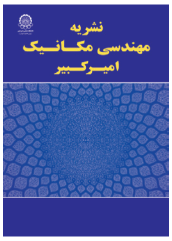

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Imitating Sound Ankle Behavior with a Powered Below-Knee Prosthesis and Validation of its Mechanical Performance

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ABSTRACT: Lower extremity amputation constitute high percentage of limb amputation which significantly reduce the motion ability of the amputees. Therefore the most important goal in the design of prosthesis is to restore function of the limb. Most of the commercially ankle-foot prostheses are passive and thus cause many gait pathologies for below knee amputees. Several powered prosthetic devices have been designed to improve amputee's walking experience by exploiting active elements. However, most of them include heavy and bulky actuators which is used to produce the power of propulsion. The main purpose of the present design is to store energy during stance period and release it at push off using a combination of springs as well as a low power actuator. Therefore, this prosthesis can provide high mechanical power and torque observed in natural human walking, by employing a small and light actuator. Moreover, in the designed mechanism, the ankle stiffness is mimicked properly in each phase of walking based on the characteristics of a sound ankle. The performance of the proposed prosthesis, was verified by MATLAB/SimMechanics simulation. The results indicate that the ankle-foot prosthesis is capable of following the torque-angle and the power-percent gait cycle characteristics of a normal ankle, sufficiently.

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1- Introduction

Various prostheses have been designed for transtibial amputation which can be classified into two main categories; passive and active. Most commercially available prostheses are passive device and their mechanical features do not change with different walking speed and the conditions of the terrain [1]. In addition, these passive prostheses have abnormal gait, limited shock attenuation and other gait pathologies [2]. In recent years, active prostheses have been received new attentions to improve above limitations. In these prostheses, using pneumatic or electric actuator, energy is injected into the system during forward propulsion. In this way, gait characteristics are improved and the metabolic cost of the amputee is decreased [3]. The SPARKY project [4], MIT powered ankle-foot prosthesis [5] and four-bar prosthesis [6] are examples of the active prosthetic feet. These actuated devices require heavy and bulky actuators to provide high torque in short time. However, a wise solution is to store energy into elastic components in specific part of the gait cycle and to release this energy during push off phase [7].

In this paper, a new design for better adaptation of torque-angle characteristic of the prosthesis and a sound ankle is proposed. To this end, a compliant mechanism consists of several springs beside a series elastic actuator is devised. The main parameters of the system are obtained through an optimization process. The proposed mechanism provides the possibility to mimic the behavior of the human ankle during normal walking in terms of trajectory and consumed power. In comparison with the state of the art, the proposed design use smaller actuator under almost the same condition. The theoretical findings are verified through several simulations in MATLAB/SimMechanics environment.

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2- Mechanical Design of the Prosthesis

The main motivation of this study is to follow the torque-angle characteristic of an intact ankle using optimal power distribution in the prosthesis. By exploiting passive and active elements, the energy needed for phases of walking specially for push off during powered plantarflexion is provided efficiently. In order to decrease the required power rating dramatically, the idea is to increase the time interval in which the actuator works.

The essential parts of the prosthesis are shown in Fig. 1. Three different springs are used to provide reasonable ankle behavior. Based on Winter's data [8], the maximum torque produced at the ankle joint for a 75 kg person, walking on the ground at normal speed, is 120 N.m. Also, according to the range of motion of the ankle joint from +10˚ at maximum dorsiflexion to -20˚ at maximal plantarflexion, the geometric parameters have been determined to cover this range. We use a compression spring k_1=18 N/mm to store energy from the controlled plantarflexion phase, and a compression spring k_2=107 N/mm to store energy from the portion of the controlled dorsiflexion phase. An electric actuator is loading a set of tension spring k_3=46 N/mm throughout the stance phase. Using a locking mechanism, the energy stored in the spring k_3, is released at right time to provide the required propulsion. Therefore, a Maxon Brushless EC motor (100 W) has been selected in combination with a gearbox and a ball screw. The transmission ratio of the chosen ball screw is 5 mm/rev and the reduction ratio of the chosen planetary gearhead (Maxon GP32C) is 5.8:1.

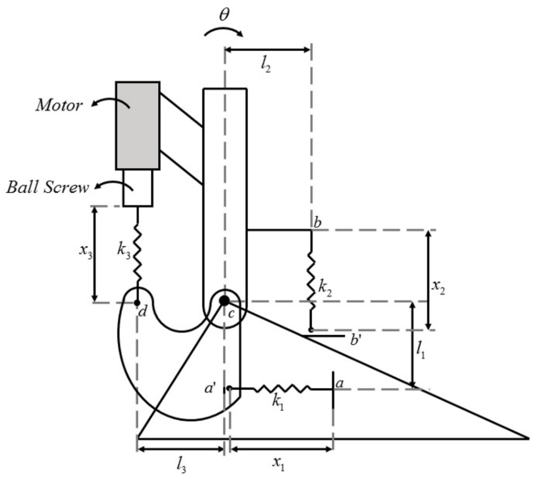

Fig. 1: Schematics of the proposed prosthesis

3- Working Principle of the Prosthesis

Human walking is a cyclic pattern of movements. Fig. 2 illustrates one complete gait cycle of the prosthesis. Based on this figure and working principle of the device, the torque that is generated during each phase, has been calculated.

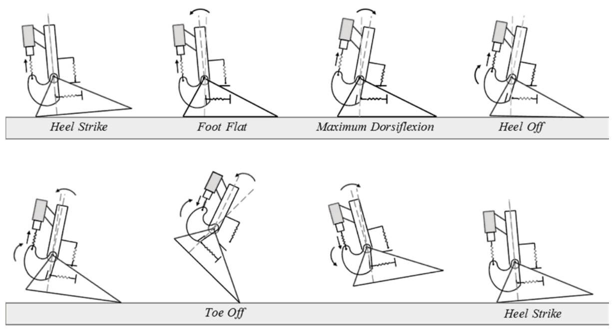

Fig. 2: Working principle of the proposed prosthesis during a complete gait cycle. The greyed parts denote interlocked bodies.

4- Validation

After initial mechanical design, we examined the performance of the prosthesis during different gait phases using theoretical calculations and MATLAB simulation. Eventually, a model of this design was simulated in SimMechanics and its outputs were analyzed.

5- Results

In Fig. 3, the torque-angle characteristic of the prosthesis in SimMechanics environment is compared to an intact ankle performance obtained by Winter [8].

It is noteworthy to mention that the prosthesis covers a moving range from +9.6° at maximum dorsiflexion to -18.6° at maximal plantarflexion. Moreover, it provides an ankle peak torque of 132 N.m at heel off, and produce adequate propulsive power at the ankle joint during flat walking. In Fig. 4, the power of the prosthesis is compared to the power consumption of an intact ankle during one stride. It can be seen that the average power generation of the prosthesis suitably matches with the expected power in sound ankle.

6- Conclusions

In this study, a new design of an active transtibial prosthesis was presented that follows the human ankle characteristics. To evaluate the performance of the prosthesis, two analyses were performed. The results indicate that the prosthesis mimics the sound ankle behaviors in terms of stiffness and power in one typical gait cycle. The proposed prosthesis provides natural behavior in comparison with the conventional passive prostheses. It also uses the energy in an optimized way to make the system compact and efficient.

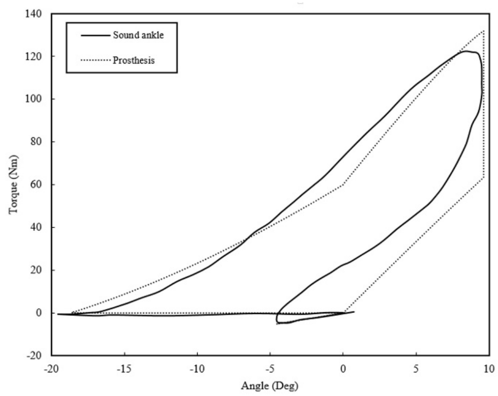

Fig. 3. Torque-angle diagram of the proposed prosthesis in comparison with the natural ankle data in [8].

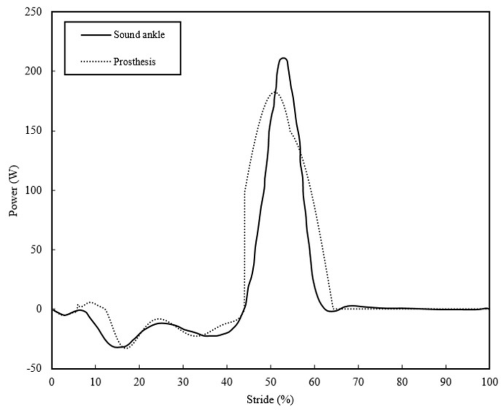

Fig. 4. Ankle power during one stride for the proposed prosthesis in comparison with the natural ankle data in [8].

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