Computational Design and Analysis of a New Hybrid Actuating System for Ankle Foot Orthosis (AFO)

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Summary: In general, a person who suffers from an ankle injury would have to spend at least four (4) to six (6) months to recover. With the existing Ankle Foot Orthosis (AFO), this rehabilitation period can be much reduced and a more effective recovery module is possible. AFO is a system used to restore human gait while providing stability during stance phase which is used in house alternative therapy session to facilitate the rehabilitation process. This system could dramatically reduce the gait recovery period with a proper guidance from the respective doctor. AFO could also help patient with paraplegia/hemiplegia problems to improve their quality of life. In ensuring patient's comfortability, AFO requires a refined design which conforms to certain ergonomics standard. Hence, this research embarks on the design and analysis of a new AFO's actuator system. This actuator is conceived to provide high precision deflection to mimic the normal kinematics human gait. The design of the actuator system is based on pitch movement of the Asian foot and limited to one degree of freedom. The derivation of equation of motion for this actuator is based on Newton's principles and Lagrange Method. A standard design of AFO was developed in assessing the proposed actuator system. The performance of the proposed actuator system was evaluated through Computer-Aided Design CATIA software. The results show that the proposed candidate was outstanding in reducing power consumption and able to track with less steady-state error.

Keywords: Ankle Foot Orthosis (AFO), Finite Element Analysis (FEA), Gait Cycle, Kinematics Analysis, Actuating System.

1. Introduction

Basically, ankle injury such as ankle sprain is a common injury that causes by sports, accidents or even foot slippery. The reason for the high incidence of residual ankle instability after an initial lateral ankle sprain is the simple fact that most ankle sprains are mistreated. With the existence Ankle Foot Orthosis (AFO), this rehabilitation period can be much shortened than usual and a more effective recovery module is possible. AFO is a system used to restore human gait, providing stability during stance phase. AFO will provide a necessary solution for patients who are suffering with many foot and ankle ailments. They can give relief and assist in the recovery of foot and ankle related concerns. Nowadays, wearable robotic mechanism can be applied onto AFO to improve more the effective recovery during rehabilitation. The mechanical system of AFO is powered with mechanism consist of electronic to control the robotic tendon that uses a motor to correct the position and tuned spring in the gait pattern [1]. One of the main design goals of a conventional AFO is to hold the foot and ankle in a suitable position to correct involuntary plantar flexion [2].

More recently, solid AFO is functional rehabilitation equipment used as a brace worn on the lower leg and foot to support the ankle and hold the foot and ankle in the correct position [3]. However, this equipment has a drawback in which limited to remedy the foot-drop without considering stance phase includes heel strike, foot flat, mid stance and toe off (push off) and swing phase includes acceleration, mid swing and deceleration. However, the solid ankle foot orthosis still be using these days without any improvement. In addition, the problem even worst amongst wearable robot AFO when motor to drive the actuator did not support the torque system enough to actuate the AFO.

Previously, there are many researches and development of AFO to fine tune the deflection angle and ergonomic to derive an ideal rehabilitation system. While, there are not many designs or researches conducted to embed AFO with powered movement actuator such as DC motor or pneumatic system that can aid the users to move. Even though there are researches conducted to develop powered AFO, most of them are still in the early stage such as the pneumatically powered Knee Ankle Foot Orthosis (KAFO) using myoelectric also called a motor action potential for activation and inhibition [4]. Another example of design is adapting a motor during dorsiflexion assisted walking [5]. Dynamic Ankle Foot Orthosis (DAFO) must assist the movement of the patient's foot even before they can move them by their own. In the research, they used proportional myoelectric control of the powered orthosis because prior research has shown that humans can quickly adapt to plantar flexion assistance with proportional myoelectric control [6].

Based on this literature reviews, it is found that the patient who had ankle injury or hemiplegic, they had problem with walking which difficult to walk as normal people because lack of dorsiflexion moment in early stance phase. Dorsiflexion is movement in a dorsal direction especially flexion of the foot in an upward direction. Plantar flexion is a movement of the foot that flexes the foot or toes downward toward the sole. The normal angle deflection of dorsiflexion and plantar flexion is 11 [deg] and 21 [deg] [7]. As a result, they cannot reach the ground from heel. Purpose of studying the characteristic of walking to analyse gait motion which to locate the phase steps of walking. Hence, drop foot in swing phase and slap foot at heel strike during walking could be avoided.

2. Concept

Hybrid Actuating System (HAS), the present project is a mechanical element, commonly referred as robotic tendon with regenerative spring that is based on the concept adding and subtracting of coil from a spring. In particular, by changing the number of coils in a spring, the actual or intrinsic stiffness of the spring is structurally changed. This simple and practical method is used to adjust the number of coils. HAS adapted from the concept of the robotic tendon with motor driven to be implemented for a new actuator system.

The most general actuating mechanism is in the form of lead screw. A lead screw device is simply a special case of the regenerative spring where stiffness can be determined. Some of the advantages of the new concept include but are not limited to stiffness of the actuator can be dynamically set-up, the spring is the lead screw also function as speed reducer or gearbox, the helical spring converts rotary motion into linear motion in terms of energy generative, a spring based actuator is able to store and release energy, a very practical actuator can be designed.

Based on [1] about this type of actuating mechanism could give the performance excellent because this system could actuate the AFO with low motor power usage. In this usage of springs, the input power can be reduced to 47.26 W and the spring and motor can provide 110 W of peak power compare to direct motor drive system required 98 W to actuate the AFO. The data showed that the power out during push off in the gait cycle was significantly greater than the power developed by the direct motor. This was possible because the spring stored energy in part of the gait cycle and released the energy at push off [1].

3. Methodology

This section emphasizes on the modelling of the actuating system based on the parameters given in Table 1. The simplified actuating system is shown in Figure 1. The mathematical modelling is governed by dynamic equation of motion which represents the spring stiffness of the system. The Mathematical model of this system can be derived via several method namely Newton-Euler, Lagrange-Euler and also Recursive Newton-Euler method.

Figure 1 represented the modelling of HAS. Table 1 explained the parameters that used in modelling of HAS. Figure 3 is a model that was represented the simplified Free Body Diagram version (a) and ideal spring (b) used in HAS.

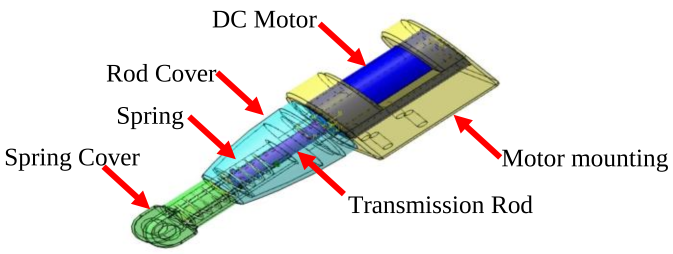


Figure 1. Hybrid Actuating System (HAS).

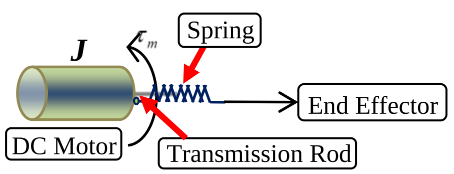


Figure 2. Schematic diagram of actuating system.

From the schematic diagram, the dynamics model of the actuating system can be determined by employing Newton's 2nd Law of Motion;

$$\sum M = J\alpha \tag{1}$$

$$+\tau_m - \tau_{spring} = J\alpha \tag{2}$$

$$+\tau_m - K_t\theta = (J_{spring} + J_{shaft} + J_{rotor})\alpha \tag{3}$$

$$+\tau_m - K_t\theta = (J_{spring} + J_{shaft} + J_{rotor})\frac{d^2\theta}{dt^2} \tag{4}$$

Table 1. Parameter in the modelling.

Parameter	Description	Value
M_{shaft}	Masses of shaft,	8×10^{-3}kg
G_{spring}, G_{shaft}	Shear Modulus of spring and shaft	80 GPa, 25 GPa
F_a	Force actuator (output)	100 N
K_m	Torque motor constant of DC motor Maxon R30	25.9 mNm/A

Taking Laplace transform of equation (4) with zero initial conditions;

$$+T_m - K_t\theta(s) = (J_{spring} + J_{shaft} + J_{rotor})s^2\theta(s) \tag{5}$$

$$+T_m = \left[(J_{spring} + J_{shaft} + J_{rotor})s^2 + K_t\right]\theta(s) \tag{6}$$

Where,

$$K_t = K_{shaft} + K_{spring} \tag{7}$$

Finally,

$$\frac{\theta(s)}{T_m} = \frac{1}{\left[(J_{spring} + J_{shaft} + J_{rotor})s^2 + K_t\right]} \tag{8}$$

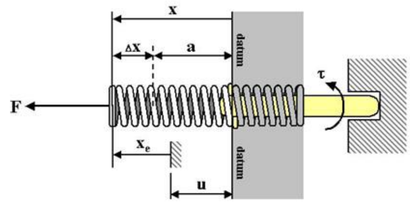


Figure 3. (a) Simplified Free Body diagram (FBD).

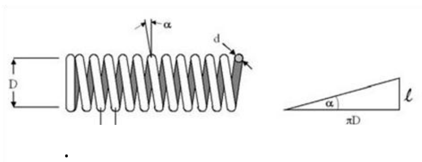


Figure 3. (b) Ideal spring.

3.1. Dynamic Equation

Dynamic equations of HAS as in Figure 2 were derived by employing the Newton's 2nd Law through equation of motion. Torque for actuating system is derived from the free body diagram of the actuator system as shown in Figure 2(a). An ideal system could be derived from general torque equation. This relationship is based on Shigley and Mischke as is shown [8].

$$\text{Torque, } \tau = F\frac{D}{2}\tan\alpha \tag{9}$$

The force on the actuator is determined by multiplying the spring constant, β, by the difference of measured lead, l to free lead length, l_o .Using this relationship, an equation describing torque in terms of lead can be determined

Finally,

$$\text{Torque motor}, \tau_m = \frac{F}{2\pi\beta}(F + \beta l_o) \quad (10)$$

Solving equation from basic spring, yields the relationship between number of active coil, and environmental position, converting into new equation of spring stiffness in terms of lead, l .

$$\text{Spring Stiffness}, K = \frac{F + \beta l_o}{x_e + u} \quad (11)$$

3.2. Overall Transfer function

Overall transfer function of HAS like shows in figure above which the input and output were voltage (electrical) and angular velocity (mechanical) in terms of complex domain(s).

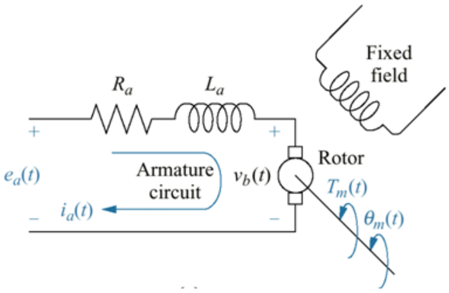


Figure 3. Schematic drawing of DC motor (Maxon RE30).

Referring to electromechanical system as shown in Figure 3, the system is a combination of electrical and mechanical system. So, derivation will start with DC motor and the output of this will drive the mechanical system. Back electromagnetic field (Back-EMF), v_b is proportional to angular speed, θ(t) produced by rotor,

Hence,

$$\text{Back-EMF}, v_b = K_b \frac{d\theta(t)}{dt} \quad (12)$$

Taking Laplace's transform of equation (12) with zero initial conditions

$$V_b = sK_b\theta(s) \quad (13)$$

$$\text{The armature voltage, } e_a(t) = R_a i_a + L\frac{di}{dt} + v_b(t) \quad (14)$$

Meanwhile, the relationship between induced $i_a(t)$ and mechanical system (Torque, τ_m) is;

$$\tau_m = K_m i_a(t) \quad (15)$$

K_m is torque motor constant

Rearrange the equation (15)

$$i_a(t) = \frac{\tau_m}{K_m} \quad (16)$$

Substituting the equation (12) and (16) into (14)

$$e_a(t) = R_a\frac{\tau_m}{K_m} + L\frac{di}{dt} + K_b\frac{d\theta(t)}{dt} \quad (17)$$

Taking Laplace's transform of Eqn. (17) with zero initial conditions

$$E_a(s) = \frac{R_a}{K_m}T_m(s) + sLI(s) + K_b s\theta_m(s) \quad (18)$$

Substitute equation (6) into equation (18)

$$E_a(s) = \frac{R_a}{K_m}\left[J_{total}s^2 + K_t\right]\theta_m(s) + sLI(s) + K_b s\theta_m(s) \quad (19)$$

Where;

$$J_{total} = J_{spring} + J_{shaft} + J_{rotor} \quad (20)$$

$$\frac{I(s)}{E_a - V_b(s)} = \frac{1}{R_a + sL} \quad (21)$$

$$\frac{\theta(s)}{E_a} = \frac{K_m}{(J_{total}s^2 + K_t)(R_a + Ls) + K_m K_b s} \quad (22)$$

Therefore, applied all parameter obtain in terms of complex domain into block diagram of AFO actuator system is shown in Figure 4.

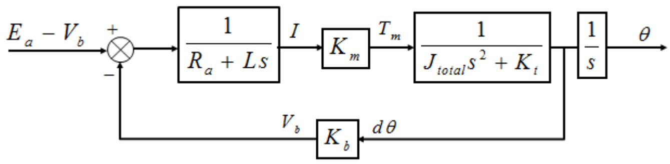


Figure 4. Block diagram for overall system.

3.3. Simulation study

A lot of current computing software is capable of simulating the kinematics or motion of a particular system. This analysis of motion is very important for designing a good and robust product, without understanding the kinematics of human gait motion one cannot develop an accurate design and hence the objective is not achieved. In recognizing the gait pattern of human foot, kinematics simulation is done using CATIA to analyse the angle deflection for dorsiflexion and plantar flexion. Therefore, maximum angle deflection could be verified.

Computational simulations and analysis under static condition computes displacements, strains, stresses and reaction forces under the effect of applied loads from the static assumption that all loads are applied slowly and gradually until they reach their full magnitudes. After reaching their full magnitudes, loads will remain constant. Dynamic loads change with time and in many cases induces considerable inertial and damping forces that cannot be neglected.

For this study, a possible load of 300 N(unpublished data) was applied plus considering the half of patient weight and effect of gravity since AFO design for right foot only The analysis was performed through Generative Structural Analysis in CATIA to develop result in terms of stress and displacement distribution contour which shown as results.

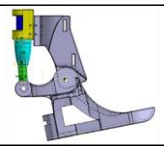
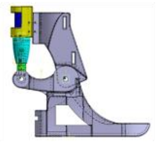
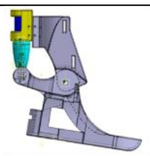
4. Results and Discussion

The results are divided into two sections to exhibit the kinematics and static study simulations.

4.1. Kinematic simulation

Refer from the kinematics simulation, the AFO motion had been analyzed by considering tolerances between each part and any clash component between parts to clarified limitation of design. From the analysis, AFO have provided maximum degree for dorsiflexion about 11[deg] and plantar flexion about -9[deg] as shows in Table 2. Refer from the Table 2, this AFO actuator system could mimic almost similar to human foot angle deflection where for human dorsiflexion is 11[deg] and plantar flexion is -22[deg] [9]. There was a big difference in degree of plantar flexion between AFO and natural human (Asian), where the range of plantar flexion angle amongst human is independent, flexible and varies. As the alternative, the angle could be adjusted through redesign the foot plate or relocated the AFO actuator to increase the length extrusion in linear motion that would cause increment angle deflection dependent to physical appearance and flexibility of the human foot.

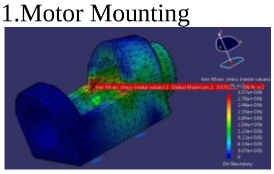
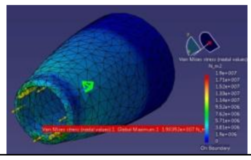
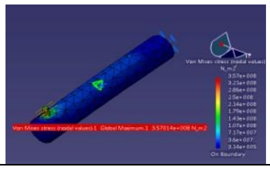
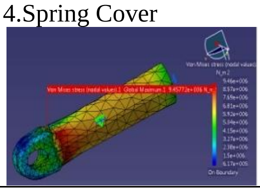
Table 2. AFO simulation from dorsiflexion to plantar flexion position.

Foot Position	Angle Deflection [deg]
	Dorsiflexion: Angle deflection: 11[deg]
	Natural: Angle deflection: 0[deg]
	Plantar flexion: Angle deflection: -9[deg]

4.2. Static simulation

Table 3 represented the stress distribution for each part of HAS. All parts of AFO actuator system have yield strength of 357 MN/m^2. Red region represented by the weakest point of applied load whereby dark blue region represented by the ideal point of applied load.

Table 3. Stress distributions for each parts of HAS.

Stress distributions	
1.Motor Mounting 	2.Rod Cover 
3.Transmission Rod 	4.Spring Cover 

Overall from the result in terms of stress and mass displacement shown in figure above, the structure for overall AFO actuator system mostly at the high stability of strength because all parts was made from Aluminium, A5052 which the material yield strength is 296 MN/m^2. However, most critical area among all parts was transmission rod which showed critical area at rod-end-tip caused by the applied load. Maximum stress produces was 357 MN/m^2 above the material yield strength. Therefore, for next project, further study should determine right material that suite with all product for optimization of the product design.

4.3. Numerical analysis

In the present study, the torque of 48 mNm was derived from AFO simulation. The torque calculated is significant to Maxon DC Motor in present study. Maxon DC motor has 85mNM of torque to cause the AFO to rotate. Therefore, the torque value of 48 mNm from simulation is able to cause the AFO to rotate. Besides, motor peak power was 44.84 W below the nominal motor power was 60 W.

5. Conclusions

From the reported results, angle deflection of dorsiflexion and plantar flexion could be spelled out that the AFO actuating system has shown positive results in gait motion and also torque generation. From kinematics simulation, angle deflections are almost similar to common Asian foot deflection from the numerical analysis, there was significant performance where the torque motor required was only 48.6 mNm to actuate the AFO compared to nominal torque of Maxon DC motor RE30 was 85 mNm. Credit to Hybrid Actuator system by applying spring concept which derives the potential energy as second source of energy besides motor into this actuating system, burden to motor had been tremendously reduced. A further study needs to be carried out using Tsai-Hill and Tsai-Wu failure criterion on static simulation which is more relevant in comparison to Von Mises failure criterion.

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