Proceedings Paper:

Awad, MI, Dehghani-Sanij, AA, Moser, D et al. (1 more author) (2015) Inertia Properties of a Prosthetic Knee Mechanism. In: Dixon, C and Tuyls, K, (eds.) Towards Autonomous Robotic Systems: Proceedings. 16th Annual Conference, TAROS 2015, 08-10 Sep 2015, Liverpool, UK. Lecture Notes in Computer Science (9287). Springer , Cham, Switzerland , pp. 38-43. ISBN 978-3-319-22415-2

https://doi.org/10.1007/978-3-319-22416-9_5

Inertia Properties of a Prosthetic Knee Mechanism

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Abstract. The prosthetic knee mechanism should be able to assist the amputees during activities of daily living and improve their quality of life. The inertia asymmetry between intact and the prosthetic sides is one of the reasons for amputee gait asymmetry. This paper shows how to calculate the overall inertia properties during the design process.

1 Introduction

Every year, thousands of lower limb amputations are carried out around the world due to complications of diabetes, circulatory and vascular disease, trauma, or cancer in limb segments [1]. The loss in mobility following amputation results in a degradation of the quality of life of the amputees as it affects many aspects of their personal and professional lives. Lower limb prostheses are used to replace the lost limbs and assist amputees in restoring their missing mobility functions. The current commercial state-of-the-art prostheses can be divided into three main categories: purely mechanical, microprocessor damping control and powered prostheses.

Purely mechanical prostheses depend only on mechanical components and require significant mental and voluntary control effort during walking. Microprocessor-damping-controlled prostheses are developed with the objective of approximating the human gait functions. These prostheses are equipped with integrated sensors to supply information to a microprocessor which is used to control the prosthesis in real-time. The main task of this type of prosthetic is to support the body weight in the stance phase and provide dynamic control during the swing phase. This group of prostheses was introduced during the 1990s with the release of the Intelligent Knee (Nabtesco), the Intelligent Prosthesis (IP) (Chas. A. Blatchford & Sons), and the C-Leg (Otto Bock). These prostheses are still passive and cannot contribute any net positive power to the gait which limits the amputee ability. Actively powered prostheses, such as the Victhom knee [2-4], commercially known as the Power Knee (Ossur) are fully actuated. This group of prostheses can be powered using either DC motors [5-7], or pneumatic actuators [8] to provide positive power to the prosthetic limb.

adfa, p. 1, 2011.

Despite the current technological advances in prosthetics, lower limb amputees still suffer from noticeable gait asymmetry [9-11] and high metabolic energy costs [12] in comparison to healthy subjects. This gait asymmetry pattern occurs due to the inertia asymmetry between the intact and the prosthetic leg [13] and other factors. The prosthesis inertia plays an important role in the gait dynamics especially during the swing phase as in passive dynamic walkers. In order to improve the prostheses performance and design efficient lower limb prostheses, the inertia properties of lower limb prosthesis should be altered without increasing the prosthetic weight to allow more energetic amputee locomotion. This paper focuses on developing a prosthetic knee actuation mechanism and studying the inertia parameters in the mechanism.

2 Kinematics Analysis of The Proposed Prosthetic Knee Mechanism

In this section, the analysis of the proposed prosthetic knee based on closed kinematics chain mechanism, shown in **Fig. 1**a, is presented. According to the geometry of the closed loop configuration in **Fig. 1**a, the screw length is calculated by applying Cosine rule in $\Delta \boldsymbol{ABC}$ as shown in the following equation:

$$\boldsymbol{L_{screw}} = \sqrt{\boldsymbol{L_1^2 + x^2 - 2L_1 x \cos\beta}} \tag{1}$$

It is clear that the knee's torque ($\mathbf{T_k}$) and speed ($\dot{\boldsymbol{\theta}}_{\boldsymbol{k}}$) relative to the motor's torque ($\mathbf{T_m}$) and speed ($\dot{\boldsymbol{\theta}}_{\boldsymbol{m}}$) are functions of the mechanism transmission ratio (**r**), the ball screw pitch (**p**) and the overall efficiency of the mechanism ($\boldsymbol{\eta_o}$) as shown in Equations (2) and (3). These relations show that the knee's torque ($\mathbf{T_k}$) will increase when the transmission arm (**r**) increases, and the knee's speed ($\dot{\boldsymbol{\theta}}_{\boldsymbol{k}}$) will increase when the transmission arm (**r**) decreases.

$$\boldsymbol{T_k = F_{screw}.r = \frac{2\pi\eta_o r}{p}.T_m} \tag{2}$$

$$\boldsymbol{\dot{\theta}_k = \frac{p}{2\pi r}.\dot{\theta}_m} \tag{3}$$

The transmission arm (**r**) of the torque arm can be calculated based on the mechanism geometry. By applying the sine rule in $\Delta \boldsymbol{ABC}$, the transmission arm (**r**) is calculated as:

$$\boldsymbol{r = \frac{xL_1}{\sqrt{L_1^2 + x^2 - 2xL_1 cos\beta}} \sin\beta} \tag{4}$$

Where:
$\boldsymbol{r}$: the transmission ratio (torque arm length) of the mechanism, $\boldsymbol{x}$: the length between joints A and C in **Fig. 1**a, $\boldsymbol{L_1}$: the length between joints A and B in **Fig. 1**a, $\boldsymbol{\beta}$: the angle of ∡**CAB** in **Fig. 1**a.

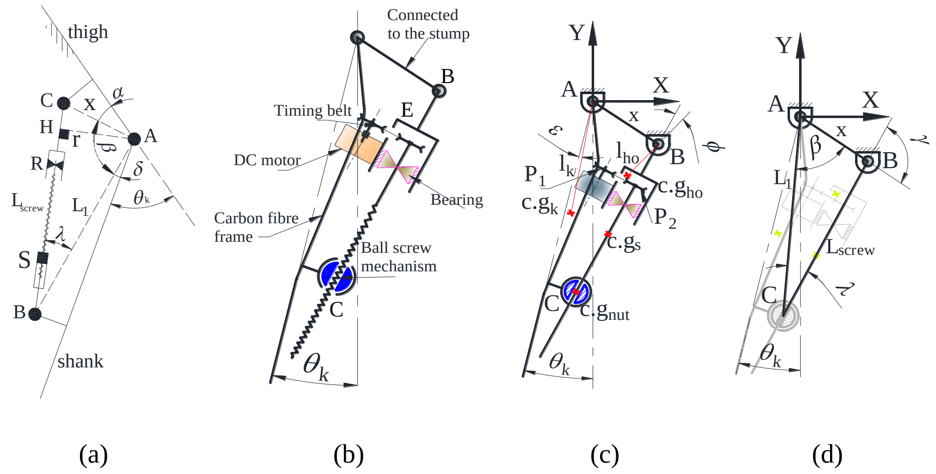

Fig. 1. Schematic diagram for closed loop kinematics chain of the knee prototype.

Based on these selected parameters and the physical constrains of the mechanical components, the prosthetic knee design shown in **Fig. 1**b was proposed to produce the maximum torque and speed profiles. This prosthetic knee mechanism consists of seven main links (**n**) as shown in **Fig. 1**b. These links are, respectively, the fixed link (**AB**) that is attached to the amputee's socket as shown in **Fig. 1**c, the carbon fibre frame for the knee, the ball screw (**CD**), the ball screw nut (**C**), the ball screw housing (**BD**), the motor shaft and the timing belt (**E**). Furthermore, there are three types of joints used in the mechanism for kinematics and physical constraints: five lower pairs revolute joints (**A**, **B**, **C**, **D**, **E**), one screw joint, and two wrapping pair joints (higher pairs) between the belt and the pulleys. These joints create constrains that restrict the mechanism mobility to one degree of freedom (DoF).

3 Sources of Inertia and Impedance Torques in The Mechanism

The mechanism components have passive elements to mechanically dissipate the energy such as friction and damping while the inertias and the potential energy of the knee weight are used as energy storage elements. Equation (5) specifies the equivalent dynamics characteristics of the prosthetic knee prototype relative to joint A, which are shown in **Fig. 1**a and b.

$$\boldsymbol{J_{eq\to A}\ddot{\theta}_k + D_{eq\to A}\dot{\theta}_k + T_{f_{eq\to A}} = T_k + T_w + T_R} \quad (5)$$

Where:

$\boldsymbol{T_w = m_{k_{eff}} g l_k \sin(\theta_k - \varepsilon)}$, $\boldsymbol{J_{eq\to A}}$: equivalent reflected inertia referred to knee revolute joint A, $\boldsymbol{\ddot{\theta}_k}$: angular acceleration of the knee at joint A (rad/sec^2), $\boldsymbol{D_{eq\to A}}$: equivalent reflected damping coefficient referred to revolute joint A (Nm/(rad/sec)), $\boldsymbol{\dot{\theta}_k}$: angular velocity of the knee at joint A (rad/sec), $\boldsymbol{T_{f_{eq\to A}}}$: equivalent reflected friction torque referred to joint A (Nm), $\boldsymbol{T_k}$: active knee torque generated by the motor at joint A (Nm), $\boldsymbol{T_w}$: equivalent torque produce by the prosthetic weight (Nm), $\boldsymbol{T_R}$: external resistance torque applied on the prosthetic knee (Nm), $\boldsymbol{m_{k_{eff}}}$: effective prosthetic weight (kg), $\boldsymbol{l_k}$: the distance between the joint A and the prosthetic centre of gravity (m), $\boldsymbol{\theta_k}$: prosthetic knee angle (rad), $\boldsymbol{\varepsilon}$: static equilibrium angle of the prosthesis.

3.1 Inertia properties of the developed prosthetic knee

The equivalent reflected inertia is the sum of all inertias in the knee mechanism reflected to joint A as follows:

$$\boldsymbol{J_{eq\to A} = J_{m\to A} + J_{p_1\to A} + J_{p_2\to A} + J_{s\to A} + J_{nut\to A} + J_k + J_{ho\to A}} \tag{6}$$

Where:
$\boldsymbol{J_{m\to A}}$: motor inertia reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_{p_1\to A}}$: inertia of pulley 1 in timing belt arrangement reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_{p_2\to A}}$: inertia of pulley 1 in timing belt arrangement reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_{s\to A}}$: ball screw inertia reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_{nut\to A}}$: the inertia of the ball screw nut reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_k}$: carbon fibre frame reflected to the revolute joint A (kg.m^2), $\boldsymbol{J_{ho\to A}}$: ball screw and bearing holder reflected to the revolute joint A (kg.m^2).

The effective reflected inertia is determined using the kinetic energy, as the kinetic energy referred to any point must provide the same kinetic energy plus the losses. Hence, equation (7) is used to derive the reflected inertia based on the constant kinetic energy concept.

$$\boldsymbol{K.E_{m\to A} = \frac{K.E_m}{\eta_{m\to A}} \quad \rightarrow \quad \frac{1}{2} J_{m_r\to A}\dot{\theta}_k^2 = \frac{1}{2} J_{m_r}\dot{\theta}_m^2 \left(\frac{1}{\eta_{m\to A}}\right)} \tag{7}$$

Where:
$\boldsymbol{K.E_{m\to A}}$: kinetic energy of the motor's rotor shaft referred to joint **A**, $\boldsymbol{K.E_m}$: kinetic energy of the motor's rotor shaft, $\boldsymbol{J_{m_r\to A}}$: the mass moment of inertia of the motor shaft referred to **A**, $\boldsymbol{J_{m_r}}$: the mass moment of inertia of the motor shaft around the rotation axis of the motor shaft, $\boldsymbol{\eta_{m\to A}}$: transmission efficiency from the motor to joint **A**. The conversion ratio of the angular velocity from the knee ($\boldsymbol{\dot{\theta}_k}$) to the motor ($\boldsymbol{\dot{\theta}_m}$) is calculated based on equation (3) as the timing belt arrangement between the motor and the ball screw has 1:1 reduction ratio. Hence, the reflected inertia of the motor shaft referred to joint **A** is calculated as follows:

$$\boldsymbol{J_{m_r\to A} = \frac{J_{m_r}}{\eta_{m\to A}}\left(\frac{2\pi}{p}\right)^2 r^2} \tag{8}$$

The motor shaft not only rotates around the motor shaft axis, but also the motor with the ball screw holder arrangement rotates around joint **B**. Hence, the motor, pulley 1 (P_1), pulley 2 (P_2) and the ball screw have two inertial values which should be reflected to joint **A** as shown in the following equation:

$$\boldsymbol{J_{m\to A}} + \boldsymbol{J_{p_1\to A}} + \boldsymbol{J_{p_2\to A}} + \boldsymbol{J_{s\to A}} + \boldsymbol{J_{ho\to A}} = \left[\frac{J_{m_r}}{\eta_{m\to A}} + \frac{J_{p1_r}}{\eta_{p1\to A}} + \frac{J_{p2_r}}{\eta_{p2\to A}} + \frac{J_{s_r}}{\eta_{s\to A}}\right]\left(\frac{2\pi r}{p}\right)^2 + \left[\boldsymbol{J_{m_B}} + \boldsymbol{J_{p1_B}} + \boldsymbol{J_{p2_B}} + \boldsymbol{J_{s_B}} + \boldsymbol{J_{ho_B}}\right]\left(\frac{1}{\eta_{B\to A}}\right)\left(\frac{\dot{\gamma}}{\dot{\theta}_k}\right)^2 \quad (9)$$

Where:
$\boldsymbol{J_{p1_r}}$: the mass moment of inertia of the pulley 1 around the rotation axis, $\boldsymbol{\eta_{p1\to A}}$: transmission efficiency from the pulley 1 to joint **A**, $\boldsymbol{J_{p2_r}}$: the mass moment of inertia of the pulley 2 around the rotation axis, $\boldsymbol{\eta_{p2\to A}}$: transmission efficiency from the pulley 2 to joint **A**, $\boldsymbol{J_{s_r}}$: the mass moment of inertia of the ball screw around the rotation axis, $\boldsymbol{\eta_{s\to A}}$: transmission efficiency from the ball screw to joint **A**, $\boldsymbol{J_{m_B}}$: the mass moment of inertia of the motor around the joint **B**, $\boldsymbol{J_{p1_B}}$: the mass moment of inertia of the pulley 1 around the joint **B**, $\boldsymbol{J_{p2_B}}$: the mass moment of inertia of the pulley 2 around the joint **B**, $\boldsymbol{J_{s_B}}$: the mass moment of inertia of the ball screw around the joint **B**, $\boldsymbol{J_{ho_B}}$: the mass moment of inertia of the ball screw holder around the joint **B**, $\boldsymbol{\eta_{B\to A}}$: transmission efficiency from joint **B** to joint **A**, $\dot{\boldsymbol{\gamma}}$: angular velocity of joint **B** (rad/sec).

Similarly, the reflected mass moment of the ball screw nut is calculated as follows:

$$\boldsymbol{J_{nut\to A}} = \frac{m_{nut}}{\eta_{nut\to A}} \boldsymbol{r^2} + \frac{J_{nut}}{\eta_{C\to A}}\left(\frac{\dot{\lambda}}{\dot{\theta}_k}\right)^2 \quad (10)$$

Where:
$\boldsymbol{m_{nut}}$: the ball screw nut mass in kg, $\boldsymbol{\eta_{nut\to A}}$: transmission efficiency from the pulley the ball screw nut to joint **A**, $\boldsymbol{J_{nut}}$: the mass moment of inertia of the ball screw nut around the joint **C**, $\boldsymbol{\eta_{C\to A}}$: transmission efficiency from the joint **C** to joint **A**, $\dot{\boldsymbol{\lambda}}$: angular velocity of joint **C**.
Further work is required to optimize the distribution of the masses and inertia parameters to provide the prosthetic knee ($\boldsymbol{J_{eq\to A}}$) with inertia properties similar to the natural limb without increase its weight. Also, these inertia parameters are important during the selection process of the actuator.

4 Conclusions

This paper study the kinematics and the inertia properties of the developed knee mechanism. These parameters are important to optimise and improve the performance of the knee mechanism and then reduce the amputee gait asymmetry. The significant sources of inertia in the proposed knee mechanism are highlighted and studied in this paper.

Acknowledgement

This work is linked to a current research sponsored by EPSRC (EP/K020462/1).

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