

# **DESIGN OF AN EFFICIENT BACK-DRIVABLE SEMI-ACTIVE ABOVE KNEE PROSTHESIS**

MOHAMMED AWAD<sup>+</sup>, KIAN SEK TEE, ABBAS DEGHANI

*Institute of Engineering Systems and Design, School of Mechanical Engineering,  
University of Leeds, Leeds, LS2 9JT, United Kingdom.*

DAVID MOSER, SAEED ZAHEDI

*Chas A Blatchford & Sons Ltd, Lister Road, Basingstoke,  
Hants, RG22 4AH, United Kingdom.*

This paper presents the design and development of an electrical above knee prosthesis, which works as a passive knee prosthesis in part of gait cycle phases and as an active knee prosthesis during other portions. During the passive mode, the system works as a non-holonomic system, and the dynamic coupling between the thigh segment and the knee prosthesis is used to control the prosthesis. Therefore, this knee prosthesis is designed to be back-drivable in passive mode. In order to present a proper design for the knee prosthesis, the mechanism synthesis and analysis for the proposed back-drivable semi-active knee prosthesis are covered in this paper.

## **1. Introduction**

In the past, walkers, crutches, open socket peg legs, wheelchairs were used to help amputees to walk; but with limitations. Therefore, there was a need to develop a more efficient prosthesis to restore the lost locomotive functions for the amputees. Hence, the research in prostheses field has started in MIT since 70's of the last century [1-4]. Furthermore, commercial adaptive passive prostheses were developed; such as Otto Bock C-Leg, Blatchford smart IP+[5], and Ossur's Rheo Knee. These passive prostheses interact with the amputee's healthy segments according to the passive dynamic walking concept which was introduced by McGeer [6]. This concept provides an excellent technique to generate a natural gait for a biped by using inertia between segments. Therefore, an amputee's hip is considered the main engine source to control the inertia interaction between thigh and prosthesis knee as shown in figure 1. This technique is called voluntary control for the prostheses. However, adding more energy at hip to control produces uncomfortable walking experiences for the

---

<sup>+</sup> Academic staff of Design and Production Engineering Department, Mechanical Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt.

amputee due to extra pressure between stump-socket interface. Moreover, there are some periods during level ground walking, ramp and stair climbing which require a generated energy by knee. Therefore, there is a need for an actuator during certain gait periods.

This research aims to design and develop a back-drivable semi-active above knee prosthesis for more efficient gait. Whilst other researchers have developed fully actuated prostheses by using pneumatic actuator [7] or by using DC electrical motors [8, 9], these prostheses do not get the benefit of using the dynamic coupling during some periods to reduce the consumed energy and the actuator size. In addition to that, Ossur developed a commercial power knee which is full actuated. And whilst there is another knee prosthesis [10] that could perform as a semi-active device by using a hydraulic actuator, the effect of the dynamic coupling between the amputee's thigh and the knee prosthesis has not been studied in it. Moreover, the proposed design focuses on using a DC electric motor in which has less noise and higher efficiency in comparison to hydraulic system.



Figure 1: Above knee amputee movement mechanism

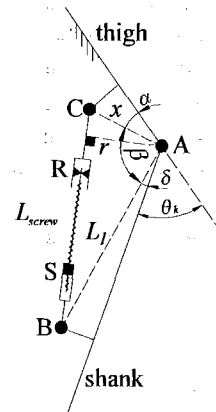


Figure 2: Schematic diagram for closed loop kinematic chain

## 2. Mechanism Design Synthesis and Analysis

### 2.1. Mechanism Selection

To determine which mechanism is suitable for developing the back-drivable prosthesis, open and closed kinematics chain were studied. The open kinematic chain has the ability to deliver constant transmission ratio with respect to the knee angle. This configuration could be implemented by connecting a Dc motor

with a geared harmonic to drive the knee prosthesis axis directly. However, the harmonic drive has rather high back-driving resistance. On the other hand, closed kinematic chain developed with low friction and high lead angle ball screw could back-drive easily. Therefore, closed kinematic chain was chosen.

## 2.2. Mechanism Analysis

The first step in accomplishing an efficient design is to find all possible assembly modes and the most significant parameters which affect on the mechanism performance. The assembly modes were investigated by finding the closed form equation (1) of the mechanism shown in figure 2. Hence,  $\partial r / \partial \beta = 0$  was calculated in order to find  $\beta^*$  which define the angle  $\angle CAB$  at maximum torque arm  $r_{max}$ . Therefore, there were four answers for  $\beta^*$  as shown in equation (2) which shows that the mechanism could be assembled in four different configurations as shown in figure 3. Furthermore, the knee angle at maximum transmission ratio for the mechanism is calculated according to equation (3). In order to find which configuration has better transmission ratio, the torque arm  $r$  was calculated to these configurations as shown in figure 4. It is clear from figure 4 that assembly modes 2 and 4 have better torque arm variation which allows better transmission ratio. Furthermore, the effect of the  $\beta^*$  parameter on the mechanism performance was studied in figure 5 which shows that the smaller  $\beta^*$  the better transmission can be achieved. However, if  $\beta^* < \theta_k^*$ , the singularity would happen at small knee angles. Therefore,  $\beta^*$  range should be within  $\theta_k^* < \beta^* < 90^\circ$ , and should be chosen smaller as possible.

$$r = \frac{xL_1}{\sqrt{L_1^2 + x^2 - 2xL_1 \cos \beta}} \sin \beta \quad (1)$$

$$\beta^* = \left\{ \begin{array}{l} + \tan^{-1} \frac{\sqrt{L_1^2 - x^2}}{x} \quad \text{if } L > x \text{ mechanism configuration (a)} \\ - \tan^{-1} \frac{\sqrt{L_1^2 - x^2}}{x} \quad \text{if } L > x \text{ mechanism configuration (b)} \\ + \tan^{-1} \frac{\sqrt{x^2 - L_1^2}}{L_1} \quad \text{if } x > L \text{ mechanism configuration (c)} \\ - \tan^{-1} \frac{\sqrt{x^2 - L_1^2}}{L_1} \quad \text{if } x > L \text{ mechanism configuration (d)} \end{array} \right\} \quad (2)$$

$$\theta_k^* = \pi - [(\alpha \pm \delta) + \beta^*] \quad (3)$$

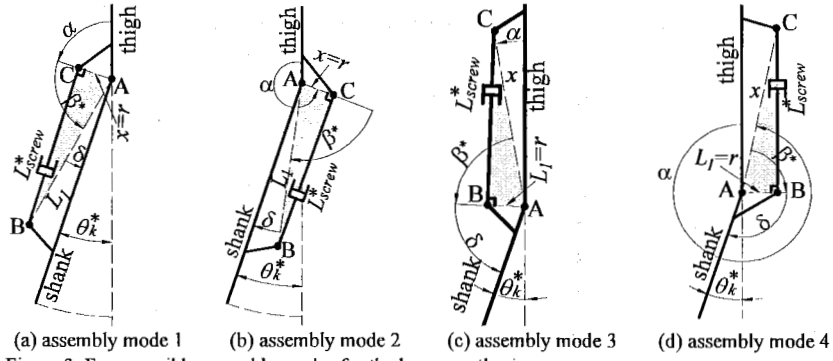


Figure 3: Four possible assembly modes for the knee prosthesis.

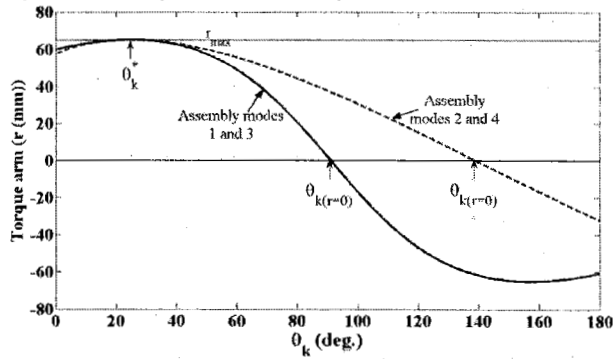


Figure 4: The torque arm  $r$  variation according to the knee angle for the four possible modes.

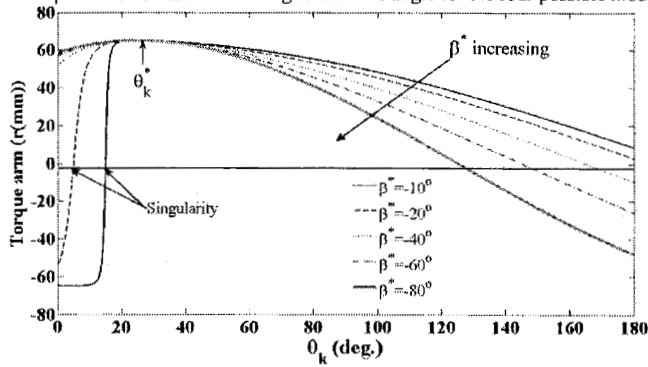


Figure 5: The torque arm  $r$  variation according to the knee angle at different mechanism dimensions.

### 3. Dynamic Coupling Model

As explained before, this research focuses in designing a back-drivable prosthesis applying the dynamic coupling effect between the thigh and the

prosthesis to help amputee to walk and to reduce the consumed power from the actuator. Therefore, a simple dynamic model for a simplified prosthesis as shown in figure 6 was deduced. This mode was simplified to 4 degree of freedom system in sagittal plane. The hip joint could move in  $X_0Y_0$  plane by  $x_h$  and  $y_h$  respectively, and the thigh and prosthesis shank could rotate by  $\theta_h$  and  $\theta_k$  respectively. The shank and foot are considered as one link in this model for simplification. Furthermore, the effect of all other active segments in human body such as trunk and healthy leg are seen in hip kinematic data  $x_h$  and  $y_h$ . Therefore, the hip and knee torques were derived by using Lagrangian formulation as shown in equations (4) and (5) respectively.

On the other hand, if both hip and knee are fully controlled and actuated, the system behaves like holonomic system. However, it could be used the dynamic coupling effect between the hip and the knee to control the knee at some extend during walking. The dynamic coupling effect for the knee is clear in equation (5) in  $M_{41}, M_{42}, M_{43}, M_{44}$ , and  $V_{cen43}$ . Therefore, the hip kinematics data could be used to control the knee angle acceleration and speed in case of passive mode or non-holonomic system as shown in equation (6). This technique is used to control the passive prosthesis during swing phase, and it is called voluntary control which done by amputee to control the prosthesis. Therefore, a gait analysis kinematics data for healthy hip subject was used to solve equation (6) under no ground reaction forces, and figure 7 shows the knee angle performance under the hip movement without the need for actuator at knee in comparison to knee angle of a healthy subject.

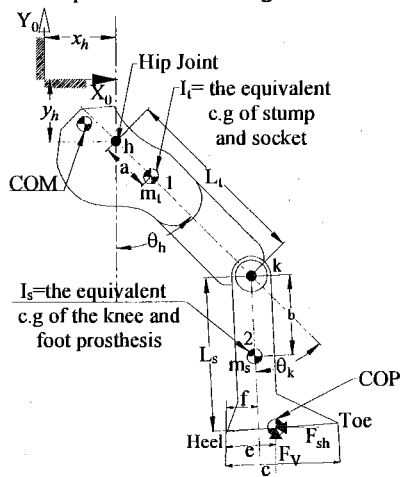


Figure 6: Simplified diagram for the dynamic model of knee prosthesis.

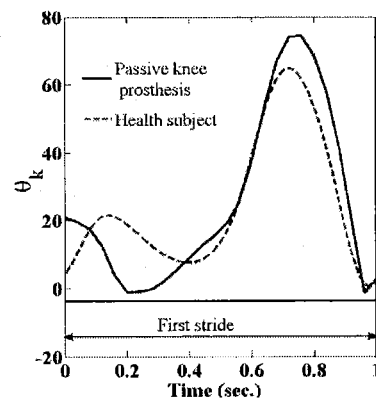


Figure 7: The performance of passive knee prosthesis under dynamic coupling effect.

$$\begin{aligned} \tau_h = & M_{31}\ddot{x}_h + M_{32}\ddot{y}_h + M_{33}\ddot{\theta}_h + M_{34}\ddot{\theta}_k + V_{cen34}\dot{\theta}_k^2 + V_{cor3}\dot{\theta}_h\dot{\theta}_k \\ & + G_3 + \frac{\partial x_{cop}}{\partial \theta_h} F_v + \frac{\partial y_{cop}}{\partial \theta_h} F_{sh} \end{aligned} \quad (4)$$

$$\begin{aligned} \tau_k = & M_{41}\ddot{x}_h + M_{42}\ddot{y}_h + M_{43}\ddot{\theta}_h + M_{44}\ddot{\theta}_k + V_{cen43}\dot{\theta}_h^2 + G_3 \\ & + \frac{\partial x_{cop}}{\partial \theta_k} F_v + \frac{\partial y_{cop}}{\partial \theta_k} F_{sh} \end{aligned} \quad (5)$$

$$\begin{aligned} \ddot{\theta}_k = & -M_{44}^{-1}[M_{41}\ddot{x}_h + M_{42}\ddot{y}_h + M_{43}\ddot{\theta}_h + V_{cen43}\dot{\theta}_h^2 + G_3 + \frac{\partial x_{cop}}{\partial \theta_k} F_v \\ & + \frac{\partial y_{cop}}{\partial \theta_k} F_{sh}] \end{aligned} \quad (6)$$

#### 4. A Back-Drivable Semi-Active Knee Prosthesis Mechanical Design

##### 4.1. Design Considerations and Specifications

The design has been carried out according to the considerations from sections 2 and 3. Those considerations could be summarized in the following points:

1.  $\theta_k^* = 25^\circ$  to cover level ground walking at high speed.
2.  $\beta^* = 66^\circ$  because it is limited to the mechanism dimensions.
3. The prosthesis weight affects on both equations (4) and (6). Therefore, the heavy prosthesis requires more hip torque generated by the amputee, but lighter prosthesis reduces the effect of the dynamic coupling in non- holonomic mode. Therefore, there is a need to find the suitable prosthesis weight to perform natural walking.
4. The back-driving effect which achieved by using a ball screw with high lead helix angle.

##### 4.2. Mechanical Design

The prosthesis was designed by using of a ball screw which has 95.5% efficiency in forward direction and 95.2% efficiency in back-driving direction. The prosthesis was driven by a 42V DC motor in active mode which is connected to the ball screw through a timing belt. Figure 8a shows the CAD model for the knee prosthesis. The prosthesis was designed to cover the working range for most human tasks. The extreme positions during fully knee extension flexion are shown in figures 8a and 8b when the knee angle is zero and  $104^\circ$ .

On the other hand, the stress analysis was tested by developing a finite element model where a real human ground reaction loads and knee angle

trajectory for level ground walking are imported to the model. This model is divided into frames and the motion kinematics and ground loads are set at each individual frame. Hence, the motion analysis at each joint and link were done to import those motion loads and boundary conditions to the model. Figure 8c shows the maximum von Mises stress which happens at frame number eight

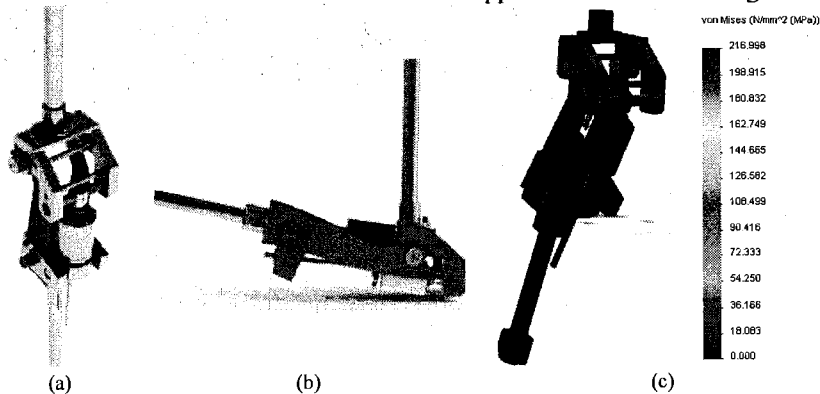


Figure 8: CAD model and FEA of the back-drivable semi-active knee.

## 5. Conclusions

An investigation into the design of an efficient back-drivable semi-active prosthetic system has been carried out. Investigations have accordingly provided the key design parameters of the mechanism which affect the prosthesis performance. Furthermore, an analytical work was carried out on the dynamic coupling effect between the hip and the knee. Among these it was noticed that the prosthesis weight has an important effect on the passive dynamic walking performance.

## Acknowledgments

The corresponding author (M. Awad) would like to acknowledge the Egyptian Government and Egyptian Cultural Bureau in the UK for their financial support.

## Appendix

1. The parameters of dynamic equations (4), (5) and (6) are the following:

$$\begin{aligned}
G_3 &= m_t g a \sin \theta_h + m_s g [L_t \sin \theta_h + b \sin(\theta_h + \theta_k)] \\
G_4 &= m_s g b \sin(\theta_h + \theta_k) \\
\frac{\partial x_{cop}}{\partial \theta_h} &= -(e - f) \sin(\theta_h + \theta_k) + L_t \cos \theta_h + L_s \cos(\theta_h + \theta_k) \\
\frac{\partial x_{cop}}{\partial \theta_k} &= -(e - f) \sin(\theta_h + \theta_k) + L_s \cos(\theta_h + \theta_k) \\
\frac{\partial y_{cop}}{\partial \theta_h} &= (e - f) \cos(\theta_h + \theta_k) + L_t \sin \theta_h + L_s \sin(\theta_h + \theta_k) \\
\frac{\partial y_{cop}}{\partial \theta_k} &= (e - f) \cos(\theta_h + \theta_k) + L_s \sin(\theta_h + \theta_k)
\end{aligned}$$

### References

1. W.C. Flowers, "A Man-Interactive Simulator System for Above-Knee Prosthetics Studies", Department of Mechanical Engineering, PhD Thesis, MIT, 1972.
2. W.C. Flowers, "Use of an Amputee-computer Interactive Facility in Above-Knee Prosthesis Research", Proceedings of the 1974 Annual Conference -Volume 1, Association for Computing Machinery (ACM), New York, 1974.
3. D. R. Lampe, "Design of A Magnetic Particle Brake Above-Knee Prosthesis Simulator System", Department of Mechanical Engineering, PhD Thesis, MIT, 1976.
4. B. Hunter, "Design of self-contained, active, regenerative computer controlled above-knee prosthesis", Department of Mechanical Engineering, PhD Thesis, MIT, 1981.
5. S. Zahedi, A. Sykes, S. Lang and I. Cullington, "Adaptive prosthesis- a new concept in prosthetic knee control", *Roboica*, Cambridge University press, vol. 23, pp.337-344, 2005
6. T. McGeer, "Passive walking with knees", IEEE International Conference on Robotics and Automation, Cincinnati, OH, USA, May 13-18, 1990.
7. F. C. Sup and M. Goldfarb, "Design a Pneumatically Actuated Transfemoral Prosthesis", Proceedings of IMECE2006, ASME International Mechanical Engineering Congress and Exposition, Nov. 5-10, 2006, Chicago, Illinois.
8. K. Fite, J. Mitchell, F. Sup, and M. Goldfarb, "Design and Controlled of an Electrically Powered Knee Prosthesis", IEEE International Conference on Rehabilitation Robotics, Noordwijk, The Netherlands, June 12-15, 2007.
9. Bedard et al., "Actuated Leg Prosthesis for Above-Knee Amputees", United States Patent, US 7,314,490 B2, Jan. 1, 2008.
10. B. Lambrecht and H. Kazerooni, "Design of a Semi-Active Knee Prosthesis", IEEE International Conference on Robotics and Automation, Kobe, Japan, May 12-17, 2009.