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OPTIMIZATION AND IMPROVEMENT OF GAS SPRING DESIGN IN AN ENERGY STORING PROSTHETIC KNEE

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ABSTRACT

This paper discusses the optimization and improvement of gas spring design. The gas spring is used as the suspension component of an energy storing prosthetic knee. The gas spring replaces the quadricep muscles of a transfemoral amputee. Deterministic and stochastic optimizations are proposed in this research. Both models are used to determine the optimal design variables of the gas spring: cylinder diameter, cylinder length, extension stroke, and compression stroke. The optimal design variables that result from the deterministic optimization model must be further analyzed to determine the effect of their variation from the objective function. A Monte Carlo simulation is used to determine the effect of such variations and make improvements when necessary. The process capability index (Cp) is used as a criteria to make this improvement while considering the contribution in variation of the design variables to the objective function. Stochastic optimization is proposed to find the optimal design variables by taking into consideration the randomness of its parameters. The objective function of stochastic optimization is to maximize the capability process. Both the Monte Carlo simulation and stochastic optimization were solved using Oracle Crystal Ball Software. From the simulation, the reduction of the compression and extension stroke standard deviations resulted in a 30% improvement in the energy storage standard deviation. The Cp was also improved by about 70%, from 0.99 to 1.44. The stochastic optimization resulted in extension and compression strokes shorter than deterministic optimization, with a 1.55 process capability index.

Keywords: Gas spring; Improvement; Monte carlo simulation; Stochastic optimization

1. INTRODUCTION

The energy storing prosthetic knee (ESPK) is a sub assembly used to connect the thigh of a transfemoral amputee to a thigh/knee base plate that has a pivot aperture (McQuail & Reck, 2013). It replaces the quadricep muscle function by using suspension. The suspension is used to store and release energy when the users need to flex or extend their knees. According to Savaresi et al. (2010), a suspension is a mechanical component used to reduce or eliminate the disruptive effects of a certain output variable. Suspension can be categorized into passive suspension and controlled suspension. Passive suspension uses a mechanical spring or gas spring as its elastic component. The mechanical spring uses the elasticity of torque given by the coils and its material, while a gas spring uses gas pressure principles to produce the elasticity. The gas spring is a common component used for suspension in the ESPK of an endoskeletal prosthetic.

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It gives a smoother transition from flexion to extension compared with a mechanical spring. The problem in ESPK design is how to determine the optimal design variables of the gas spring while satisfying the constraints. The design variables of the gas spring will determine the comfort of the ESPK in terms of the transition from flexion to extension. Higher stiffness of the spring will make amputees spend more energy in flexion compared to the spring with lower stiffness. In the transition from flexion to extension, the spring will release a lot of energy and unbalance the amputee's gait. Therefore, the design variables of the spring must be determined in an efficient way to satisfy the comfort requirement.

Spring design may be performed using two methods: iterative and optimization (Childs, 2004). The iterative method starts with setting the force and length of the spring; the designer specifies the spring material, estimates a trial diameter for the spring by considering the available space, checks the values calculated for spring rate and free length, and if necessary tries a new wire diameter. This method needs a lot of time because the designer has to try all dimension's combinations until the value corresponding to the desired objective function is found. According to Arora (2004), the design of systems can be formulated as problems of optimization in which a measure of performance is to be optimized while satisfying the constraints. The optimization method is considered more efficient in obtaining the optimal solution of the problem than the iterative method. System optimization can be performed by three approaches: trial-and-error, analytical method, and different models of design of experiments (DOE) (Kroll et al., 2011). Trial and error is the weakest approach, since the method has no structure. The analytical method is based on a mathematical model to represent the system under investigation and needs complex mathematical analysis. The design of experiment is a method used to optimize the system in which the structure of the relationships of its variables cannot be derived analytically.

Many studies have been conducted in spring design. Azarm and Papalambros (1982) developed a spring design optimization model and a computer application to determine optimal spring design variables. According to that research, spring design has four possible objective functions: weight, reliability, energy storing, and natural frequency. Nelson II et al. (2001) developed a model for designing a helical compression spring of a nail-gun using multi-criteria optimization. Other studies in the field of spring design have also been conducted by Arora (2004), Tudose and Jucan (2007), Tudose et al. (2009), and Nugraha et al. (2011). We found mechanical spring design for orthotics and prosthetics. Kalaidjieva et al. (2009) conducted research to find mechanical spring dimensions for a foot ankle orthotic. The orthotic was designed for people with drop foot, a condition in which the foot cannot move the ankle and toe upfront, which is also known as dorsiflexion. Cherry et al. (2006) designed and manufactured a knee orthotic using a leaf spring. The model was developed using relationship plots between spring deflection and the resulting force. The relationships were then used to derive a curve that could explain the relationship between the torque coefficient and knee swivel angle. Haberman (2008) focused on the analysis of the mechanical properties of dynamical energy in a prosthetic leg and compared several brand and prosthetic leg system in terms of resulting energy.

Gas spring design has also attracted several researchers. Uhrmeister (2000) developed an experimental simulation to design gas springs for landing gear military aircraft. The objective of the research was to reduce vertical acceleration when the aircraft wheel touched the runway. Hasegawa (2002) conducted a study in gas spring design for a linear compressor in air conditioning using an experimental design. Kroll et al. (2011) used a six-sigma method in gas spring design to result in high quality product performance. Rosyidi et al. (2012) developed an optimization model for a transfemoral endoskeletal prosthetic. The objective function of the model is to maximize the energy storage of the gas spring. The research of Rosyidi et al. (2012) considered several constraints, such as gas spring characteristics and maximum allowable force in the deterministic sense. According to Koch et al. (2004), a deterministic model will result in a high-risk solution, since it has a high probability of failing when used. A deterministic model is usually suited to problems with relatively small randomness; when the level of uncertainty is high, stochastic approaches are necessary for system analysis and design (Choi et al., 2007). In gas spring design, the uncertainty may come from the conditions of use, production facilities, and deterioration of design variables due to wear. The design variables may contain variations that will influence the performance of the gas spring. Due to the variations involved, Monte Carlo simulation is one of the most effective and efficient methods to predict the performance of gas springs.

In this research, a deterministic optimization model from the research of Rosyidi et al. (2012) is used to determine the optimal design variables of the gas spring in ESPK. The optimal design variables from the deterministic model will be used as input for the Monte Carlo simulation to determine how the variation of the design variables will influence the performance of the gas spring. The simulation is similar to the work of Rosyidi et al. (2014a) but in a different scenario. We also develop an optimization model using stochastic parameters, which will be compared with the results of the Monte Carlo simulation. The Monte Carlo simulation and stochastic optimization models are developed using Oracle Crystal Ball software.

2. METHODOLOGY

2.1. Energy Storing Prosthetic Knee

ESPK is a sub assembly that is commonly used in endoskeletal prosthetic. An endoskeletal prosthetic is a lower-limb support that consists of an internal pylon usually covered with a lightweight material, such as plastic foam (Medical Dictionary, 2009). Figure 1 shows the ESPK in this research. The figure shows the gas spring in the compression position; h_1 denotes the gas spring compression length, and h_2 denotes the upper adapter length. One of the ESPK advanced designs was performed by Symbiotech, USA. The design, XT9, provides advanced innovations in ESPK. The XT9 ESPK is a hydraulic prosthetic knee that is designed for extreme sports and high levels of activity (McQuail & Reck, 2013). Detailed information about XT9 ESPK by Symbiotech can be seen in symbiotechsusa.com (2006). Ultahar (2011) has developed a simpler design of ESPK (Figure 1). The detailed design specification of the ESPK can be found in Ultahar (2011) and Rosyidi et al. (2012). The ESPK consists of several components with the body frame, gas spring, and upper adapter as the main components. The design has been tested on an amputee and resulted in a more balance gait compared with the normal leg.

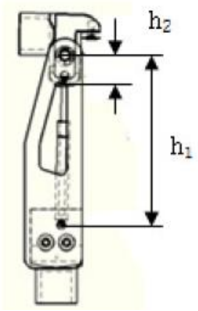


Figure 1 Gas spring in compression position (Ultahar, 2011)

2.2. Deterministic Model

The deterministic model in this research is based on the research of Rosyidi et al. (2012). According to Rosyidi et al. (2014b), the objective function of an optimization model will depend on the existence of the target value of its performance. When the target value is known, the objective function of the model is to attain the target. When the target value is unknown, which can happen for several reasons, the objective function of the model is to minimize the undesired effect or maximize desired effect. Since we do not have any information about the amount of energy needed to flex the knee, the objective function of the model is to maximize the desired effect in which in this research is the energy storage of the gas spring. The energy storage is expressed in Equation 1 (Cortesi, 2003). In the equation, A denotes the area of the cylinder, P is the air pressure, L denotes the length of the cylinder, x denotes piston displacement, and γ represents the ratio of the specific heats of diatomic gas.

$$E(x) = \int_0^x AP\left[\left(\frac{L}{L-x}\right)^{\gamma} - 1\right] dx \tag{1}$$

The constraints of the optimization model in this research are as follows:

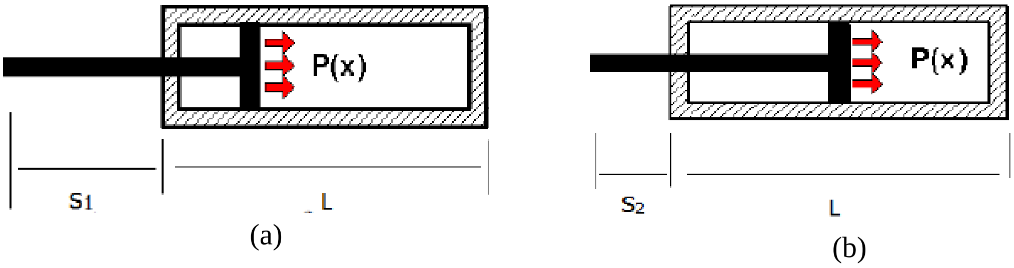
1. Extension length. Extension length is the length of the gas spring while it is attached to the ESPK. The gas spring will form an angle of 17.75° with the vertical axis while it is in the extension position. The extension length will depend on the angle and frame length (h_1). Equation 2 expresses the relationship between the extension length, angle, and frame length.

   $$h_1 = L_E \cos\theta \tag{2}$$

   where h_1, L_E, and θ represent frame length, extension length of the gas spring, and angle between the gas spring and vertical axis respectively.
2. Compression length. Compression length is the length of the gas spring while it is fully compressed in the ESPK. According to Figure 1, the compression length of the gas spring will be determined by frame length (h_1) and upper adapter length (h_2) as shown in Equation 3.

   $$L_C = h_1 - h_2 \tag{3}$$

3. Compression and extension stroke. Figures 2(a) and 2(b) shows the extension and compression stroke of the gas spring, respectively. From those figures, we can find Equations 4 and 5, which express the equations for extension and compression stroke, respectively. In these equations, s_1 and s_2 denote extension stroke and compression stroke, respectively.



(a) (b)

Figure 2 (a) extension stroke, (b) compression stroke

$$L_E = L + s_1 \tag{4}$$
$$L_C = L + s_2 \tag{5}$$

4. Piston displacement. We can use Equations 4 and 5 to determine piston displacement inside the cylinder of gas spring. It can be found by subtracting Equation 4 from Equation 5, which will result in Equation 6.

   $$x = s_1 - s_2 \tag{6}$$

According to Lift Support Technologies (2012), a gas spring is capable of exacting about 60% compression from its total length. This constraint is expressed in Equation 7.

$$x \leq 0{,}6\,L \tag{7}$$

5. Gas spring characteristic. Gas spring characteristic is defined as the ratio of gas spring force at the compressed condition and the force at the extended condition. According to Stabilus (1995), the ratio of the force is between 1.01 and 1.6, as expressed in Equation 8.

$$1.01 \leq r \leq 1.6 \tag{8}$$

The gas spring force equation is expressed in Equation 9.

$$F = AP\left[\left(\frac{L}{L-x}\right)^{\gamma} - 1\right] \tag{9}$$

6. Range of solution space. We consider four design variables in this research: cylinder diameter, cylinder length, extension stroke, and compression stroke. The solution spaces of those variables are expressed in Equations 10, 11, and 12, respectively.

$$D^{min} \leq D \leq D^{max} \tag{10}$$

$$L^{min} \leq L \leq L^{max} \tag{11}$$

$$s^{min} \leq s \leq s^{max} \tag{12}$$

2.3. Monte Carlo Simulation

The Monte Carlo is a type of simulation that relies on repeated random sampling and statistical analysis to compute the results (Raychaudhuri, 2008). There are many differences between Monte Carlo simulation and sensitivity analysis (Bergman, 2009). The most important difference is the information on the needed input variables. Monte Carlo simulation needs the complete statistical distribution of the variables and has to be known or very often guesses in some intuitive ways. The sensitivity analysis only needs the mean and standard deviation of the input variables. Another important difference is in the Monte Carlo simulation, where an approximate distribution of the response is estimated; however, in the sensitivity analysis the statistical distribution is not estimated. The Monte Carlo simulation has become popular in industrial applications because of its simplicity and the effectiveness of the method. In product design, the Monte Carlo simulation is used to predict the variance of response due to the variance of design variables (Delaney & Phelan, 2009). In this research, the prediction is important, since the variance will determine the quality of gas spring’s performance due to the variation of design variables. The variation of design variables is apparent in the real system due to the nature of the production facilities used to manufacture them. Variation in conditions of use, production variations, and deterioration of design variables will propagate through the product and influence the performance.

Figure 3 shows the schematic diagram of the Monte Carlo simulation. It needs a transfer function to convert the input into output. The transfer function in this research is the energy storage of the gas spring shown in Equation 1. In this research, the design variables are assumed to be identical and independent; distribution is normal distribution. Through the transfer function, the input will be converted into output, energy storage in this case, with its mean and standard deviation. From the output of the simulation, we also know the contribution of each design variable to the output. This information is important for the designer so he can focus to the design variables in the large contribution to improve the quality of product performance.

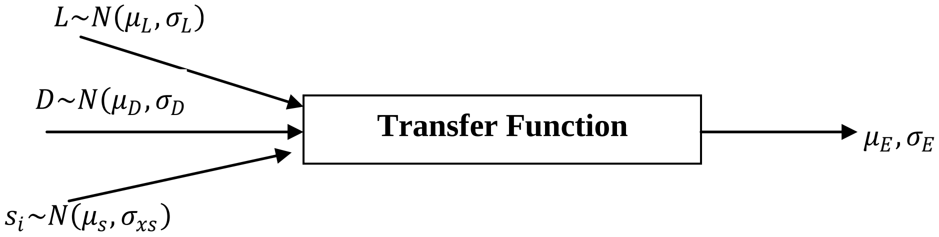


Figure 3 Schematic diagram of the Monte Carlo simulation

2.4. Stochastic Optimization Model

Stochastic model is a model that can consider randomness or uncertainty in the data (Choi et al., 2007). These methods ensure robust designs, insensitive to given uncertainties that provide designer with a guarantee of satisfaction with respect to the objective function, performance constraints, and design variables. In this research, we consider several parameters of the model to be random. Those parameters are body frame length, upper adapter length, and angle between the gas spring and vertical axis. Figure 4 shows the schematic diagram for the stochastic optimization.

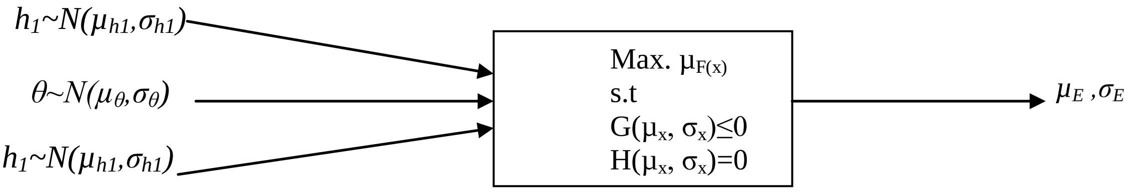


Figure 4 Schematic diagram for stochastic optimization

For the stochastic optimization, the objective function of the model is to maximize the process capability index (Cp). The index is commonly used to measure the capability of a process in producing the desired performance. The capability index can be expressed in Equation 13. The stochastic optimization model in this research can be stated to maximize the process capability index of energy storage subject to all constraints in the deterministic model with several uncertainties in parameters: body frame length, upper adapter length, and angle between the gas spring and vertical axis. Those parameters are assumed to be normally distributed with their respective parameters μ and σ. The optimization model can be formulated, as shown in Equation 14.

$$Cp = \frac{USL-LSL}{6\sigma_{Energy\ storage}} \tag{13}$$

$$\begin{gathered}\text{Max } Cp\\ \text{s.t. Equation (2)–(12)}\end{gathered} \tag{14}$$

$$\begin{aligned}\text{where } & h_1 \sim N(\mu_{h1},\sigma_{h1})\\ & \theta\sim N(\mu_\theta,\sigma_\theta)\\ & h_2 \sim N(\mu_{h2},\sigma_{h2})\end{aligned}$$

3. RESULTS AND DISCUSSION

3.1. Deterministic Model and Monte Carlo Simulation

The parameters in Table 1 are used for deterministic optimization (Rosyidi et al., 2012). The optimal design variables are shown in Table 2. Here, we can see that the optimal cylinder diameter, cylinder length, extension stroke, and compression stroke are 13.10 mm, 105 mm, 63 mm, and 35 mm, respectively. The piston displacement is 28 mm, which results in energy of 899.85 Joules.

Table 1 Parameters for a deterministic model

Parameters	Notations	Value	Units	Sources
Extension length	L_E	168	mm	Ultahar (2011)
Compression length	L_C	140	mm	Ultahar (2011)
Cylinder length	L^{min}	32	mm	Dictator (2012)
	L^{max}	110	mm	Dictator (2012)
Extension stroke	s_1^{min}	0.6 L	mm	Lift Support Technologies (2012)
	s_1^{max}	100	mm	Dictator (2012)
Compression stroke	s_2^{min}	10	mm	Dictator (2012)
	s_2^{max}	100	mm	Dictator (2012)
Cylinder diameter	D^{min}	10	mm	Dictator (2012)
	D^{max}	35	mm	Ultahar (2011)
Gas spring	r^{min}	1.01	-	Stabilus (1995)
characteristic	r^{max}	1.60	-	Stabilus (1995)
Force	F^{min}	10	N	Dictator (2012)
	F^{max}	100	N	Dictator (2012)

Table 2 Results of optimization

Design Variables	Notations	Optimal Value
Cylinder diameter	D	13.10 mm
Cylinder length	L	105 mm
Extension stroke	s_1	63 mm
Compression stroke	s_2	35 mm

The results of deterministic optimization are then used as inputs for the Monte Carlo simulation. We use Oracle Crystal Ball software to predict the effect of uncertainty of the design variables on the energy storage of the gas spring. The design variables contain variations in their dimensions, and those variations will propagate to the performance of the gas spring. In this research, we assume that the design variables have independent identical normal distribution; the parameters of the distribution are shown in Table 3. The need for improvement in the design variables will depend on the results of simulation. We used the Cp as the criteria to make a decision on whether improvement is needed or not. The Cp of a performance is regarded as acceptable if it has a minimum value of 1. The specification of the gas spring's energy storage is set at 899.85 J for the target value with lower and upper specification limits at 848.71 J and 922.03 J, respectively.

Table 3 Distribution parameters for simulation

Design Variables	Mean	Standard Deviation
Cylinder length	105	0.15
Cylinder diameter	13.10	0.15
Extension stroke	63	0.10
Compression stroke	35	0.10

The simulation was performed in 10,000 trials using Oracle Crystal Ball software. The simulation resulted in energy storage mean and standard deviations of 885.37 J and 12.22 J, respectively. This means that the introduction of variations into the design variables resulted in a difference of energy storage by 44.48 J or almost 5% compared with the deterministic model. The Cp of the gas spring performance from the simulation is 0.99, which is under the minimum requirement of an acceptable level. The gas spring performance must be improved to an acceptable level. The first thing that must be decided is to shift the target of energy storage to 885.37 J and reduce the standard deviation of the design variables to increase the process capability. We used the contribution to variance to decide which design variables must be improved, and then we performed the second simulation. Table 4 shows the contribution to the variance of each design variable. From the table, we know that compression stroke, extension stroke, and cylinder diameter explained 99.2% of the performance variance. Due to limited resources, it was decided that both the standard deviations of the compression stroke and the extension stroke were reduced to 0.05 mm.

Table 4 Contribution to variance

Design Variables	Contribution to Variance
Compression stroke	35.6%
Extension stroke	33.9%
Cylinder diameter	29.7%
Cylinder length	0.8%

The second simulation resulted in mean energy storage of 885.29 J and a standard deviation of 8.47 J. These results are better than the first simulation results. The reduction of the compression stroke and extension stroke standard deviations resulted in a 30% improvement in the energy storage standard deviation. The Cp was also improved by about 70%, from 0.99 to 1.44.

3.2. Stochastic Optimization

In this research, stochastic optimization is developed using Oracle Crystal Ball software. The stochastic model is characterized by the stochastic parameters as seen in Table 5. The table shows that three stochastic parameters are used in the model: body frame length, angle between gas spring and vertical axis, and upper adapter length. Those parameters are assumed to be normally distributed with the same standard deviation. The optimization was performed in 500 runs with the objective function to maximize the process capability of the energy storage. Table 6 shows the comparison of the design variables resulting from stochastic optimization, existing design variables, and the optimal design variables from deterministic optimization. From the table, we can see that the stochastic optimization resulted in a longer cylinder length and smaller cylinder diameter than the existing design and deterministic optimization. The extension stroke and compression stroke are shorter than the existing design and deterministic optimization. The displacement resulting from stochastic optimization is longer than the existing design and deterministic optimization. The displacement of the piston from stochastic optimization is 36.02 mm compared to 19.9 mm and 33.12 mm of the existing design and deterministic optimization, respectively. The displacement from the stochastic optimization results in energy storage mean and standard deviation of 883.39 J and 7.88 J, respectively. The stochastic optimization resulted in process capability index of 1.55, which is higher than that of the Monte Carlo simulation. This paper has two main practical limitations. First, the optimal design variables may not be implemented in the ESPK design because the design variables result from the maximization of energy storage. This limitation can be alleviated if there is information about the required energy for flexion and extension of the knee. Second, the model is static, while the ESPK system will be used in a dynamic environment. Hence, the dynamic aspects in the ESPK design must be considered.

Table 5 Parameters for stochastic optimization

Parameters	**Mean**	**Standard Deviation**
Body frame length	160.00 mm	0.10
Gas spring angle	17.75 deg	0.10
Upper adapter length	28.00 mm	0.10

Table 6 Comparison of optimization results

Design Variables	**Optimal Value**	**Existing Design**	**Deterministic Model**
Cylinder length	110.00 mm	118.10 mm	105.00 mm
Cylinder diameter	10.00 mm	15.10 mm	13.10 mm
Extension stroke	58.20 mm	71.70 mm	63.00 mm
Compression stroke	22.18 mm	51.80 mm	47.32 mm

4. CONCLUSION

In this research, the optimization and improvement of gas spring design in an energy storing prosthetic knee is discussed. A Monte Carlo simulation is developed to study the effect of the variation of design variables to the gas spring energy storage. The results of the simulation show that the energy storage target value shifted and the process capability of the energy storage was under an acceptable value. Improvement must be made by reducing the standard deviation of the design variables with the largest contribution to performance variance. The second simulation resulted in a significant improvement; the energy storage standard deviation was reduced by 30%, and the Cp was improved by about 70%. In this research, stochastic optimization was also developed by assumed that several parameters were normally distributed. The objective function of the optimization was to maximize the process capability index of energy storage. The optimization resulted in a process capability index of 1.55, which is higher than that of the Monte Carlo simulation. In the next research, the model can be extended to consider the dynamic characteristics of the gas spring design, which will provide more realistic and practical results.

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