MINIATURE HYDRAULICS FOR A MECHATRONIC LOWER LIMB PROSTHESIS

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ABSTRACT

In Germany alone, 10,000 to 12,000 transfemoral amputations occur every year. Persistent rehabilitation efforts and advanced medical devices like prosthetic knee joints are crucial to reintegrating amputees into daily life successfully. Modern knee joints represent a highly integrated mechatronic system including special kinematics, a lightweight design, various sensors, microprocessors and complex algorithms to control a damping system in the context of the given situation. A knee joint is a passive system and normally has no actuator for an active movement. To enable a natural gait pattern, dampers decelerate the swinging speed of the prosthesis depending on the walking speed and situation. The invention of a novel knee joint called *VarioKnie* provides two kinematics - a monocentric and a polycentric one. Both kinematics have diametrical advantages and the user can choose the preferred setting through an electromechanical switching unit. With this knee joint in mind, a special hydraulic damper is developed to support both kinematics. Requirements and technical data are provided in the present paper. State of art are microprocessor-controlled knee joints with only one kinematic and either a hydraulic, a pneumatic, or a rheological damper.

Keywords: amputee, exoprosthetic, knee joint, artificial knee prostheses, miniature hydraulic

1. INTRODUCTION

Artificial knee prostheses enable amputees to live a self-determined life and allow many daily movements, such as climbing stairs, kneeling, or navigating down inclinations. Even more demanding activities like running or cycling are supported by modern prosthetic knee joints. Everyday activities can constitute a challenge for the patient, as the whole body weight must be carried by the prosthesis reliably without active control of the knee joint. A high confidence in the technology and a long learning process are necessary requisites to utilizing a lower limb prosthesis. To obtain a natural gait pattern, the artificial knee prosthesis (passive system) has to control and damp the swing and stance phase within the gait cycle. For instance, miniature hydraulic cylinders are used to control the flexion and extension of the prosthetic knee joint. Thereby the damping in the swing and stance phase is adapted to different walking speeds. In addition, requirements like low weight and small

package dimensions necessitate the development of a highly integrated mechatronic system.

2. STATE OF THE ART

A typical gait cycle is shown in **Figure 1**. It is subdivided into eight gait phases which are classified into two main phases – stance and swing phase. The stance phase includes every situation with ground contact, while the swing phase represents all situations without.

Modern prostheses are microprocessor-controlled knee joints based on either a monocentric or polycentric kinematic (**Figure 2**). Both kinematics have diametrical advantages. Artificial knee prostheses are usually passive systems (customers reject active knee joints because of noise emissions and higher weight). The only possibility to control pendulum movements is to decelerate, i.e. to damp or to lock, the system. Polycentric and monocentric knee joints are usable in daily life (indoor, outdoor), are splash proofed, support users up to 150 kg, weigh between 0.69 kg to 1.2 kg (2.7 kg

Figure 1: Gait cycle of a human being with eight gait phases cf. [3]

actuated), have a maximum flexion angle of up to 150° and one battery charge can power an operating time of up to five days.

Figure 2: Typical structure of a monocentric (left) and polycentric kinematic (right) with an electrohydraulic and fixed damper cf. [4]. A monocentric kinematic represents a simple revolute joint. This allows a simple and lightweight design. Furthermore, the user benefits from high stability within the stance phase because a weight shifting backwards (posterior) causes no sudden flexion. Another advantage is the possibility to go stairs both upwards and downwards in an alternating way. To control the swing and stance phase, hydraulic, pneumatic or rheological damper systems are mainly used. This allows for a deceleration of the flexion and extension in every situation in order to achieve a natural gait pattern, to include safety functions or to optimise the damping value for different walking speeds. A decisive disadvantage is the distance between knee and ground during the swing phase because of the rigid prosthetic foot (**Figure 3**). The user is

forced to lift the prosthesis to prevent a fall caused by the prosthetic foot sticking to the ground. To lift up the prosthesis it is necessary to lift the hip or to stretch the healthy foot. Both compensations are an unnatural movement and cause overstraining.

Figure 3: Comparison of a polycentric (left) and monocentric kinematic (right) during the swing phase

A polycentric kinematic consists of a kinematic, usually including a lever mechanism with four or up to seven joints. During the swing phase, a polycentric kinematic shortens the distance between knee and toe (**Figure 3**). The benefit is a more natural gait cycle without unnatural compensation movement and consequently lower loads for the skeleton. Therefore, a reduction of distance between knee and toe of 10 to 20 mm is sufficient. In general, a polycentric knee joint is not microprocessor-controlled. This means that the installed damper is not able to adapt to the specific situations. Only one damping value is adjustable for flexion and extension. The result is an optimised gait pattern for only one walking speed. Besides this, a polycentric kinematic has disadvantages concerning its stability behaviour (uncontrolled flexion due to posterior and unintentional weight shift) and functionality in specific situations, such as no alternating climbing of stairs, no cycling, no short sprints or no safety functions (e.g. no stumbling protection, no stop when falling back in the seat). The main

reason for these disadvantages is the missing microprocessor-controlled damper as a result of the difficult design space of the lever mechanism while simultaneously requiring a large flexion angle. However, it is possible to design a four-bar linkage that allows the use of a mechatronic damper. Therefore, the instantaneous centre of rotation (ICR) has to be positioned in a specific point relative to the Trochanter-Knee-Ankle line (TKA line) (**Figure 4**). Lever mechanism with significant and different behaviours can be designed [1].

In general, amputees with artificial knee prostheses require anywhere from 30% to 70% higher energy input to walk in comparison to a healthy person [2]. Reasons are unnatural gait patterns, less recuperation (no tendons) and the passive system that only decelerates the pendulum movement.

3. MOTIVATION AND GOALS

The research project “*VarioKnie*” involves two universities and four companies from the fields of mechanical engineering, hydraulics, medicine, orthopaedic technology and electronics. The main goal is a microprocessor-controlled knee joint which includes a monocentric and polycentric kinematic. An electromechanical switching unit enables a choice between both options. Advantages of both kinematics are combined and can be used in various situations. The switching operation is initialised via a motion routine or via an app on their smartphone. An electrohydraulic damper is implemented to control the swing and stance phase. Requirements like lightweight and small design space lead to the development of a highly integrated and miniature hydraulic cylinder that damps both kinematics.

As with modern knee joints, many sensors have to be combined (sensor fusion) to create more intuitive behaviour of the system. Sensor data have to be interpreted to identify each specific situation correctly and to determine the required behaviour of the prosthesis in real time. An incorrect interpretation and reaction would lead to a stumble or fall. The following data are available for the interpretation of the current situation of the user and of the knee joint: piston position via ultrasonic sensor (piston position; ~speed; ~acceleration; flexion angle), strain gauges (qualitative force curve; forefoot; heel),

and inertial measurement unit (IMU) (acceleration vector, gyroscopes).

Additional goals are the detection of vital data like blood circulation or temperature of the stump inside the prosthesis stem in order to protect the user from overstressing. Furthermore, environmental detection will be able to predict the behaviour of the knee joint for imminent situations, such as climbing stairs or obstacles. Nowadays, the user has to actively switch to a new mode using a motion routine or an app when faced with new circumstances, e.g. climbing stairs. These aspects increase the comfort for the user but are not explained in detail in this paper.

4. DEVELOPEMENTS

A constructive development process was used to design the *VarioKnie*. Therefore, the *VarioKnie* is divided into three main assemblies: the chassis, switching unit and miniature hydraulic. Three stepper motors are implemented within the design to serve as an electromechanical switching unit and an electrohydraulic damper system.

4.1. Kinematics

The geometric relationships of the kinematics influence the required design space and the behaviour of a knee joint (flexion resistance, inner forces or maximum flexion angle) or hydraulic parameters (pressure, stroke and reversal point of piston). In addition, the geometry of a polycentric kinematic influences the mechanical lock of the lever mechanism, which depends on the position of the ICR and TKA line (**Figure 4**). The reduction of the

Figure 4: Schematic design of the combined monocentric and polycentric kinematic

distance between knee and toe during the swing phase is based on this geometry as well.

A monocentric kinematic requires a TKA line that passes the revolute joint directly through the axis of rotation or little posterior to achieve an easy swing initialisation (**Figure 4**). In contrast, the polycentric mechanism can be designed in three main configurations [1]. The first results in a stable behaviour of the knee joint by designing a TKA line anterior to the ICR of the four-bar linkage (hyper stabilised). The characteristics here include a high flexion resistance and a high stability (wide range of the mechanical lock). This is useful for users with low demands concerning dynamics and a high desire for safety or stability. The second represents the opposite and the TKA line is located posterior to the ICR (elevated instant centre). The results are a low flexion resistance and no mechanical lock while standing. The third configuration is a compromise between the first and second (both illustrate extreme positions), whereby the TKA line is slightly anterior to the ICR (voluntary control). A low flexion resistance and middle stability/mechanical lock are achieved by this design and the hydraulic cylinder does not have to hold the weight of the user while standing.

The combination of both kinematics has to fulfil all mentioned constraints in order to have two kinematics with full functionality. The geometric link for the monocentric and polycentric combination is the position of the TKA line (**Figure 4**). This prerequisite allows for a deduction of all further geometric parameters while following the requirements of an artificial knee prosthesis.

4.2. Switching unit

The switching unit represents a new assembly in the field of artificial knee prostheses and implements the option to choose between a monocentric and polycentric kinematic. An electromechanical system enables easy handling by the user and locks one of the kinematics. The switching unit consists of a stepper motor, gear stages and four spindle drives which actuate the locking bolts. Because of the limited design space and lightweight restrictions, the switching unit is located in the proximal connection (**Figure 5**).

Based on DIN EN ISO 10328, parts have to be dimensioned to specific load cases. High strength materials like aluminium, steel and titanium are

used to find a compromise between design space, weight and mechanical stress. Especially the switching unit and the lever mechanism are subject to these conditions.

Figure 5: Switching unit as electromechanical system

4.3. Miniature-Hydraulic / damping unit

The damping system is the decisive component to make an artificial knee prosthesis smart. It is the only option to influence the gait pattern by decelerating or locking the flexion or extension. The *VarioKnie* uses a hydraulic differential cylinder with two proportional valves to control the extension and extracting of the piston separately (separate control edges). This configuration represents the state of the art in the industry of knee prostheses.

Requirements

The main goals of a knee prosthesis are a natural and intuitive gait pattern preferably with a low effort of energy. Therefore, four operational modes are necessary to ensure sufficient system behaviour and to implement all required functions. The first one allows for a controlled extracting of the piston with a proportional valve and storing of the displaced volume. The opposite is found in the second mode, which enables a controlled extension of the piston while using the stored energy of the piston accumulator. At this point, a conflict of objectives arises. On the one hand, a low flexion resistance is required to reduce energy efforts needed for walking. On the other hand, the stored energy should be reused to support the extension, a so-called 'assist spring'. The crucial component is the spring and the preloading of the piston accumulator, which has significant influence on the flexion resistance and

Good controllability of the hydraulic system and of the damping effect is guaranteed if the main pressure difference is generated in the proportional valves. Therefore, the cross-section areas of the check valves are designed to be six times larger than that of the proportional valve.

This approach supports the efforts to create a hydraulic system with low hydraulic losses. It provides benefits regarding thermal aspects, as well. A sectional view of the hydraulic cylinder is given in **Figure 7**.

A prediction of system behaviour is analysed with numerical methods like CFD and a cross-domain simulation including a mechanical and hydraulic system. Components of the hydraulic circuit are simulated by using CFD to estimate pressure losses with different input parameters. In addition, a test arrangement was used to measure the characteristics of the proportional valve at different volume flows and valve openings.

Figure 7: Sectional view of the hydraulic cylinder

5. VARIOKNEE

In **Figure 8**, the *VarioKnee* is shown including a switchable kinematic (monocentric or polycentric) and the miniature hydraulic cylinder. It represents a mechatronic system with several sensors and actors. The housing is made of an aluminium alloy to ensure a lightweight design. The 3D printing manufacturing process (SLM) enables an esthetical and functional design.

The *VarioKnee* project is now in the final year of its three-year development phase and the design, production and assembly have been completed. Preliminary tests on the actors and sensors have been carried out. In the next step, the software development will be finalised in order to allow for the detection of the current situation and to determine the requested system behaviour. Different walking modes, functions and motion routines have to be implemented. Several amputees will test the *VarioKnee* in the last project phase under laboratory and real conditions.

6. SUMMARY AND OUTLOOK

The main innovation of the project is the combination of two kinematics in one artificial

knee joint that are supported by a newly developed damper in the form of a miniature hydraulic cylinder. Two stepper motors allow for separate controlling of the extracting and extension of the piston, thereby enabling a specific damper value for flexion or extension. Adaptability of the system behaviour facilitates a natural gait pattern and supports different functions based on the electrohydraulic damper system. A highly integrated design fulfils the requirements of a lightweight design.

Figure 8: Design of the *VarioKnee*

An electromechanical system allows a smart control of the switching unit, initialised by a motion routine or an app on a smartphone. In the next step, the software of the *VarioKnee* has to be developed to allow for intuitive operability for amputees. Therefore, amputees are involved in the project for testing under laboratory and real conditions. The *VarioKnee* will be usable for the initial temporary application to gain experience with different kinematics, for rehabilitation and for daily life.

NOMENCLATURE

<i>CFD</i>	Computational Fluid Dynamics
<i>CV</i>	Check Valve
<i>EPD</i>	End Position Damping
<i>ICR</i>	Instantaneous Centre of Rotation
<i>M</i>	Motor
<i>PA</i>	Piston Accumulator
<i>PV</i>	Proportional Valve
<i>PRV</i>	Pressure Relief Valve
<i>SLM</i>	Selective Laser Melting
<i>TKA</i>	Trochanter-Knee-Ankle
<i>TV</i>	Throttle Valve

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