# Concept, design and construction of an active supporting foot prosthesis

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## Abstract

Numerous foot prostheses are currently on the market for persons with an amputations at the lower extremity. The common prosthesis is passive, causing many clinical problems, including non-symmetric gait patterns, poorer shock absorption, and higher gait metabolism. This has lead to gradually more attention being paid to the incorporation of active elements in prosthetics since the 1990's. However, most of these devices are still on research level. Those which were made market ready still have disadvantages such as, high weights, low battery capacity or an insufficient energetically support of the gait. In this paper an active foot prosthetic model was developed using a wide requirement catalogue. Following the recent literature the concept implements the idea of a series elastic actuator (SEA) and a second parallel-arranged spring. The series spring reduces the peak output and absorbs shocks from the actuator. The prosthetic model is built on a market available passive foot prosthesis, which obtains good elastic properties. The implemention of a parallel spring stores energy during the stance-phase and supports the push off. The maximum range of motion (20° plantar-flection and 13° dorsal-flection) enables walking on level-ground as good as on a ramp or stairs. This concept yields a prosthetic model that compensates the downfalls of the current model, and facilitates an improvement of the everyday life of the user.

## 1 Introduction

Today more than 40.000 people annually have to have amputations at the lower extremity in Germany[1]. Exoprostheses make some cosmetic and functional compensation. The common foot prostheses are normally completely passive during the stance-phase of walking. Leaf springs are used to save and restore energy while walking[2]. The human foot however functions with much greater complexity, with muscles and ligaments generating moments such as 143 Nm while plain walking. The greatest different between conventional foot prosthesis and the human ankle is its ability to provide net positive mechanical work, especially at moderate to fast walking speeds. This difference ensues many clinical problems during locomotion, including non-symmetric gait patterns, slower self-selected walking speeds, and higher gait metabolic rated compared to intact individuals[3,4].

This has motivated the development of powered foot prostheses, capable of providing sufficient active mechanical power during the stance period of walking.

Foot prostheses have become more and more complex, using flexible carbon fiber parts and microprocessor-driven motors for active mechanical control of the prosthesis. This enables a more natural and energy efficient walking pattern on level-ground as well as on stairs or on ramps[2]. The main principle used by active foot prosthesis is the series elastic actuator (SEA). The SEA which was engineered for robot technology acts as a force controllable actuator. A SEA compromises of a DC motor in series with a spring via mechanical transmission. It enables force control by controlling the extent the series spring is compressed. It is possible to obtain the force applied to the load by measuring the deflection of the series spring[5]. Major part research development on prosthetic feet using electrical actuators was developed at Massachusetts Institute of Technology (MIT). Au et al. engineered a powered foot prosthesis that imitates normal ankle behaviour (copare to image 1). This system uses a combination of a SEA and a parallel spring to provide desired requirements for normal walking[6].


**Image 1:** The active ankle "Biom" (iWalk, USA)[7] (left) and the bionic foot 'Proprio Foot' (Össur, Neatherlands)[8]

To assist with the gait support a group of foot prostheses has been developed called "bionic foot". This system is not a true actively powered foot because it does not provide more power to the user than the power stored during gait. It supports with changing the neutral position in an unloaded condition. Currently, there is only one commercially bionic foot available on the market – "Proprio Foot", manufactured and developed by Össur (Neatherlands)[8].

## 2 Development of the Concept

The active foot prosthesis shall be designed to support an active user to manage the every day life better. That implies walking on level-ground, stairs and ramps up to 15° as well as wearing shoes with different highs.

One of the main questions in developing an active ankle is the scope of the energetical support. To gain understanding of the importance of the required energy while walking is demonstrated by an ankle-moment versus ankle-angle plot[8]. This allows for comparison of the necessary generated energy (for movement) between an intact ankle and a passive foot prosthesis. Image 2 shows the hysteresis loop of an intact ankle.

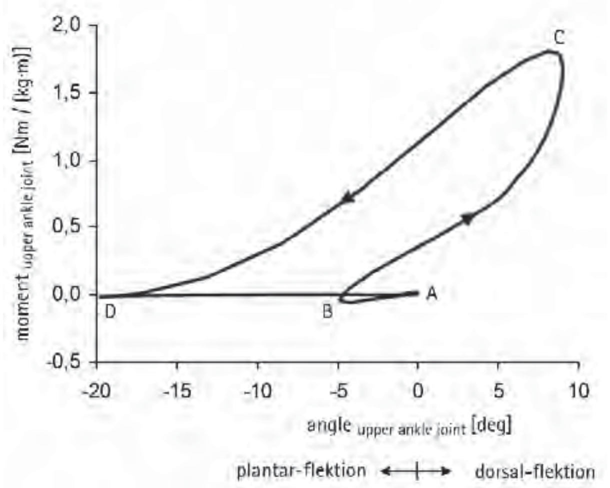


**Image 2:** Ankle-moment versus ankle-angle plotted for the physiological gait, normal gait walking speed on level-ground[8]

Positive angles means, dorsal flection. Point A represents the moment of initial heel contact. At B, the whole foot touches the ground. Point C shows the moment of maximum ankle torque and in D the toe-off the ground. The hysteresis loop moves in counter clockwise rotation, which means energy is generated in the system.

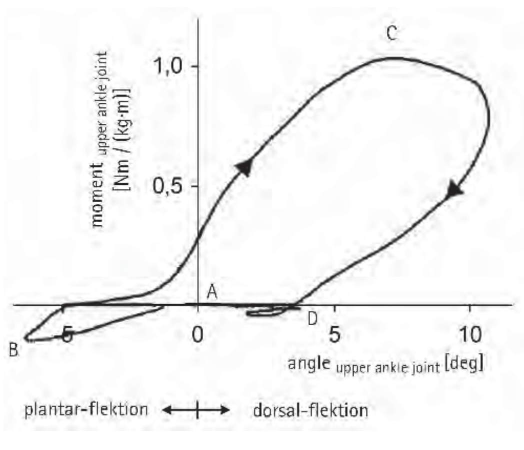


**Image 3:** Ankle-moment versus ankle-angle plotted for a transtibial amputee with passive foot prosthesis, normal gait walking speed on level-ground[8].

Image 3 shows a characteristic plot of amputee walking with a conventional foot prosthesis.The hysteresis loop moves clockwise rotation and this shows that energy is dissipated. The maximum plantar-flexor moment reaches only 1 Nm/kg Bodyweight, which is low in comparison to healthy walking[9].

This comparison shows the necessity of the generated energy. The human foot produces the energy, which is also uses by knee and hip to move forward. If this energy is missing, the body has to compensate and leads to several issues described below.

The active ankle Biom is able to generate moment and ankle behaviours that are similar to the physical ones. However this prosthetic has considerable disadvantages. The strong energy support and the high distal weight caused by the powerful motor, leads to a massive swing movement. Therefore the user has to generate energy to compensate it[9,10]. The bionic foot systems, like Proprio Foot, have an alternative approach that supports the gait and spare weight and installation space. Their bionic foot increases the range of motion with an adjustable neutral position. This simplifies walking on ramps and stairs[11]. However, it certainly does not solve the problem of restoring the missing energy. This work develops a model between these approaches. The challenge was to minimize the installation space and to get at the same time the required energy support.

The second, and also of high important question was to configure the assembly of the main components. Following the current literature the developed concept uses a SEA and a second parallel-arranged spring.

## 3 The final Concept

The final concept was the result of the trials to arrange the necessary components in different pre-concepts.

### 3.1 Design and function

The final concept tries to fulfill all the necessary requirements including low weight, small installation space and efficient energy support. A good possible location to place the motor is in the naturally available space of the ankle. This concept includes a pancake motor, which is located coaxial to the ankle axis (compare to Image 4). Moreover, it uses a passive carbon foot structure that promises good elastic properties.

The motor is part of the core element, the SEA and a second spring, which works parallel. A torsional wave, which is used as the main axis in the foot prosthesis describes the series spring.

A u-shaped flat-spring fulfills the function of a parallel spring. The prosthesis supports the gait at the end of the stance-phase (push-off) by using the energy of the motor and the parallel spring, which is loaded during overrun in stance phase. The series spring absorbs shocks and reduces the peak power of the motor.

The parallel arranged flat-spring has an effect when the neutral position is reached. It is compressed by the dorsal-stop and releases the energy while pushing off of the ground.


**Image 4:** The final concept with name main components

The function is shown in the following surrogate model (Image 5).

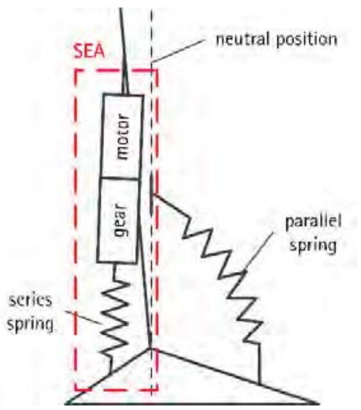


**Image 5:** Functional surrogate

To manage daily tasks it is necessary to have a range of motion from 20° plantar-flection and 10° dorsal-flection[12]. This requirement is adhered by the prosthesis (compare to Image 6). The range of motion is 20° plantar-flection and during deformation of the flat spring a dorsal-flection of 15° is reachable.


**Image 6:** the maximal positions : α=20 ° plantar-flection, neutral position and β=15° dorsal-extension

## 3.2 Computation

The most strength-releated components are the flat-spring, and the torsional wave. The flat-spring gets a mechanical load, when the dorsal stop is deforming it. To find the optimal size, the spring was approximately analytical computated as well as analysed with finite element method. The suitable material for the torsional wave was dependent from the necessary spring stiffness. Using the Saint-Vernant's Principle an approximate computation is possible[13]. The computation yields that titanium offers more spring-energy than spring steel. Therefore it was chosen for this component.

# 4 Conclusion and outlook

This work developed a concept of a foot prosthesis that tries to fullfill the necessary requirements for an ideal active foot prosthetic model. This implies the user receives essential support during the push off while maintaining an ideal weight, installation space, design height, with minimal noise generation and the battery serve life maximized. The final concept uses a series elastic actuator and a parallel arranged flat-spring. The series spring reduces the peak output and absorbs shocks from the actuator. The prosthesis is built on a passive foot prosthesis, which maintains good elastical properties. This has been shown to be especially beneficial, especially while using the prosthesis in passive mode (for example with an empty accumulator). Moreover, the parallel spring stores energy during the stance phase and supports the push off. The maximum range of motion is 20° plantar-flection and 13° dorsal-flection. This enables walking on level-ground as good as on a ramp or on stairs. The prosthesis is burded with moments up to 300 Nm. An estimated computation was done for all the strength-releated components and adapted to the requirements. All in all, the prosthesis uses the given installation space and therefore enables wearing normal shoes, moreover the design height is not to high, so many amputees can be included in the user group. The final motor-gear has not yet been chosen. Therefore the total weight as well as, the final energetical support are currently unknown and will be assessed in future research.

This thesis yields a concept for an active foot prosthesis, which is an alternative to current devices. The concept satisfies the necessary requirements and compensates the disadvantages of existing systems. The main aim of developing a prosthesis that facilitates the everyday life of the user is achieved.

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