542. A CAD Based Dynamic Analysis Approach to AK Prosthesis Design

Mr. Manoj Soni [a], Prof. S. Maji [b], Prof Sneh Anand [c], Dr. U Singh [d]

[a] Assistant Professor, Deptt. of Mechanical and Automation Engineering, Maharaja Agrasen Institute of Technology, Affiliated to Guru Govind Singh Indraprastha University, Delhi, India.

[b] H.O.D- Deptt. of Mechanical, Production & Industrial Engineering, Delhi Technical University, Delhi, India.

[c] Prof. & Head- Bio Medical Engineering, Indian Institute of Technology, Delhi / All India Institute of Medical Sciences, India.

[d] Prof. & Head – Department of Physical Medicine and Rehabilitation, All India Institute of Medical Sciences, New Delhi, India.

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Abstract. Paper introduces dynamic simulation approach based on computer aided design (CAD), which was applied for development of a passive above-knee (AK) prosthesis to enable a one leg amputated patient with a reasonable size of stump. A locally-fabricated prosthetic knee was modified to develop a pneumatic damper-controlled AK prosthesis. Design studies were carried out to find center of gravity and moment of inertia of the assembly. CAD dynamic analysis was conducted on ProE software and the results were compared to actual swing time found experimentally in the lab. The leg was tested for validation on subjects with positive results.

Key Words: CAD, AK prosthesis, swing time and dynamic analysis.

Introduction

CAD modeling has become the design technique of the day. A dynamic analysis approach to designing above-knee prosthesis has been introduced. Instead of spending time on complicated mathematics, CAD software has the potential to do a mechanism analysis in short time and within reliable limits. The software use mathematics at back, but the power to simulate and speed with which calculations are done, makes them indispensable for preliminary design and analysis. This work presents a dynamic analysis, performed in Pro-E software to design a passive above-knee prosthesis for swing time and its experimental validation. John P. Paul (1999), stated that throughout the history of development of joint replacement implants and external prostheses, there have been mechanical failures due to a discrepancy between material strength, cross-sectional characteristics and the loads developed in normal or abnormal function by the patient utilizing the device. CAD modeling is present day solution for such problems. CAD has been extensively used for structural analysis and socket design, but mechanism design applications are still unexplored. This paper presents use of CAD for mechanism design for above-knee prosthesis. Tae Soo Bae et. Al., (2007), studied to quantitatively evaluate amputee gait by dynamic analysis of the musculo-skeletal system during level walking and stair climbing. Jaroslav Mackerle (1992), listed complete bibliography of conference proceedings papers and theses / dissertations on the finite element (FE) and boundary element (BE) applications in different fields of biomechanics between 1976 and 1991. Carlos et al., (2001), presented a tutorial article that reviewed the use of partitioned analysis procedures for the analysis of coupled dynamical systems. T. K. Wang et al., (1992), stated that conventional designs of an above-knee prosthesis are based on mechanisms with mechanical properties (such as friction, spring and damping coefficients) that remain constant during changing cadence and since the nonlinear and time-varying dynamic coupling between the thigh and the prosthetic limb is high during swing phase, an adaptive control is necessary to control knee joint motion and thus an active knee is a necessity. On the other hand, active knee joints are not popular due to need of a power source all the time. Passive knees are sold the most and thus there is a need to concentrate research on passive knees as well. R. Di Gregorio et al., (2004), modeled ankle passive motion and stated that the use of (equivalent) planar and spatial mechanisms for the kinematic modeling of joint passive motion can also be successfully utilized for the knee joint. In order to control the swing phase of a passive type above-knee prosthesis, weight of the prosthesis plays an important role. C.S. Tsai et al., (1986), developed a detailed dynamic model of the stump-prosthesis system for an above-knee amputee to examine the influence of controls and design parameters on the limb system performance during the swing phase of gait. Their simulations suggest that lightweight prosthesis designs do not perform as well as heavier designs. On the contrary, with CAD modeling technique this problem has been solved and an optimum design can be easily developed. One developed by us and experimented upon does not weight more than 2.5 kg and swings well to match normal cadence. Prior to CAD design mathematical modeling was also performed. R. Rafael et al., (2008), presented a review of current researches for development of knee prosthesis.

Hao et al., (1969), did a systematic analysis to simulate a mathematical model for the control mechanism of above-knee leg prosthesis. The CSMP-360 continuous system-modeling program was used to study various parameters, from linear to piecewise-linear controls. F. Carli et al., (1996), provided an approach to the kinematic analysis of knee joint prosthesis. C. Frank et al., (2006), presented a paper describing the design of an above-knee prosthesis with actively powered knee and ankle joints, both of which are actuated via pneumatic actuators. E. S. Grood et al., (1983), presented a joint coordinate system that provided a simple geometric description of the three-dimensional rotational and translational motion applied to the knee. Our work concentrates on motion in a sagittal plane only. The prosthesis after fabrication was fitted to a stand and was validated for swing time. Lorin et. al., (2005), designed and developed a five-axis simulator to simulate dynamic loading activities on either cadaveric knee specimens or total knee prostheses mounted on fixtures. The passive AK prosthesis must swing because of gravity force and also use the energy gained in spring assembled in the assembly. This paper presents a CAE solution to perform a mechanical design of a prosthesis using motion module of ProE software to match the swing time as per required cadence.

The purpose of this research work is to propose a CAD-based technique to mechanically design AK prosthesis for swinging time for normal plain surface walking.

CAD Modeling

The artificial leg should be able to swing with the speed comparable to the able leg for optimum cadence of the amputee, to walk comfortably. The mechanical legs swing velocity and swing time depends upon moment of inertia of the swinging components of the leg, the damper co-efficient and the spring constant, which had gained energy during flexion phase. Dynamic analysis offered by CAD software is a simulation tool and one offered by Pro Engineer software was used to design this mechanism. The knee and socket were made as ground, while spring and damper assembly was made as indicated in Fig. 1. Control elements and spring have not been shown in the figure considering patent requirements. The complete assembly has all the parts with same specifications as in real model, including shank strips, cover, foot and shoe. The foot design was approximated to include the shape and weight of shoe, used in prototype.

The spring and damper used were tested to find the spring constant and damper co-efficient. Subsequently, these values were used to carry out mechanism design. Spring constant in compression was taken as 15 N/mm and damper constant at complete throttle opening was taken to be 0.14 Ns/mm. Total weight of swinging part was taken as 2.17 kg.

Only gravity load was applied and the model was made to swing from the specified flex angles to zero flex angle – the normal straight position.

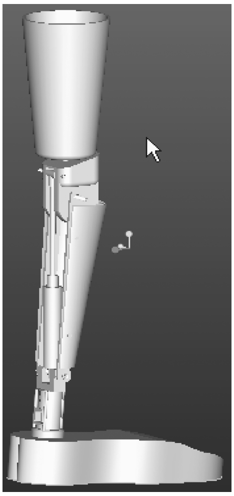

Fig. 1. A Pro-E CAD model of the prosthesis used for dynamic Analysis

Mechanical Model

The experimental prototype consisted of prosthetic knee fabricated at Alimco, India that was modified to include a pneumatic piston with an external spring. The spring gained energy during flexion, and this energy along with gravitational force was used to extend the prosthesis during walking.

The control of this energy regulates the swing time and a damper was used to control this rate of energy consumption. The complete assembly was checked for alignment and was then fixed to a stand with an optical encoder along with a control circuitry having an Atmel 8052 micro-controller to measure angle and swing time of the leg. Fig. 2 provides a photograph of an LCD screen fitted to ATMEL 8052 controller, displaying the swing time for a particular swing angle.

Fig. 2. A photograph showing swing time displayed on LCD screen connected to ATMEL 8052 micro controller

Results

The CAD model was developed for mechanism design and dynamic motion analysis was performed. Simulated results of acceleration, velocity and position with respect to time at different swing angles have been plotted. A prototype was developed and it was made to swing on a stand and its swing time was determined experimentally.

The swing is comparable to case of a compound pendulum. The acceleration is maximum at top starting position and becomes zero at the normal straight position after which it again increases in opposite direction, but since the leg is constrained, it stays zero. Fig. 3 indicates how the leg accelerates as it is left from a specific flex angle. Negative value in the plot represents direction since clockwise direction is represented as negative in software.

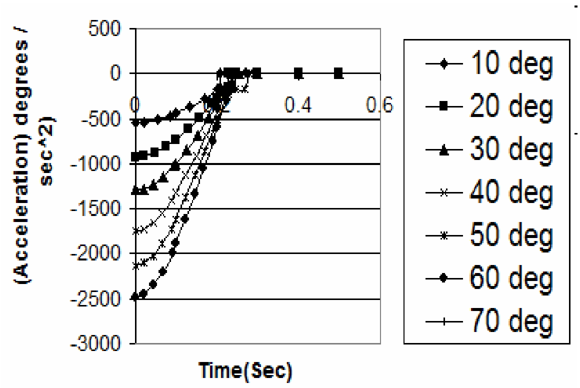

Fig. 3. Pro-E dynamic analysis result showing acceleration of the swinging portion of prosthesis with respect to time for different swing angles. The acceleration is maximum at starting. Negative sign is indicative of direction, clockwise is taken as negative

Considering velocity, it is zero at start of swing phase and increases as it reaches normal straight position of minimum acceleration, but the leg is constrained and cannot move ahead and the velocity immediately becomes zero. Fig 4 gives relation of changing velocity of the leg as it is left from the specific flex angle Again the negative values here represent direction.

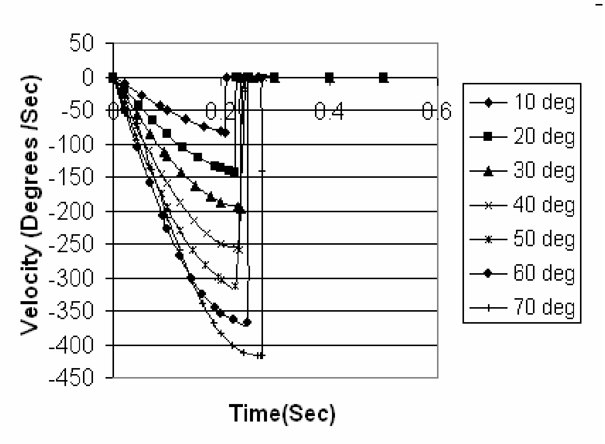

Fig. 4. Dynamic analysis result showing velocity of the swinging portion of prosthesis with respect to time for different swing angles. Velocity is minimum at starting of swing

Simulated result of angular position of the swinging part of the artificial leg with respect to time gives the time for the leg to reach zero flex state. Fig. 5 provides the relation between angular positions of the leg with respect to time. From the graph, it is clear that as the swing angle to be covered is larger, time consumption is larger as well. The graph can be used to find the time in which the artificial leg will swing for the given spring constant, damper co-efficient and weight of the swinging component of the leg.

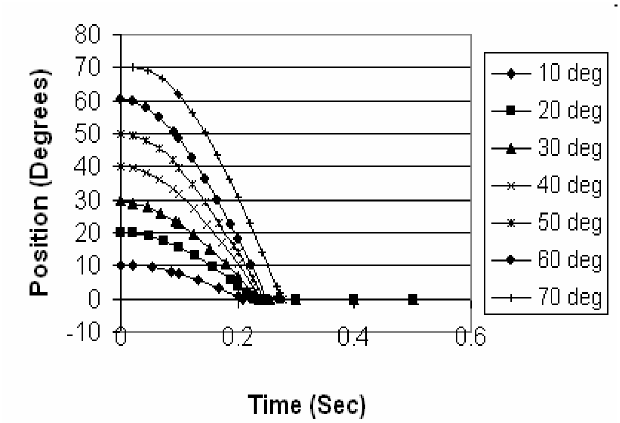

Fig. 5. Dynamic analysis result showing position of the swinging portion of prosthesis with respect to time for different swing angles

Simulated results needed to be validated on a prototype. A prototype with optical encoder fitted to the knee and a micro-controller programmed to display the flex angle and swing time was developed. Fig. 6 illustrates relative swing time between CAD (Pro-E) simulations and experimental results. The design was also thereafter validated on two patients in AIIMS, New Delhi, India, with positive results.

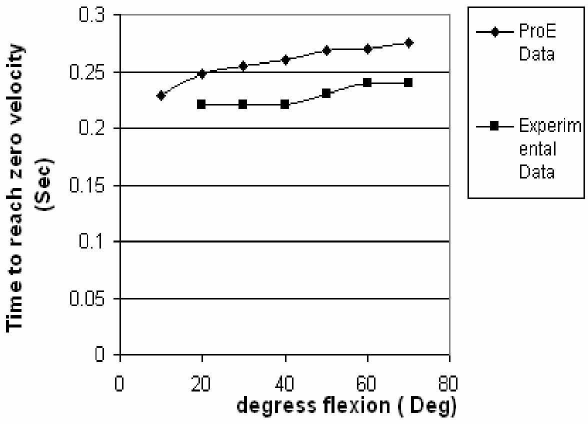

Fig. 6. Graph compares the prosthesis swinging time at different flexion angles of simulation model and experimental model. The error is very less and clearly indicates that simulation data approach experimental results

Key Findings

CAD-based dynamic analysis is a reliable software tool to perform motion analysis of the above-knee prosthesis.

The graph of angular position with respect to time can be used to determine the time the prosthesis will take to complete the swinging motion.

Discussions

Design is essentially a decision making process and for every problem, we need to design a feasible solution. CAD modeling is a tool to simulate a decision before going for fabrication. The present design is a new process of the prosthesis. For above-knee prosthesis the mechanical design has to ensure that the prosthesis swinging time is within controllable limits for normal cadence. Considering normal cadence of 35 double steps per minute, time taken per double step is 1.71 seconds. Approximating swing phase time for one leg to be 40 % of single step time comes to 0.34 seconds. Clearly the mechanical design has to ensure that the swing of the compound pendulum completes within 0.34 seconds. In case the compound pendulum takes more than 0.34 seconds to swing, it will become a major design fault. Any thing less than 0.34 seconds can be controlled by suitable damper assembly. Swinging motion of the mechanical assembly depends upon the location of centre of gravity and moment of inertia of the assembly. As complex-shaped components are added into the assembly, it becomes very difficult to find the centre of gravity and moment of inertia. This is where the CAD software such as Pro-Engineer comes handy. The dynamic analysis module of Pro-E software simulated a rotational system with an external spring and damper attached.

As it is evident from the plotted results generated by dynamic analysis, the prosthesis swing time completed within 0.3 seconds validating success of mechanical design for the requirement.

The results received from Pro-E simulation converged to experimental model with minimal errors as is evident in Fig 6.

The error is a constant one and can be attributed to deficiencies in hardware, such as friction in bearing about which swing took place or error due to sensor response.

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