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A mechanism synthesis and modeling for correction of hip dysplasia in medium and large dog breeds

Síntesis y modelado de un mecanismo para corrección de displasia de cadera en perros de raza mediana y grande

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Abstract

Hip dysplasia is an incurable but treatable disease that affects medium and large dog breeds. It appears as a result of genetic disorders, overweight, among other causes. Currently, there are no specialized mechanisms that provide comfort to the life of these pets, while adapting to the canine condition and promoting the use of their hind legs until mobility is completely lost. Therefore, in the present study, a versatile device was synthesized and modeled to help to improve the life quality of dogs, taking as a reference the "German Shepherd" breed. It was designed considering the health and welfare of these animals, taking into account the mobility and safety of their limbs. This device uses a linkage mechanism to provide structural support to the dogs, while allowing for mobility within an specified range of motion. It aims to incorporate a gear and spring system that controls the weight lifted by the device, so that dogs partially use their hind legs. The static and dynamic behavior of this mechanism were mathematically modeled, finding an optimal solution.

Keywords: biomechanics; mechanism synthesis; optimization; prosthesis for dogs; hip dysplasia.

Resumen

La displasia de cadera es una enfermedad incurable pero tratable que afecta a razas de perros medianas y grandes. Esta aparece como resultado de trastornos genéticos, sobrepeso, entre otras causas. Actualmente, no existen mecanismos especializados que brinden comodidad a la vida de estas mascotas; además, se suele promover el uso de sus patas traseras hasta que se pierda por completo la movilidad. Por lo tanto, en el presente estudio se sintetizó y modeló un dispositivo versátil para ayudar a mejorar la calidad de vida de los perros, tomando como referencia la raza "Pastor Alemán". Fue diseñado teniendo en cuenta la salud y el bienestar de estos animales, considerando la movilidad y la seguridad de sus extremidades. Este dispositivo utiliza un mecanismo de eslabones para proporcionar soporte estructural a los perros, al tiempo que permite la movilidad dentro de un rango específico. También se proyecta una posible incorporación de un sistema de engranaje y resorte que controla el peso levantado por el dispositivo, para que los perros utilicen parcialmente sus patas traseras. El comportamiento estático y dinámico de este mecanismo fue modelado matemáticamente, y se encontró una solución óptima.

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Palabras clave: biomecánica; síntesis de mecanismo; optimización; prótesis para perros; displasia de cadera.

1. Introduction

Hip dysplasia is a genetic disease that causes progressive separation of the head of the femur from the hip before completely dislocating (Figure 1). The British Veterinary Association (BVA) [1] recognizes that the most affected breeds are German Shepherd, Labrador Retriever, Golden Retriever, Rottweiler, Bernese Mountain and Newfoundland. According to the Colombian Canine Club Association (ACCC) [2], 12% of the canine population tends to suffer from this disease. However, no adequate control is developed to prevent the accelerated progression of the disease, which causes many animals to be exposed to surgeries and completely lose the mobility of their hind limbs. This is due to the lack of knowledge in the macro-scale epidemiology of the disease, which prevents the development of veterinary tools that mitigate the evolution of this disease, physiologically. As a result, products are built without an engineering design process that ensures the life quality of the canine.

Figure 1. X-ray of the hip of a dog with hip dysplasia.

The anatomy, the musculoskeletal system, the disease of hip dysplasia, its symptoms and its treatments (conservative, medical and surgical) were investigated to mark a starting point in the development of the mechanism presented in this paper [3]. Likewise, several media models, offered by various companies around the world, were consulted and studied. An analysis of these models revealed that no machine meets the criteria of functionality, maintainability, ergonomics, and cost, which are the pillars of this research. Some machines were economical, but of low quality and others very capable of helping the canine, but at a high price.

Therefore, the functioning of a hip dysplasia corrector was modeled to ensure the health, safety and quality of life of animals, especially the German shepherd breed, taken as the reference breed for the design of the device. Similarly, by following a design methodology it is possible to configure certain parameters in order to obtain the most economical and efficient version possible. Moreover, knowledge contribution is offered to our society in terms of an innovative mechanism that can be adapted to different dog breeds suffering from the same disease.

2. Methodology

2.1. Conceptual design

Understanding the need addressed and taking into account the objective with its respective restrictions: a height of 50 cm and weight of 32 kilograms, certain possible solutions were devised. These are a summary of the system requirements, which are described in the first part of this subsection.

2.1.1. System requirements

Thinking about the greatest benefit for dogs and the society, the mechanism needs to be:

- Safe
- Comfortable
- Easy driven
- Long-lasting
- Lightweight
- Excellent quality
- Easy maintenance
- Low price
- Aesthetic

2.1.2. Design alternatives

Four solutions that aimed to meet the greatest number of requirements were devised through engineering sketches. To choose the most optimal one, a matrix of quality function was performed, and a support mechanism was selected, so that it provides and adjusts the stability of the animal, following the movements of the rear parts, respecting the degrees of freedom in the limbs, and supporting the hip.

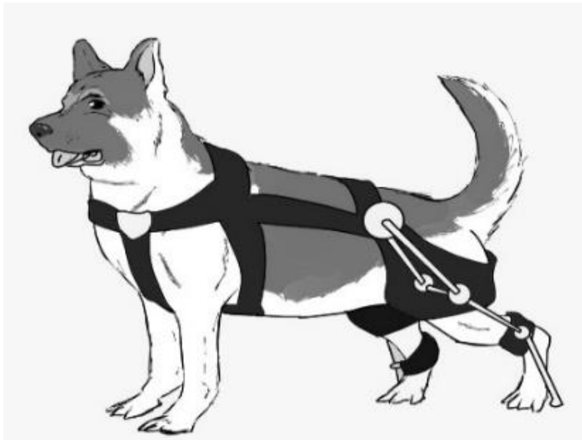

Figure 2. Conceptual Design of Mechanism. Source: Self-made.

2.1.3. Description of the chosen solution

Based on the selected solution, some modifications were made to meet all the requirements. These modifications were made, incorporating some advantages that the other solutions offered.

In the base design, the upper part of the support, consisted of three links, which would not allow the dog to sit easily. Therefore, it was decided to place a fourth link that introduces an extra degree of freedom. The mechanism is a model based on the Grashof condition case III [4], where the longest link is fixed and the shortest one is rotated according to the degrees of freedom of the other two links.

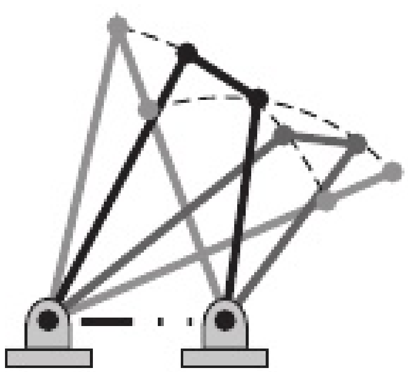

Figure 3. Grashof case III, applied to the system. Source: A. Arosemena. Introduction to mechanisms and kinematics

Likewise, it was decided to have a wheel support system, because in certain pathologies or degrees of disease the animals have already completely lost the mobility of their hind legs, and these wheels can help them move without difficulties.

Finally, it was chosen to place a small piston between nodes B and C so that the animal had extra help, through a damping system [5], when it needs to recover from its sitting position. This design was synthesized so that this piston worked under tension when the dog is standing, and under compression when it wants to sit down.

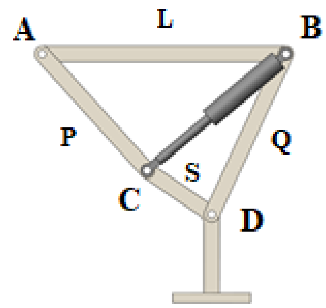

Figure 4. General framework. Source: self-made.

2.1.4. CAD

To verify that this design does behave according to the expected movement of the dog, a parametrized model was developed in SolidWorks [6]. In the synthesis of the mechanism, an initial position (active canine) and final position (resting canine) were established, with which the ranges of motion that may occur were established. Knowing this, the design began as an iterative process in search of an optimal structure. In the absence of calculated measures, a prototype with coherent values was designed and a study of motion or animated simulation was conducted to demonstrate its conceptual functionality.

2.2. Synthesis and modeling

2.2.1. Kinematics analysis

Initially, a kinematic analysis was performed in order to determine the original position of the links based on the natural movement of the animal. It allows to relate the angles of the forces with those of the positions of the links, following the kinematic equations (equations 1 and 2), where θ_3 and θ_4 are the angles of links P and S with respect to direction of link L. It is important to note that in equations 1 and 2, the kinematic solution is forced to find the open position of the mechanism throughout its range of motion, thus avoiding any kind of interference with a cross solution.

$$\theta_3 = 2tan^{-1}\left(\frac{-E-\sqrt{E^2-4DF}}{2D}\right) \quad (1)$$

$$\theta_4 = 2tan^{-1}\left(\frac{-B-\sqrt{B^2-4AC}}{2A}\right) \quad (2)$$

$where:$

$A = \cos(\theta_2) - K_1 - K_2\cos(\theta_2) + K_3$

$B = -2\sin(\theta_2)$

$C = K_1 - (K_2+1)\cos(\theta_2) + K_3$

$D = \cos(\theta_2) - K_1 + K_4\cos(\theta_2) + K_5$

$E = -2\sin(\theta_2)$

$F = K_1 - (K_4-1)\cos(\theta_2) + K_5$

$K_1 = \frac{L}{Q}$

$K_2 = \frac{L}{P}$

$K_3 = \frac{Q^2-S^2+P^2+L^2}{2QP}$

$K_4 = \frac{L}{S}$

$K_5 = \frac{P^2-L^2+Q^2+S^2}{2QS}$

The parameters given for the determination of the angles are taken by conducting a vector analysis of the Grashof mechanism. These follow this behavior as long as the length of L plus S is less than the length of P plus Q. Having the kinematic angles identified, the geometric relationships between these angles and the angles of the forces (figure 5) are stablished through equations 3, 4, 5 and 6.

$$\propto = 180 - \theta - \theta_4 \quad (3)$$

$$\beta = 360 - \theta - \theta_3 \quad (4)$$

$$\gamma = \theta + \theta_2 \quad (5)$$

$$\varphi = tan^{-1}\left(\frac{Qsin(\gamma) - Ssin(\beta)}{Qcos(\gamma) + Scos(\beta)}\right) \quad (6)$$

2.2.2. Static analysis

The forces acting on the mechanism were determined by Newton's second law. However, it should be considered that the mechanism is not a regular truss, since the elements L and S are not two-force elements, due to the fact that the dog's weight and the damping system reaction are not applied in the link nodes.

Figures 6 and 7 summarize the FBD's of the mechanism. It should be noted that the difference between these figures lies on the presence of the reaction force R3 that only appears when the dog is recovering from its sitting position and its due to the contact between its butt and the ground.

The equations used are elaborated from the FBD of the elements that are not two-force members and the general FBD of the entire mechanism. This is stated in equations 8 to 14.

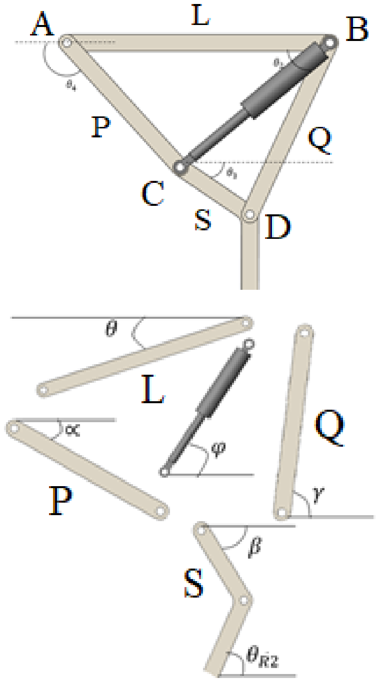

Figure 5. Angles of the mechanism. Source: self-made.

$General\ Analysis:$

$$\sum F_y = R_1 + R_2 - W = 0 \quad (7)$$

$$\sum M_A = R_2\big(Pcos(\alpha) + Scos(\beta)\big) - W\frac{L}{2}\cos(\theta) = 0 \quad (8)$$

$Analysis\ of\ Link\ L:$

$$\sum F_x = F_P\cos(\propto) - R_S\cos(\varphi) + F_Q\cos(\gamma) = 0 \quad (9)$$

$$\sum F_Y = R_1 + F_P\sin(\propto) + F_Q\sin(\gamma) - R_S\sin(\varphi) = 0 \quad (10)$$

$$\sum M_B = F_P\cos(\propto)\,Lsin(\theta) - F_P\sin(\propto)\,Lcos(\theta) + W\frac{L}{2}\cos(\theta) - R_1Lcos(\theta) = 0 \quad (11)$$

$Analysis\ of\ Link\ S:$

$$\sum F_x = R_S\cos(\varphi) + F_Q\cos(\gamma) - F_P\cos(\propto) = 0 \quad (12)$$

$$\sum F_Y = R_2 - F_P\sin(\propto) - F_Q\sin(\gamma) + R_S\sin(\varphi) = 0 \quad (13)$$

$$\sum M_C = F_Q\cos(\gamma)\,Ssin(\beta) - F_Q\sin(\gamma)\,Scos(\beta) + R_2S\cos(\beta) = 0 \quad (14)$$

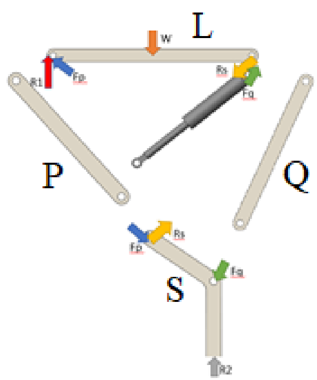

Figure 6. FBD of the mechanism in a standing animal position. Source: self-made.

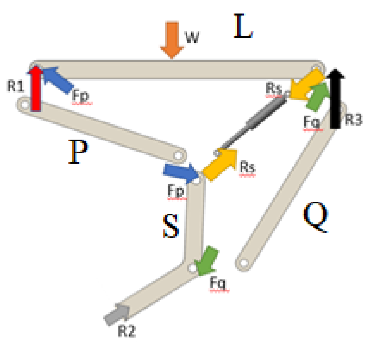

Figure 7. FBD of the mechanism in a lying animal position. Source: self-made.

2.2.3. Optimization

An optimization code was developed by using MATLAB (Mathworks Inc,, Natick, Massachusetts), to evaluate the different possibilities of link lengths and positions, considering the respective static equations (subsection 2.2.2) and some movement restrictions and parameters [7]. This is reflected in Figure 8, where the logical processes performed are described, with the objective of obtaining a uniform distribution of the loads in the four links, so that there is no prevalence in the critical area of the links. Thus, a variable that accumulates the difference between the magnitudes of the axial forces is defined. This indicator allows us to find the best configuration, considering other design options that share the continuity required for the mechanism.

2.2.4. Force Study according to Link Position

Since the linkage mechanism moves during its operating condition, the magnitude of forces experienced by each link changes accordingly [9]. Therefore, a code was programmed in MATLAB (Mathworks Inc,, Natick, Massachusetts), which considers the previous equations described, to find the magnitude of the forces according to the angle between links L and Q. This angle is considered as the input for the system, and when the dog is standing this angle is 65 ° and when lying it is 35°.

3. Result and mechanism description

The results obtained from the mathematical modeling and optimization process are presented below. Through the optimization process, 10 optimal solutions were found that satisfy the requirements of the mechanism. It should be noted that the "best" solution is dictated by a minimum value of the residual variable, indicating the most uniform distribution of forces possible. This is reflected in Table 1, which shows the vector of lengths that meet the conditions of the system along with the representative angles of the Grashof linkage, and the residual value mentioned above as the difference between the resulting axial forces in each link.

Table 1. Optimization results

Configuration No.	Lengths [S,L,P,Q] [mm]	Theta [°]	Theta_2 [°]	Residual Value [N]
1	[50,250,150,160]	0	50	3100
2	[60,250,150,170]	0	55	2426
3	[70,250,160,170]	0	60	2340
4	[70,250,160,180]	0	60	2289
5	[80,250,160,180]	0	65	2073
6	[70,250,170,180]	0	65	2072
7	[90,250,170,180]	0	70	1952
8	[100,250,180,190]	0	75	1855
9	[110,250,180,190]	0	80	1756
10	[120,250,190,200]	0	85	1695

Source: MATLAB (Mathworks Inc,, Natick, Massachusetts).

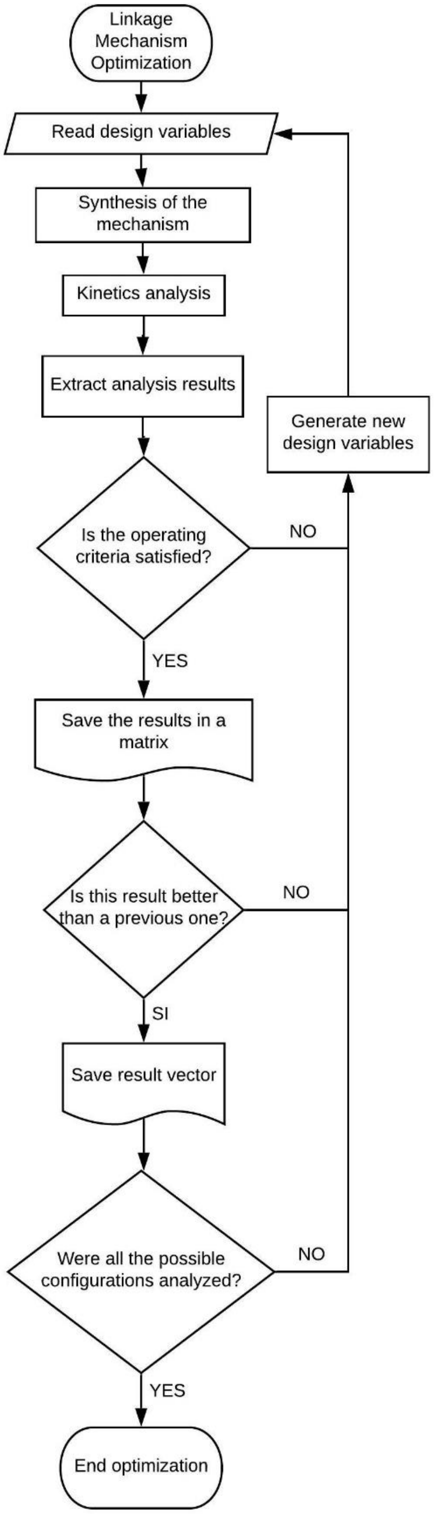

Figure 8. Optimization code flow diagram. Source: self-made.

From these optimal solutions, the mechanism highlighted in Table 1 was chosen as the best solution. Although its residual value is not the lowest, this configuration has a distribution of forces close to the minimum, and based on the linkage configuration, it facilitates the design and manufacturing of the rest of the mechanism due to its geometry. It should be noted that the uniform distribution of axial forces is the primary metric used to guide the selection of the optimal mechanism, but the final decision is made upon the construction feasibility of the entire mechanism geometry. Below are the fundamental parameters that describe the selected mechanism.

Table 2. Length of the links of the best solution

Link	Length [mm]
L	250
S	80
P	160
Q	180

Source: self-made.

Tables 2 and 3 show the lengths of the links the angles that they form with respect to each other when the linkage mechanism behaves as a structure (dog in its standing position). Table 4 shows the axial forces experienced by each of the links when the dog is in its standing position. Moreover, Figure 9 displays the forces on the linkage mechanism when the dog is transitioning from a standing to a lying position.

Table 3. Angles found from the Kinematics Analysis

Links	Angle [°]
LQ	65,00
QS	39,75
SP	33,98
PL	47,75

Source: self-made.

Table 4. Axial Forces of the Links

Link	Axial Force [N]
L_AW	-31,18
L_WB	31,18
P	46,37
Q	-94,70
R	11,50
S_CD	-48,26
S_DE	112,80

Source: self-made.

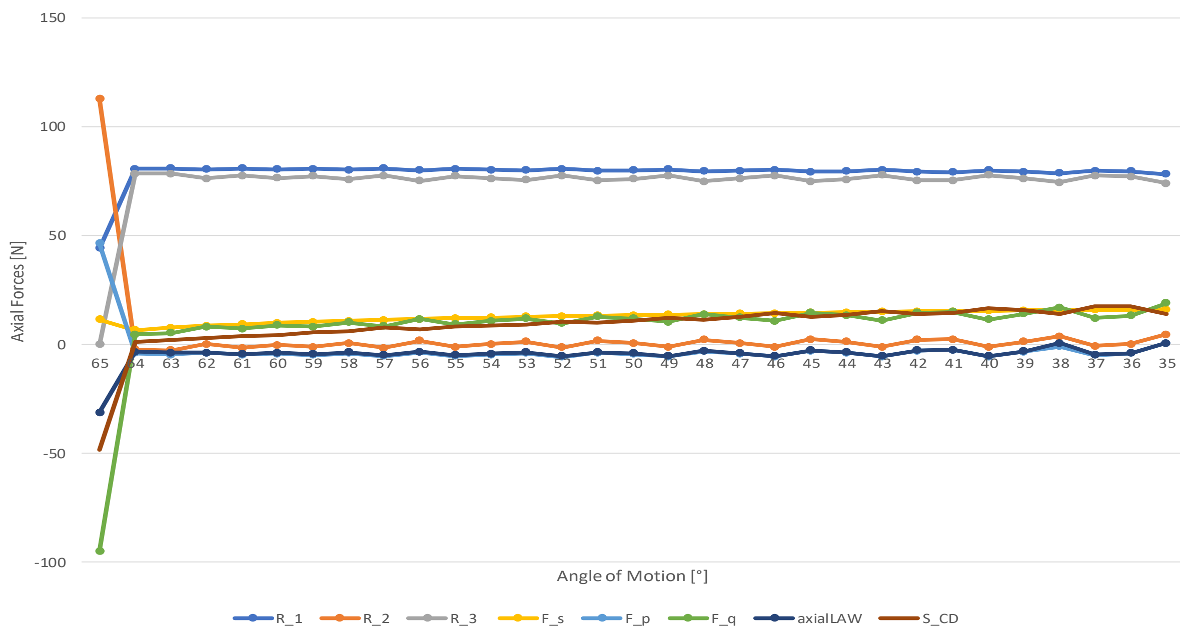

Figure 9. Axial Forces on the Links for the Range of Motion of the Linkage Mechanism. Source: Self-made.

It should be noted that the axial loads in Table 4 correspond to loads in the appropriate sections of the elements L and S, since these are divided by a transverse force that distributes the axial loads according to the direction being analyzed. For instance, the load L_AW consists of the axial force in L from node A to the point of action of load W.

Starting from the static solution of the mechanism, its movement was analyzed from its initial position to its final one. The element Q, which directs the movement due to the displacement of the dog's hip, moves from 65° to 35°, where the mechanism is in its folded position (dog lying down). Figure 9 shows the transition from the equilibrium position of the mechanism to a continuous rotation until equilibrium is reached again in its horizontal position. As evidenced, once the dog starts sitting most of the forces on the links remain constant due to the effect of the damping system induced by the presence of the spring in the fifth link or piston.

The mechanism obtained in this study successfully satisfies the system requirements stated in section 2.1.1. It is safe and easy to operate by the dog since it constantly accommodates to the position of the dog and helps when recovery from a sitting position is necessary. Due to its folding synthesis, this linkage mechanism is comfortable in the sense that it does not interfere with any range of motion expected from the dog. The analytical results of the optimal mechanism lead to a design that supports loads evenly distributed, therefore allowing a lightweight and low-price design and manufacture. The use of a single shear configuration for the link joints is suitable for this application since no excessive loads are expected during operating conditions, which adds the benefit of easy maintenance. The combination of these achievements fulfills the objective of modeling and synthesizing an excellent quality mechanism that outstands from the current available device in the market [9].

4. Conclusions

- The design was made considering a theoretical and contextual framework in which a linkage mechanism was created for medium and large dog breeds with hip dysplasia, so that more people had access to this solution to help the animals, as well as providing veterinarians with a new, more effective, and economical medical alternative.

- Bringing the design to the construction and its proper use will offer benefits for both humans and animals, since the former can help your pet and interact with it, while the later will already have a support for your hip that improves its health and comfort.

- The solution based on a Grashof linkage, instead of a three-links truss, proves to be more stable and to allow the required degrees of freedom in transitioning from a standing to a sitting position of the dog.

- The modeling, synthesis, and optimization of the mechanism developed in this study satisfied the requirements of section 2.1.1. It is expected to impact future work in mechanical devices that address hip diseases in dogs. An example being the current studies that aim to treat the Lumbosacral Transitional Vertebrae (LTV) [10].

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