesis

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Abstract - This paper presents the computer-aided design (CAD) methodology and documentation strategy for a modular, hydraulically-damped transfemoral prosthetic lower limb system. Using SolidWorks, individual components—including the polycentric knee joint, hydraulic damping mechanism, protective leg case, and energy-storing foot—were modelled with detailed, dimensioned drawings to ensure manufacturability and precise assembly. The resulting CAD assembly demonstrates a fully constrained, functional model suitable for kinematic analysis and production planning. The design emphasizes modularity for adjustable height and component replacement.

Key Words: Prosthetic lower limb, SolidWorks, CAD design, hydraulic.

1. INTRODUCTION TO MODULAR PROSTHETIC DESIGN

Modern prosthetic limbs rely on modularity, allowing components to be swapped for repair, height adjustment, or functional upgrades. For knee amputees, controlling the swing phase of the knee is critical for a smooth, natural gait. This is often achieved using mechanical or hydraulic systems. The CAD approach detailed here leverages precise part modelling to define all components of a transfemoral prosthesis featuring a hydraulic damping unit housed within a structural pylon shell.

2. COMPONENT PART MODELING AND DETAILING

The design is comprised of several interlocking parts, each modelled parametrically in CAD. Key components were documented with multi-view engineering drawings (as shown in the below figures) that include all necessary dimensions (in millimeters) for fabrication.

2.1 The Knee Joint and Pin

The **Knee Joint** component (Fig. 1) serves as the proximal connection point and the main pivot for the system. It is a block with two distinct pin bores, defined by dimensions such as the 33.75 mm width and the Ø12.00 mm bore, demonstrating the precise geometry required for bearing surfaces.

The corresponding **Knee Joint Pin** (fig. 2) is a simple cylindrical feature Ø12.00 mm with a head, modelled for attachment and rotational freedom, with a total inserted length of 27.50 mm.

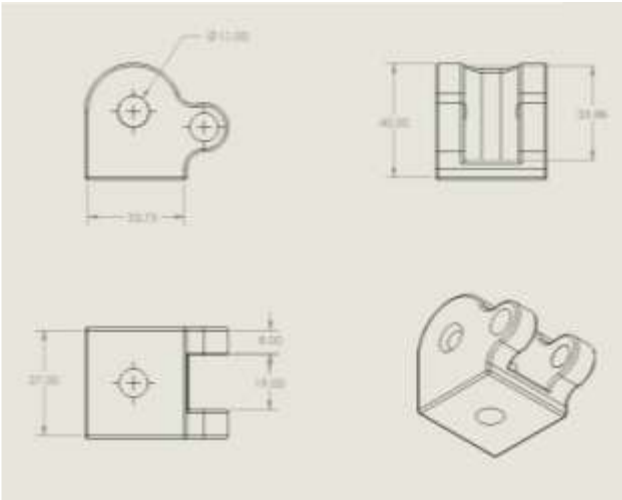

Fig. 1 Knee Joint

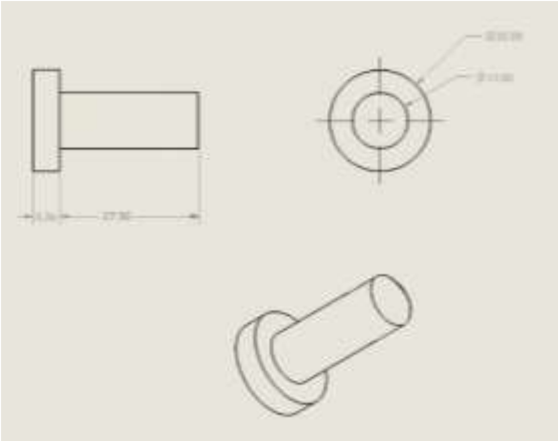

Fig. 2 Knee Joint Pin

2.2 Hydraulic Damping System

The heart of the design is the damping mechanism, modelled as two distinct parts:

1. **Hydraulic System** (Fig. 3): This component represents the main cylinder or body of the damper. The drawings indicate critical dimensions, including an overall body length of 150.00 mm and a Ø34.00 mm main body diameter, along with internal features Ø16.00 mm bore essential for accommodating the piston shaft and fluid.

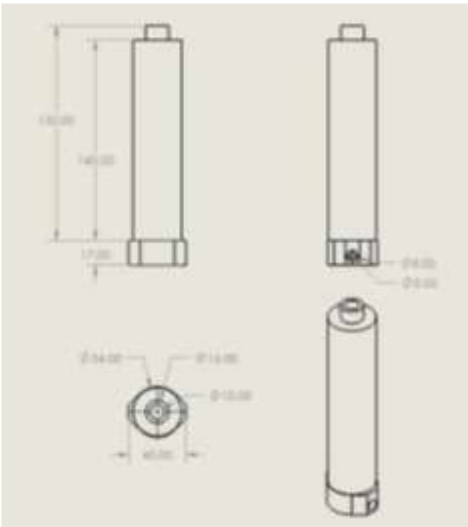

Fig. 3 Hydraulic system

2. **Hydraulic Shaft** (Fig. 4): This is the piston rod that moves axially within the system. It is a slender element 120 mm long designed to withstand axial loads, with a terminal connection radius of R8.50, ensuring proper linkage to the knee joint.

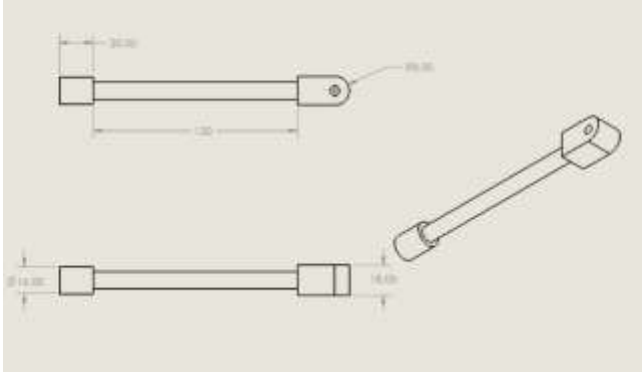

Fig. 4 Hydraulic shaft

2.3 Structural and Adjustable Pylon

The pylon structure is split into a housing and an adjustable length mechanism:

1. **Leg Case** (Fig. 5): This part acts as the structural enclosure for the hydraulic mechanism and the main load-bearing element of the shank. Its tapered design provides strength while minimizing volume. Key features include the proximal connection point R25.00 mm radius for the knee joint and the distal connection point Ø50.00 mm for the adjustable height tube.

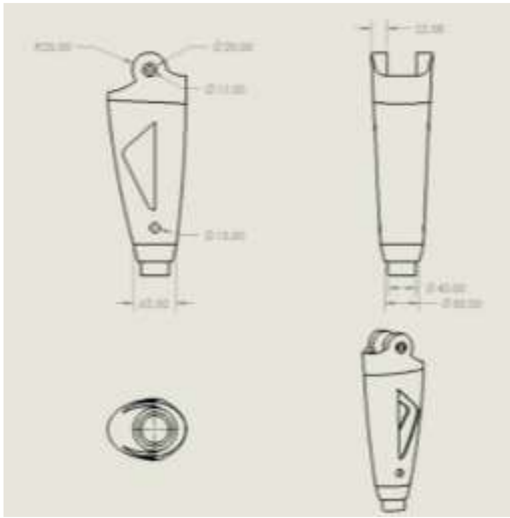

Fig. 5 Leg case

2. **Height Tube** (Fig. 6): This cylindrical component enables precise adjustment of the prosthetic limb's total length. The drawing specifies a length of 100.00 mm

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and a primary diameter of Ø40.00 mm, designed to interface snugly within the Leg Case.

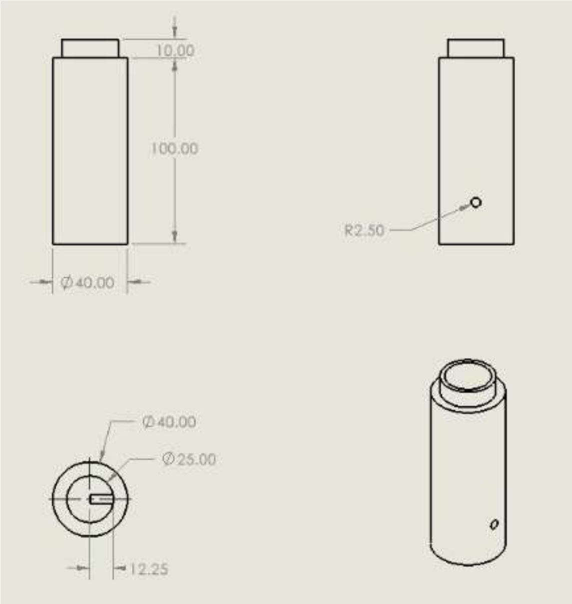

Fig. 6 Height tube

2.4 Energy-Storing Foot Unit

The **Foot** (Fig. 7) is modelled as a C-shaped, energy-storing component, commonly known as a "J-foot." The profile is defined by a series of precise radii and angles (e.g., 172.41º, 137.4º), indicating critical flexibility and load-return characteristics. The overall length and thickness of 3.00 mm are essential parameters for material selection and performance analysis.

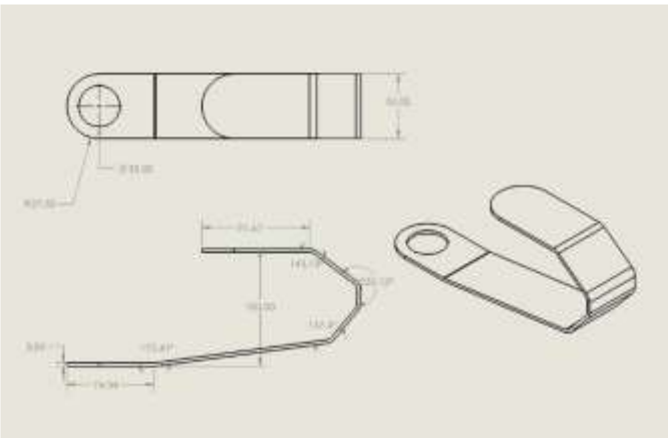

Fig. 7 Foot

3. ASSEMBLY AND INTERCONNECTIVITY

The individual parts are combined in the final **Assembly** (Fig. 8 & Fig. 9). This process validates the dimensional compatibility of all interfaces.

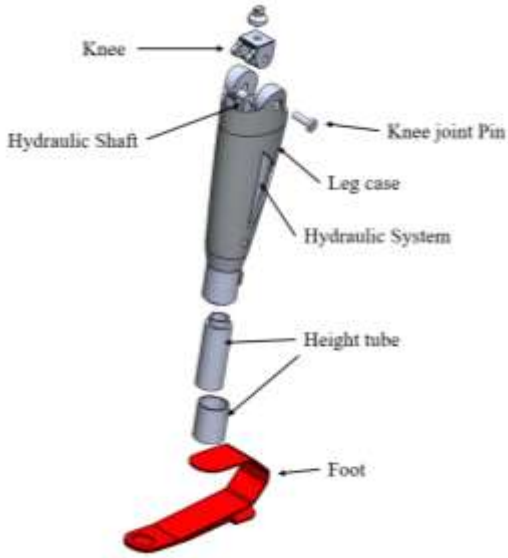

Fig. 8 Prosthetic Lower Limb

The successful mating of components in CAD confirms that:

1. The **Knee Joint Pin** properly constrains the **Knee** to the **Hydraulic Shaft** within the **Leg Case**.
2. The **Hydraulic System** is rigidly positioned within the **Leg Case**.

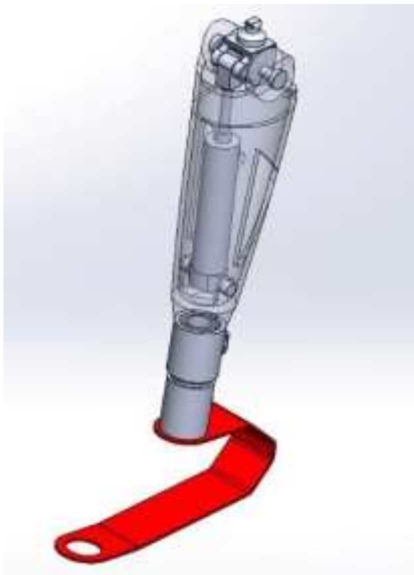

Fig. 9 ASSEMBLY

3. The **Height Tube** allows for telescoping adjustment into the distal end of the **Leg Case** before connecting

to the **Foot**. The final assembly represents a kinematically correct model of the lower limb that can move through a defined range of motion.

4. CONCLUSION

The CAD models and associated engineering drawings provide a robust foundation for manufacturing and analysing a hydraulically-damped prosthetic lower limb. By documenting each component with precise dimensions and organizing them into a functional assembly, the design process ensures accuracy, facilitates quality control, and allows for future modifications. The use of advanced damping mechanisms, like the hydraulic unit modelled, highlights the importance of CAD in integrating complex mechanical systems into comfortable and functional devices.

5. FUTURE WORK

The CAD models developed represent the ideal geometry; however, several critical steps are required to transition the design from a virtual model to a practical medical device.

5.1 Finite Element Analysis (FEA) and Optimization

The primary next step involves conducting detailed **Finite Element Analysis (FEA)** using the CAD geometry. This analysis will:

- **Stress Testing:** Simulate various load cases corresponding to different phases of the gait cycle (e.g., heel strike, mid-stance) to identify high-stress concentration areas, particularly in the **Knee Joint** and the **Foot** component.
- **Topology Optimization:** Utilize FEA results to optimize the mass and material usage of the **Leg Case** and **Knee Joint** components, potentially reducing the prosthetic's overall weight while maintaining structural integrity.

5.2 Manufacturing and Material Selection

Based on the FEA results, final material selection and manufacturing plans must be confirmed:

- **Material Validation:** Finalize the materials (e.g., carbon fiber composite for the Foot, aerospace-grade aluminum for the Pylon connectors) to meet both strength and weight requirements.
- **Prototyping:** Transition to physical prototyping, potentially utilizing **Additive Manufacturing (3D Printing)** for initial component testing and fit checks before committing to more expensive production methods like CNC machining.

5.3 Kinematic Simulation and Control Integration

For the hydraulic system, further work is required in dynamic simulation:

- **Dynamic Simulation:** Integrate the CAD model with motion simulation tools to fine-tune the damping coefficients of the **Hydraulic System** under different walking speeds and terrains.
- **Sensor Integration:** Plan the CAD modifications necessary to house and integrate electronic sensors and microprocessors, which could allow the hydraulic unit to evolve into a semi-active or **microprocessor-controlled knee (MPK)** system in the future.

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