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Development and control of a Controlled Semi Active Prosthetic Ankle

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Abstract

This work develops a controlled semi-active ankle prosthetic using parallel and series spring systems. The model of the controlled semi-active prosthetic ankle is composed of parallel springs, leaf series springs, and a cam. for reduction torque and power consumption as much as feasible, the parallel and series springs must function as a nonlinear system. As a result, the cam system is used, which has parallel and series springs. The controlled semi-active ankle prosthetic with parallel and leaf series spring was modelled using the CAD-CAM software. The controlled semi-active ankle prosthetic behaves similarly to a non-amputee ankle. The power consumption of the motor has been reduced by 51.67 percent. The angle and torque of the controlled semi-active ankle prosthetic are strikingly like those of non-amputee ankles.

Keywords: prosthetic, leaf series springs system, parallel spring system, cam, transmission.

1.Introduction

The human leg is a magnificent machine that allows humans to do a wide range of activities [1]. Approximately 2 million persons in the United States have had limbs amputated, with an estimated 185 000 amputees per year. Amputation rates are anticipated to more than double 2050, owing to population ageing and a rise in the incidence of dyscalculia diseases [2, 3, 4, 5, 6 and 7]. Amputations of the lower limbs are life-changing occurrences that can have a significant impact on an amputee's physical, psychological, and social well-being. The loss of movement is the most obvious side effect after lower limb amputation. Amputees are unable to walk without some form of assistance, making them more susceptible to falls and collisions. Daily tasks that were previously taken for granted become significantly more difficult or outright impossible to perform following an amputation [7]. However, while prosthetic limbs can replace a missing part of the human body, their effectiveness is dependent on the patient's level of activity and health. The replacement of the lost limb with a prosthetic leg may help the amputee regain some of the normal functionality [8]. The research effort in this field focuses on improving of the characteristics of the artificial leg to closely mimic the functionality of the human limb. Prosthetic limbs which are able to more accurately mimic the functions of the normal limb led to a more comfortable gait for the amputee and to lower energy expenditure.

Ankle foot prostheses must be the same weight and size as a normal ankle. Electric motors and batteries are utilized to power the prostheses and batteries are used At least the ankle prostheses must work for one day after full charging. The researchers should try to minimize the electrical motor's power needed. The energy efficiency of prostheses is very important. Because the stiffness of the ankle is variable, the passive elements are used. This passive element is used to store and return the energy [8]. The passive component can be connected to the motor in series or parallel.

A power ankle prosthetic PAFP was actuated by an elasticity parallel actuator EPA. The direct drivetrain and PEA, which had been founded on the biomechanics of a typical ankle of a person, were used to measure PAFP's energy demands initially. The electromechanical design of the changeable compliance operator used in a dynamic ankle prosthetics, as well as the research that was conducted with it, were in [10]. Two small inertia measurement units on the shank and foot collected data [11], To predict ankle energy, machine learning techniques were used, providing a viable alternative to traditional methods. A torsional fat springs (TFS) [12] was presented for the ankle of person series elastic muscle tendon operator mechanism to deliver great deformation and compliance values. Because a torsional fat spiral spring can only create torque in one direction, the suggested torsional fat spring uses two torsional fat spiral springs in opposite orientations. In [13], a mechanical transmission dependent on a chain pulley enabling human-like actuators in human-scale prosthetic ankle joints was proposed. A power ankle-foot prosthesis [14] was created with the goal of providing a large variety of motivations and sufficient force for a stride in which you force. For human-like actuators in

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human-scale artificial ankle joints, a mechanically transmission based on a chain pulleys was developed. The increasing effects of a prosthetic that actuates both the ankle and the knee joints [15] were examined to the effects of ankle actuated alone. An electromyographically (EMG) controlled 2-degree-of-freedom (DOF) ankle-foot prosthesis was devised to improve rock climbing skills in those who had their tibias amputated in [16]. Authors in [7], described an effective PAFP employing a series change stiffness actuator. The springs of the gear five bars with gear five bars SGFB actuator to create the series elastic actuator SEA, the GFBS mechanism was joined with the conventional SEA. The new SGFB actuator combines the benefits between the SEA and the GFBS actuators in terms of mimicking human ankle biomechanics and lowering motor maximum power. The passive elastic components were created to minimize the number of actuators needed in power ankle prosthetics. The difficulty is to produce most of the non-linear ankle respond with the passive component while keeping the torque for the ankle from the actuator low [17]. A compact parallel springs system was used to build an innovative PAFP [18]. Actuators ‘torque and power requirements are reduced using the parallel springs mechanism, which consists of two linear springs and a cam. In [19], the force of friction was considered in the cam spring mechanism. Authors in [20], described a power biarticular transtibial prosthetic that combines a commercial PAFP with a controlled robotic knee orthosis.

A hydraulic damping design for application in a foot with a trans - femoral prosthetic was presented in [21]. Two one-way flow control valve is used in the hydraulic prosthetic foot joint to vary the dynamic response in dorsiflexion and plantar flexion, respectively. A carbon prosthetic ankle combined with springs and a damper could help to better simulate natural foot movement. The controlled semi-active ankle prosthetic CSAAP is modelled in this paper using a DC motor, leaf series springs, and parallel springs with a cam profile mechanism. When the heel strike cannot meet bandwidth demands, the leaf series springs are employed to raise the level of the stiffness of this spring that preserves the gears and belt transmission from damaging. During the control dorsiflexion phase, the parallel springs with the cam profile mechanism are employed to maximize the stored energy and return it during the subsequent push-off stage. As a result, the motor's demand power is reduced. This allows us to use a lower-powered motor. The cam's design reduces the required actuator torque. The energy efficiency of CSAAP is a key component in lowering their weight. The electric motor is reduced, and the batteries are downsized after employing the cam. The energy system's efficiency has improved [8]. CAD-CAM is used to model the prototype of a CSAAP. The results showed that this model's mobility is extremely similar to that of a non-amputee ankle.

The remainder of this document is as follows: Section 2 discusses human ankle biomechanics at the walking level, Section 3 discusses CSAAP modelling and improvement, Section 4 gives the cam parameter, section 5 presents the mechanical design, Section 6 discuss the results of this model from CAD-CAM, and Section 7 concludes the full paper.

2. Human Ankle Biomechanics in Walking

It is very significant to understand the biomechanics of human for designing, improvement, and progression of the CSAAP. The gait process commences with the heel on the earth and concludes with the heel on the earth virtually exactly the same way. This gait period is composed of two main stages: stance stage (60%), and SP (40%) as presented in fig. 1,2. The stance process starts at the heel-strike and comes to an end at the same foot's toe-off, which contains three sub-stages: Power Plantar flexion PP, Controlled Plantar flexion CP, and CD. The SP commences with toe-off and finishes with the sequent heel-strike of the same foot, which completes the gait period when the foot is off the earth [22,18,17,23].

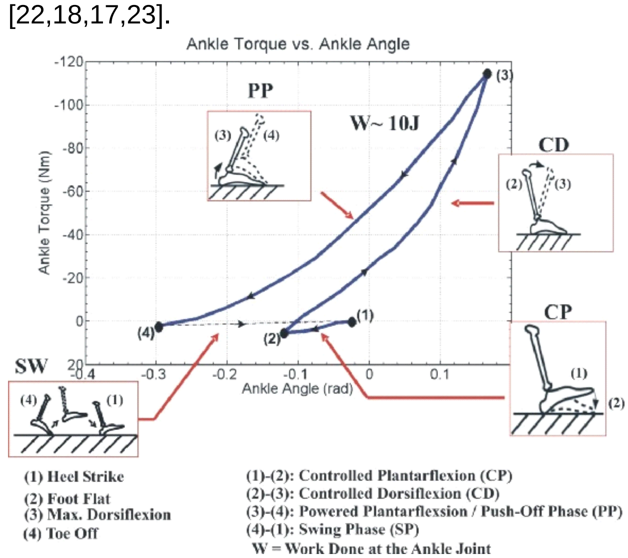


Figure 1: the angle-torque behavior of the non-amputee ankle [24].

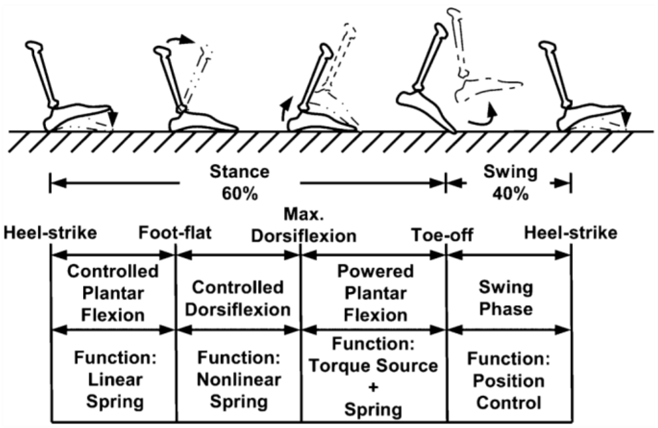


Figure 2: the biomechanics of non-amputee when walking on flat ground [25].

Controlled Plantar Flexion (CP)

The first juncture of ankle position happens with heel striking and finishes with foot flat. As the foot acclimates to the weight of the individual being put to it, and shock absorption occurs owing to heel tissue and shoe material, this phase is also known as weight acceptance [26,27]. According to [27], the activity of the ankle joint during cp is similar with linear springs response, with joint torque linked to joint position. Figure 1 section (1)-(2) [27] shows the ankle's linear spring action.

Controlled Dorsiflexion (CD)

CD usually starts with the foot flat on earth and extends until the ankle reaches full dorsiflexion. During the CD period, ankle torque versus position is commonly depicted as non-linear springs, with stiffness rising as the position of the ankle increases. During CD, the human ankle's primary role is to conserve the energy of elasticity required to move the body up and backwards during the PP phase. The nonlinear springs behavior of the human ankle joint during CD is seen in sections (2)-(3) of Fig 1 [27].

Powered Plantar Flexion (PP)

PP initiates after CD and stops at toe-off. For moderate to quick walking velocities, the work produced during PP is greater than the corresponding work absorbed during the CP and CD phases, therefore extra energy is delivered along with the stored spring energy during the CD phase to achieve a high level of PP at the conclusion of stance. As a result, the ankle can be represented as a torque source parallel to the CD spring during PP. The magnitude of ankle entire work done is represented by the area work (W) enclosed by the points (2), (3), and (4) [26, 27].

Swing Phase (SW)

SW denotes the part of the gait cycle when the foot is off the earth, and it starts with toe-off and stops with heel strike. The ankle can be represented as a position source to restore the foot to a chosen position of equilibrium during SW before the next heel impact. [26, 27]

3. Design Issues

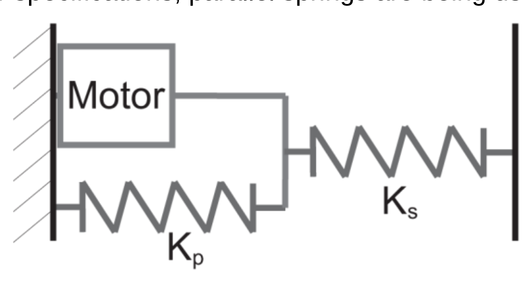
The problem of design is being to efficiently simulate the characteristics of ankle stiffness in various parts of the stance phase. In addition, ankle power absorption can be represented by negative power, and the generation of ankle power can be represented by positive power. As a result, an ideal device should optimize maximize imbibition of energy by passive elements through the loading stage of stance and return energy through the unloading juncture of stance.[17]

4. simulation and Optimization:

Design schools are parallel springs with actuator, series springs with actuator and parallel springs and series springs with actuator. series elastic component is used to rise the tolerance of shock and minimize reflected inertia, but the parallel elastic component is used to reduce torque requirement [21]. So parallel and series springs are very important elements the maximum level of series stiffness that adequately protects the transmission from damage during heel strike fails to satisfy bandwidth requirements. Parallel motor elasticity is being used to limit the forces derived by the SEA, rising force bandwidth to an acceptable standard for biomimetic ankle-foot behavior, as a solution to this problem. [17,28]

Modeling:

The CSAAP is modelled. The modeling of CSAAP is consisting of the motor, leaf series springs and parallel springs. The leaf series springs are used to increase the level of series stiffness that adequately protects the transmission from damage during heel strike fails to satisfy bandwidth requirements. To minimize torque and power specifications, parallel springs are being used.



$$\theta_{ac} = \theta_{kp}$$

Figure 3: Schematic model of the Series Elastic and Parallel Elastic Actuator (SE+PEA)[29].

Where $K_p(N.m)$ is the parallel springs stiffness constant, $K_s(N.m)$ is the series springs stiffness constant, θ_{ac} is the angular displacement for motor, and θ_{kp} is the angular displacement for the parallel springs.

From [17], a differentiation between a linear and nonlinear parallel elastic actuator discovers that a Nonlinear Parallel Elastic Actuator NPEA can obviously minimize the demand torque of the active element. As a result, the parallel spring (Anchor Lamina JIS Compression Spring 95-5060) is set to 817KN/m [17]. The cam device is being used to achieve nonlinearity. [7, 18, 17]

4. Selection Cam Parameters

The parameters that can be selected are the integration constant c in the cam profile s, the prime radiusR_p, the roller radiusR_r, the eccentricity d, and the follower-spring constant k_c. The chosen prime radius was R (p)=25mm, and the roller radius was R (r)=9.5mm, in order to keep the cam size minimal. The restrictions are satisfied by the chosen cam parameters [17]. Figure 5 [17] depicts the resulting cam form.

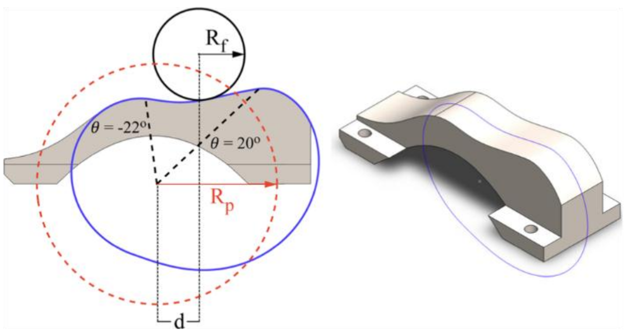


Figure 5: Cam prototype for SE+PEA mechanism.

5.Mechanical Design of the Ankle-Foot Prosthesis

The model of the CSAAP consists of active and passive elements that contribute to generate the total positive power at the ankle joint during the stance stage of walking [8] as shown in Fig. 6 by using CAD - CAM program. In this design, the prototype of the CSAAP contains a carbon fiber foot, actuator, leaf series springs and parallel springs with cam profile mechanism. During heel-strike, the carbon fiber foot is being used to absorb shock. The actuator mainly includes a DC motor, gears and belt and a ball screw. Considering the requests of the actuator on torque, speed and peak power, the CSAAP is actuated by DC motor. A pair of custom gears and belt are worked as convey the rotation from the output of the DC motor to the ball screw. The gear-belt transmission is being used to minimize the velocity of the DC motor. Shock and vibrations from the outside world are dissipated by the gear-belt transmission. To make sure that the artificial limbs keep moving effective and efficient, maximum accuracy and sensitivity are needed in ankle joints, and a ball screw nut is being used. Gear drives used for the rigid transmissions always perform well in terms of operation stability, dependability, and transmission efficiency. [25]. And also, the ball screw nut that is used to convert the rotation motion into linear motion.

When the transmission fails to meet bandwidth requirements, the leaf series springs are employed to raise the level of series elasticity that effectively preserves the transmission from destruction during heel striking. [17, 28]. A cam, follower, and spring element make up the nonlinear parallel springs system. The cam profile was designed in [17], so the nonlinear parallel springs mechanism can mimic human ankle dorsiflexion stiffness. Because the cam is attached to the ankle mechanism by four screws, it can be replaced if necessary. Furthermore, as illustrated in Fig. 5, a particularly constructed ramp section is integrated into the cam form, allowing the springs to be unloaded by turning the ankle sufficiently in the plantarflexion direction. A conventional pyramid adapter is also included on the gadget's top, which is used to connect the device to a patient's prosthetic socket. The model of the CSAAP is developed. After using the parallel spring and cam, the model is behavior as the non-amputee ankle. The power consumption is decreased. The model of semi-active ankle achieves the design specification and the target angle-torque [23].

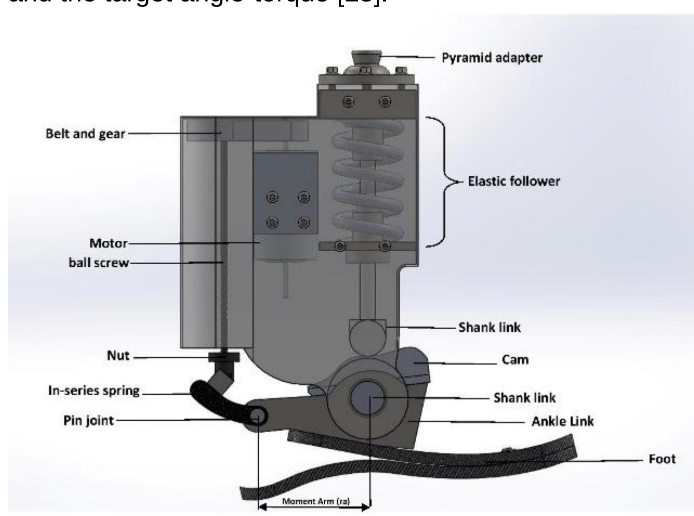


Figure 6: the model of the CSAAP in CAD - CAM program.

7. Results and Discussion:

The results of the CAD-CAM simulation for gait evaluation of the CSAAP while walk is described in this section. Where the reference data is from [30]. Figure 9 shows power of the motor from CAD - CAM. During CD juncture, The motor is turned off because the parallel spring element generates the desired torque. The initial benefit of this design is that the motor's working time will decrease, as is the energy expenditure on the motor windings. It's worth noting that the CD juncture's negative mechanical energy is stored in the parallel spring element. The energy conserved in the parallel spring is released at the PP junction to assist the motor in propelling the wearer ahead. The crest power of the electrical motor is 155 watt where the reference crest power is 300 watt [30]. So, the power of motor is decreased by approximately 51.67%. The CSAAP is set free to the equilibrium position in the SP, and just a small amount of electrical energy is wasted. Figure 10 shows that the reference torque and the ankle torque from CAD - CAM is very close. figure 11 shows the motor torque from CAD - CAM. The maximum of motor torque can be reached to 56.7857N.m by gear-belt transmissions. The difference between ankle torque and torque from gear-belt transmissions is the torque that is produced by parallel spring. Figure 12 shows that the velocity of motor as input signal to model, motor velocity from CAD - CAM. Figure 13 shows that the position for the non-amputee ankle and the position for CSAAP from CAD - CAM. The position for CSAAP is extremely near to the reference position especial in the first 60% of the gait period. Figure 14 shows the ankle torque and angle behavior for an 84.4kg person from CAD - CAM. The ankle torque and angle behavior is extremely near to the reference the ankle torque and angle behavior as shown in figure 1. When High performance control system will be used, the ankle torque and angle behavior will be the same as the reference the ankle torque and angle behavior. The stages of the foot at heel strike, foot flat, peak dorsiflexion, and toe-off are represented by the points (1), (2), (3), and (4), respectively. The angle-torque characteristics of the ankle during the CP, CD, PP, and SP phases of gait are illustrated by the sectors (1)-(2), (2)-(3), (3)-(4), and (4)-(1), respectively. As may be included in sectors (1)-(2) and (2)-(3), the human ankle joint exhibits different spring tendencies during CP and CD, respectively.

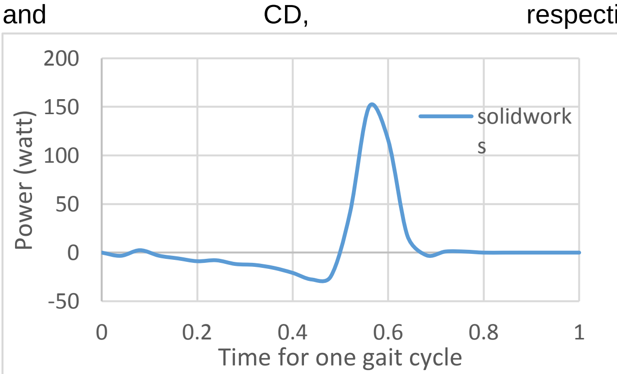


Figure 9: The motor power (watt) from CAD - CAM.

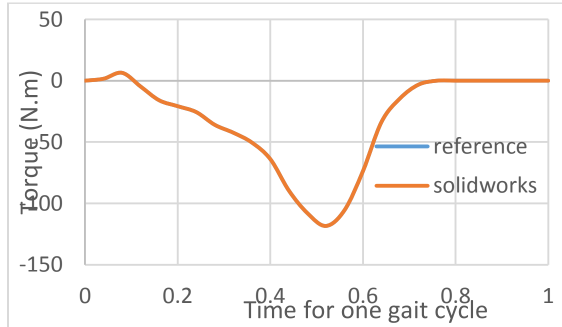


Figure 10: the reference torque for ankle and the torque for ankle from CAD - CAM.

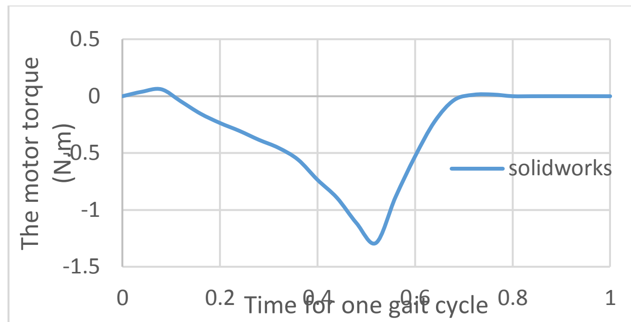


Figure 11: The torque for motor from CAD - CAM.

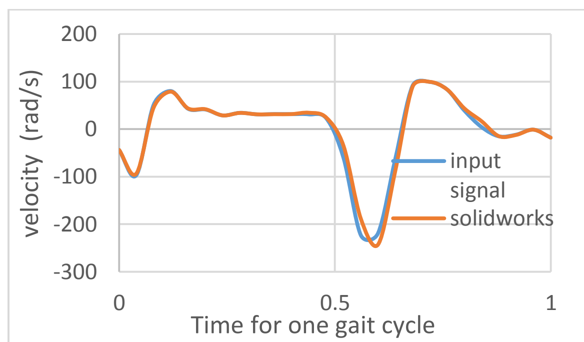


Figure 12: The input signal and the velocity of motor from CAD - CAM.

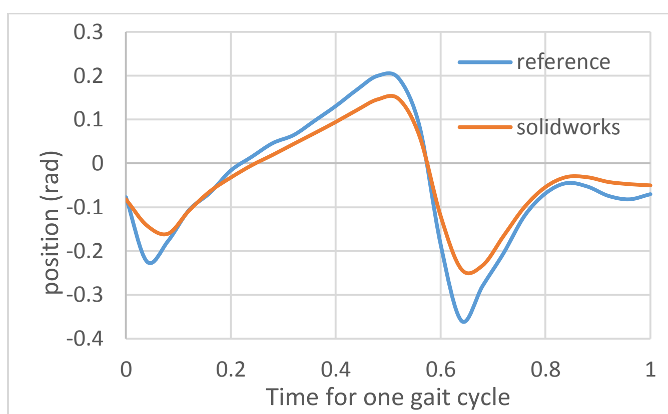


Figure 13: the reference position and position from CAD - CAM for the CSAAP.

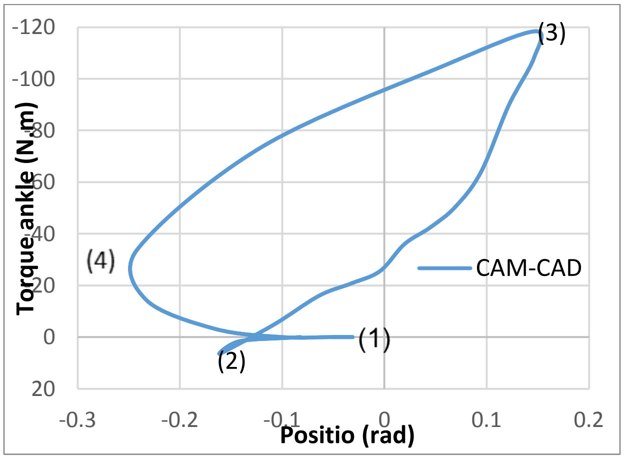


Figure 14: the angle–torque of the CSAAP for one gait period from CAD – CAM.

7.conculsion

The CSAAP with series and nonlinear parallel springs mechanism was developed. The nonlinear parallel springs was achieved by using the cam. The nonlinear behavior of parallel spring contributed to decrease the torque and power consumption of motor. The CSAAP with series and nonlinear parallel spring mechanism was modeled by using CAD - CAM program. The results presented that the torque and the power exhaustion of the motor were reduced. In the future work, the control system for the CSAAP will be done and this model will be analyzed by using ANSYS program.

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