

ANALYSIS OF PROGRESS IN THE DEVELOPMENT OF HYDRAULIC ACTUATOR-BASED ABOVE-KNEE PROSTHESIS AND FUTURE GUIDELINES

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Abstract: *This paper analyzes the development of an above-knee prosthesis based on hydraulic actuators, which was initiated at the Faculty of Mechanical Engineering, Computing and Electrical Engineering at the University of Mostar, and has continued since 2023 in collaboration with the Faculty of Mechanical Engineering of the University of Montenegro. The evolutionary trajectory of the prosthetic design is presented, from the initial models with a single hydraulic cylinder in the knee joint, through the integration of an additional actuator in the ankle joint and modifications to the prosthetic foot, to modern solutions featuring double-acting cylinders and separate hydraulic power units. Experimental testing has confirmed significant improvements in user stability, functionality, and natural gait, especially when ascending stairs. The paper also emphasizes future development directions, including the implementation of servo valves in the hydraulic system to achieve more precise fluid control, smoother movements, and automatic adaptation of the prosthesis to varying walking conditions. The research results indicate that hydraulic systems represent a significant technological advancement in modern prosthetics, enabling transfemoral amputees greater independence, comfort, and quality of life.*

Keywords: *above-knee prosthesis; knee ankle; joint ankle; hydraulic cylinder.*

1. INTRODUCTION

Biomechanics, as an interdisciplinary field that combines knowledge related to biological and mechatronic systems, first emerged in the 20th century. During that period, the development of biomechanics was primarily associated with the field of prosthetic devices [1], where innovations such as powered prostheses and the integration of new materials (plastics, batteries, motors) enabled advancements in the functionality and comfort of these devices.

One of the earliest recorded medical issues among ancient human populations was amputation, as evidenced by findings at numerous archaeological sites [2]. Throughout history, numerous wars led to frequent injuries and limb loss, both upper and lower, which posed significant challenges for survivors. Faced with such losses, people attempted to compensate for missing limbs by using objects from their surroundings to ease daily functioning. Limb loss not only had physical consequences but also

deeply affected the psychological and social well-being of the individual.

Prostheses, as one of the key groups of prosthetic devices, represent effective and useful replacements for missing human limbs such as the hand, arm, foot, or leg. Their primary function is to replace lost body parts and enable individuals with amputations to resume performing everyday activities, thereby significantly improving their independence and quality of life.

With the advancement of engineering and technology, new opportunities have emerged for innovation and improvements in the mobility of individuals with upper and lower limb amputations. Modern prostheses used around the world today can be categorized into three main groups based on their functionality:

- Passive prostheses have no power source, do not allow active movement or adaptation to usage conditions, and primarily serve as aesthetic or simple functional replacements for the missing limb.

- Semi-active prostheses allow a certain degree of movement adaptation, most commonly through the adjustment of damping or stiffness, which is achieved by modifying the prosthetic joints.
- Active prostheses, powered by an energy source, enable active movement, environmental responsiveness, and provide feedback to the user, significantly improving control and the sensation of natural motion.

2. DEVELOPMENT PROCESS OF A HYDRAULIC ACTUATOR-BASED ABOVE-KNEE PROSTHESIS

This paper analyzes the development of an above-knee prosthesis based on hydraulic actuators, which has been under development for several years at the Faculty of Mechanical Engineering, Computing and Electrical Engineering, University of Mostar. Research on the development of the hydraulically powered above-knee prosthesis began under the leadership of Professor Dedic, PhD. Professor Dedic [3], through his innovative approach and enthusiasm, initiated this project with the goal of improving the quality of life for individuals with amputations, particularly by addressing the challenge of stair climbing—one of the most significant difficulties faced by above-knee prosthesis users.

For the construction of the physical model of the above-knee prosthesis, the standard Endolite SFEUK (Stanceflex Uniaxial Knee Chassis) prosthesis [4] was selected due to its market availability and affordable price at the time. This prosthesis was subsequently modified by replacing the existing damper in the knee joint with a hydraulic cylinder, which significantly improved the functional characteristics of the device. The integration of the hydraulic cylinder enabled controlled movement and adaptation to different phases of gait, as well as enhanced stability and safety when overcoming obstacles such as stairs.



Fig.1. The first prototype of a hydraulic actuator-based above-knee prosthesis [4]

In the first phase of the research [5], the focus was on determining the required forces and moments necessary for successfully performing the stair-climbing process. Through an analysis of the biomechanical demands of knee joint movement, the research team calculated the driving force that a single-acting hydraulic actuator in the prosthetic knee joint must generate to lift the user during ascent. To accurately determine these parameters, an analysis was conducted on five standard male groups, taking into account different ranges of height and body mass. Based on the collected data, optimal technical requirements for the hydraulic cylinder were defined, including the required force, piston stroke, and operating pressure, in order for the prosthesis to effectively and safely support the user while climbing stairs. These results served as a foundation for further development and optimization of the prosthesis design, with the aim of achieving more natural and stable movement, as well as increased functionality and comfort for the end user.

The research on the development of the hydraulically powered above-knee prosthesis was extended through the doctoral dissertation of Vucina [6], which focused on establishing the kinematic model of the forces and moments generated during stair climbing. In line with the previous research, the fourth group of the male population (average height 176.9 cm, weight 81 kg) was selected as the target group for further studies, as this group has the highest frequency of transfemoral amputations. This selection allowed for a focus on the most representative parameters for prosthesis design and optimization. Experimental studies showed that:

- In addition to the knee joint, the critical point in the design of the prosthesis, which bears the highest loads during stair climbing, requires a robust construction of the hydraulic actuator that can withstand dynamic forces and bending moments.
- The ground reaction forces on the rigid foot of the prosthesis create significant moments at the ankle joint, which directly affect the stability and control of movement. The lack of adaptability in the ankle joint leads to an uneven distribution of loads, resulting in a loss of balance, unstable gait, and even falls.

Vucina concluded that the introduction of an additional actuator in the ankle joint would significantly contribute to the stability and functionality of the prosthesis, and thereby improve the comfort and stability of the user.

The third phase of the research was carried out through the master's thesis by Ziga [7], which continued in accordance with the conclusions and recommendations from Vucina's previous work. The main goal was to improve the stability and functionality of the prosthesis during stair climbing, particularly addressing issues related to the ankle joint. The integration of a second hydraulic cylinder in the ankle joint enabled better control over foot movements, damping of impact loads, and dynamic adaptation during ground contact. This directly addressed the previously identified problems with the rigid foot and uneven load distribution. Both hydraulic cylinders were powered by a single hydraulic unit. The

introduction of the additional actuator in the ankle joint showed improved results compared to the previous version and confirmed the conclusions set by Vucina. Rupa [8] improves the previous model of the above-knee prosthesis by modifying the prosthetic foot, introducing a prototype with a passive joint connection at the front, thus simulating the natural joint connection between the foot and toes. This innovation allows for greater flexibility and adaptation of the foot during walking, particularly in the push-off phase (toe-off), contributing to a more natural gait pattern and better force distribution across the prosthesis.



Fig.2. Improved above-knee prosthesis with an additional hydraulic cylinder in the ankle joint [7]

The introduction of a passive joint at the front of the foot allows for better imitation of biomechanical characteristics, reduces the load on the limb residuum, and can increase the comfort and functionality of the user during stair climbing. Experimental testing compared all three previous variants of the above-knee prosthesis:

1. Above-knee prosthesis with actively powered knee and ankle joints, and a foot with passive bending at the front,
2. Above-knee prosthesis with actively powered knee and ankle joints, and a rigid foot,
3. Above-knee prosthesis with an actively powered knee joint, and a rigid ankle connection with a rigid foot.

Experimental analysis showed that the integration of the passive foot prototype with a joint connection at the front

significantly improves the naturalness of movement compared to previous models. The passive joint allows for foot rotation in the sagittal plane, i.e., dorsiflexion of the foot.



Fig.3. Prototype prosthetic foot [8]

However, the research showed that a single hydraulic unit is insufficient to operate both hydraulic cylinders positioned in the knee and ankle joints, as it limits the synchronization of movement. It was concluded that the prosthesis should be modified by installing double-acting cylinders instead of the existing single-acting ones.

The fifth phase of the research was carried out through the doctoral dissertation of Jelacic [9]. Based on the conclusions and guidelines established by previous research, Jelacic improved the prosthesis by separating the drive into two separate hydraulic units and introducing double-acting cylinders instead of the existing single-acting ones.



Fig.4. Above-knee prosthesis with separate hydraulic units and double-acting cylinders [9]

Jelacic also conducted experimental testing comparing the new enhanced model with the previous above-knee prosthesis models. The results of the testing showed improvements over previous models in terms of achieving a more adequate naturalness of gait.

3. FUTURE GUIDELINES FOR CONTINUED RESEARCH

Through the previous research, the development and progress of the above-knee prosthesis based on hydraulic actuators, which began at the University of Mostar, is clearly evident. All the authors and researchers involved in the development project have contributed to its improvement, as confirmed by numerous master's and doctoral dissertations, as well as many scientific papers on the subject.

The continuation of the research on the prosthesis development project will focus on the implementation of servo-valves in the hydraulic system to achieve more adequate and precise fluid regulation throughout the prosthetic system, which would contribute to generating more accurate forces in the hydraulic cylinders. As a result of achieving precise forces, the prosthesis would exhibit smoother movements, improving user comfort, precision in operation, and thus achieving a more natural gait. The integration of servo-valves would pave the way toward the concept of a "smart prosthesis" capable of automatic adaptation to different types of terrain and movement dynamics.

4. CONCLUSION

Hydraulic systems in active above-knee prostheses represent a significant step toward more natural mobility for users, thanks to their ability to dynamically adapt to changes in walking patterns. The ability to generate large forces at low speeds in these systems provides users with stability during the stance phase on the prosthesis, while simultaneously allowing smooth knee flexion during the transition between steps. The main advantage of the hydraulic system is its ability to dampen impact loads when the foot makes contact with the ground, reducing the transmission of vibrations to the remaining limb and spine. This is particularly important for active users who spend several hours a day in motion.

A significant benefit of an above-knee prosthesis based on hydraulic actuators is its assistance during stair climbing. The hydraulic system of the prosthesis provides sufficient force to lift the body, while simultaneously reducing the load on the ankle joint to maintain balance. For users with amputations, this technology means increased independence in daily activities, with reduced physical fatigue and pain in the remaining joints.

The main drawback of these systems is the use of oil as a hydraulic fluid, which can be mitigated with proper sealing and regular servicing of the prosthesis. Additionally, the bulkiness and slightly higher weight compared to other systems are considered disadvantages of hydraulic systems, but with advancements in technology and miniaturization of components, these barriers can be overcome.

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