Biomechanical Analysis of Canine Hind Limb: Mathematical Model and Simulation of Torques in Joints

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***Abstract*—The study and analysis of biomechanics and canine locomotion has been focused mainly on the field of veterinary medicine. For specialists, it is pertinent to obtain the necessary information that will help the recognition and treatment of diseases and/or physical traumas that generate motor deficiencies in the limbs of animals. Currently, the combination of the knowledge of veterinary medicine with the development of technology have taken a giant step in the development of new surgical procedures; however, we can not speak of a specific improvement in terms of automated post-operative processes like rehabilitation. In this paper an analysis is described that relates the kinetics and the kinematics of the movement of the canine hind limb from a veterinary point of view until it is translated into an engineering language that allows to process and analyze data through software and obtain results that are applicable in the rehabilitation of physical injuries. Results while comparing mathematical with simulation behavior provided a considerable error of 13% for the ankle and 28% for knee, in terms of torque analyzes. Simulation generated a virtual model which takes into account external variables into the simulation environment not considered in the mathematical model; generating an even more realistic representation and modeling of the functioning of hind limb.**

***Index Terms*—kinetics, kinematics, biomechanics, canine, dog, hind limb**

I. INTRODUCTION

Several specialists have developed over the years a series of studies for the analysis of canine locomotion, which provide standardized information on kinetics and kinematics for dogs of different breeds and sizes.

There are studies that have focused on the measurement of the acting forces in dogs of agility or competition in order to measure the efforts to which they are undergone, to keep track of the health of their limbs and to perform preventive treatments; however, these results differ according to the breed and the conditions of the experiment. Other studies of canine locomotion have been devoted to the study of the muscular forces on limbs, comparing the muscle-tendon systems with a physical mass-spring system so that acceleration and deceleration studies in the change of position could be calculated [1], also studies have been done while performing a static analysis for a calculation of muscle forces in three dimensions based on body weight [2], and similarly, there are studies that focus only on the analysis of the step during walking, jumping, trotting or galloping; all of them in order to describe the kinematics and postural changes of the joints during the walking cycle.

All these results are useful for the application of clinical diagnoses, surgical corrections and rehabilitation therapies; however, there are no big plans for the application of technologies or the automation of these processes that are mostly manual. This problem is also reflected in the lack of technical information provided by these studies.

Movement Studies are commonly applied in the rehabilitation of injuries, but the efficiency of the application of them is not measurable due to the processes are performed manually, without sensors or controls which allow monitoring. The manual processes in many cases allow the physiotherapist to recognize and locate pain on the animal by the opposition to the movement that it makes during the therapy. Even though there are treatments that are extremely repetitive, they would improve if the force and speed of movements remain constant; therefore it is necessary to implement a correct engineering data management. Currently there is a growth of interest in the application of technology for the rehabilitation of pets, because families invest more in their health and recovery.

In the present study, standardized information from different investigations is used to link calculations and information that is important in the technical analysis. The research could lead to improve the life quality ofpets and find a way to help veterinary medicine to implement automated processes that facilitate professionals to give a quick recovery to their patients.

II. METHODOLOGY

Kinesiology is the science that is responsible for the study of movement of dogs. Its development has focused on the kinematics that describes the movement without taking into consideration the masses or acting forces, and the kinetics that is the study of the relation of the movement with respect to the forces that generates it [3], [4]. In this study, we have combined these two analyzes

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to be able to fully describe the canine gaits and achieve three-dimensional dynamic characteristics correlated with the reaction forces to the ground [4], [5].

Force Plates Studies and Computer-Assisted Analysis have become the most productive tools for kinetics and kinematics investigations, in veterinary and medical professions, respectively. The proper use of these tools provides several advantages over clinical assessment [3].

A. Kinetic Analysis

There are factors that affect the generation of forces, such as: speed, length of stay and Body Weight (BW) [3], [4], [6]-[8], which is why several studies carried out under similar conditions were considered for this analysis.

The Ground Reaction Forces (GRF) generated by the dog in the movement are measured in three orthogonal components: vertical force (Fz), cranial-caudal force (Fy) and medium-lateral force (Fx), being Fz the largest, Fy smaller in magnitude than Fz [4], and Fx is considered negligible for the analysis [9]. These magnitudes depend on the contact time of the leg with the ground and the speed with which the experiment is performed [3]. As the speed increases, the contact time of the foot with the ground will decrease [10]; therefore, the vertical force increases [11].While walking, vertical forces are low during the first steps until reaching the speed of trot or gallop [11]. To obtain the maximum forces generated by the dog it is necessary to make an analysis during the trot.

The clinical assessment of dogs is usually carried out by means of a test with Force Plates placed on a path, which provide the magnitudes of the acting forces for each limb [12]. By making a comparison of results between pairs of forelimbs or hind limbs it is possible to identify if a limb is affected [13]. The evaluation conditions of other studies are adjusted to specific objectives, so a greater problem is identified for this analysis as no regulated conditions for the evaluation in the Force Plates are considered. Therefore, studies with similar characteristics that allow obtaining standardized results of the forces necessary for a complete analysis have been taken as reference.

A clinical study carried out previously [8], establishes that normalization is necessary to measure the ground reaction force during the trot without it being affected by the assessment conditions. For this reason, it is considered that the GRF is closely related to the body mass of the dog [8], [9] at an absolute speed rate adjusted for each test subject. By means of a regression analysis, results were obtained for the anterior and posterior limbs of the Peak Vertical Force (PVF) as a function of BW [8].

In another study, the muscle strength generated by the hind limb is taken into account to perform a static analysis of the forces involved in the knee and hip joints, considering a three-dimensional model of the musculature and obtaining some real results from the forces and moments [2].

It is necessary to take into account that all the aforementioned analysis was performed on dogs that did not have motor deficiencies in their limbs. When there is an injury, the values of the acting forces and the ranges of movement of the affected members will be reduced.

B. Kinematic Analysis

The step or canine march is the change of position of the limbs, characterized by their coordinated and repetitive movements [3]. With specialized equipment such as strobe cameras, high frequency video recorders, electro-goniometry equipment, among others; you can obtain data such as: speed of movement, frequency and length of the step, angles (flexion and extension) and angular velocities of the joints during movement [4], [5]. The goal is to obtain accurate information on the progress of joint movement. The range of motion (ROM) is the complete displacement that a joint can have in flexion and extension, used to verify that the movement of the joint is normal [14]. Muscles and joints should move periodically through their available ranges to maintain ROM [13].

For reasons of analysis, for this study is important the stance phase of the walking cycle, which is defined as the period of time since the foot makes contact with the ground until the last moment before entering the swing phase [3], [15]. In addition, the protraction and retraction angles present in the braking, landing, propulsion and take-off stages are taken into account [16]. As for the kinetic analysis, those studies carried out during the trotting of the dog were considered, and under similar assessment conditions.

The combination of kinetics (evaluation of the forces that generate movement) and kinematics (description of movement) is possible when data are measured simultaneously, resulting in a more complete analysis of the canine march [5]. For this analysis, data from both combined analyzes have been used [11], kinetic [9], [17] and kinematic [1], [18], in order to complement information on the analysis and verification of results.

III. Analysis and Design

Little information is provided about the angles of the canine limbs to the ground; however, Barclay [16] defines in his article the angles of protraction and retraction in the walk of three quadrupeds, among them dogs, in addition to the weight that supports the limb at that moment. Based on this work, we have taken the values of the angles to the ground to be able to make a more detailed diagram of the hind limb in different positions and for different percentages of weight applied at that moment.

The horizontal component Fg_y or cranial-caudal component of the GRF changes from decelerator to accelerator at approximately 50% of the contact phase during the trot [9], which is also the moment in which the maximum vertical effort is given; consequently the sign is negative for the moments before the maximum effort and positive after it for the calculations [11], [16]. This change is because quadruped dogs have more time to reposition their limbs, which causes a limb to start applying propulsion forces while it is still holding [11]. For the calculation of the horizontal component (cranial-caudal force) a relationship between the vertical and horizontal forces of several studies made on Force Plates has been obtained and presented below on Table I.

TABLE I. RELATIONSHIP BETWEEN THE GROUND REACTION CRANIAL-CAUDAL AND VERTICAL FORCE

Z Force (PVF)	Y Force (Cranial-Caudal)	Relationship Fy / Fz
70	13	0.19
1.64	0.46	0.28
110	20	0.18
55	8	0.15
75	13	0.17
24	3	0.13
39	11	0.28
32	7	0.22
Mean		0.199

Data obtained from: [3], [11], [13], [17]

The result of this relationship is an estimated coefficient of:

$$u_d = 0.199$$

To work with dogs with a weight between 20kg and 30kg, it has been decided to base this study on the maximum force function during the trot. The patient is a 13-year-old crossbreed dog and his data is:

Metatarsal length:

$$L_m = 0.190\ m$$

Tibia length:

$$L_{tp} = 0.230\ m$$

Leglength:

$$L_p = 0.240\ m$$

Weigth:

$$BW = 26.3\ Kg$$

The forces that act on the knee during walking are: body weight, the forces generated by the muscle groups, and the reaction forces of the ground [19]. The reference planes defined for the study are presented on Fig. 1.

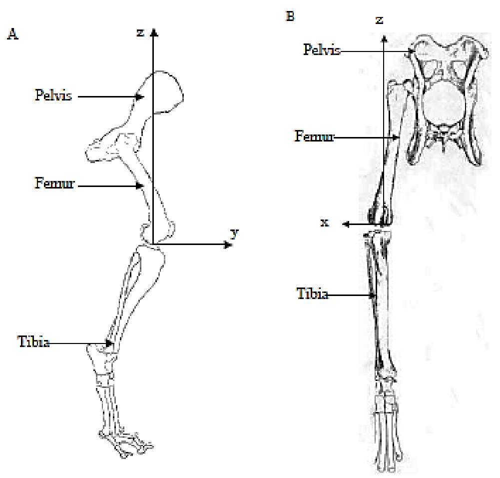

Figure 1. Schematic representation of the coordinate system of de hind limb with side view (A) and anterior view (B) [2]

The calculation of the maximum force generated during the trot is obtained from a normalized study [8].

$$Fg_z = 6.49 * BW + 20.2 \tag{1}$$

$$Fg_z = 190.89\ [N]$$

In addition, GRF uses the value obtained from formula (1) and with the coefficient u_d obtained previously and applied on (2).

$$Fg_y = u_d * Fg_z \tag{2}$$

$$Fg_y = 37.99\ [N]$$

where the resultant force will be:

$$F_g = \sqrt{{Fg_z}^2 + {Fg_y}^2} \tag{3}$$

$$F_g = 194.63\ [N]$$

Maximum reaction force of the dog is a known data (Fg_y).

The free-body diagram shown on Fig. 2 can be used to estimate the muscular forces acting on the movement of the limb.

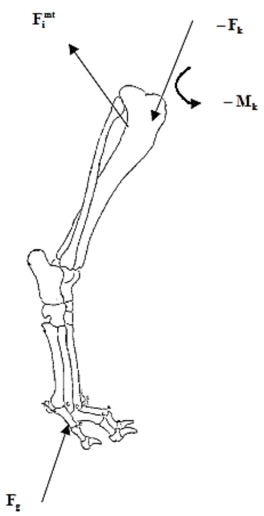

Figure 2. Free body diagram of the tibia [2].

Equation (4) includes data of the unit vectors of the muscle fibers involved; however, for the analysis only resulting forces were used and data obtained were replaced based on the body weight of the same study.

$$\sum_{i=1}^{12} |F_i^m| \Gamma_i - F_k + F_g = 0 \tag{4}$$

Due to the analysis results show an indeterminate system of equations, on [2] proposes two optimization techniques; where for each method two equilibrium equations are obtained. In order to compare the similarity of the results, it was established that the equations of equilibrium are (5) and (6).

$$Fk_1 = Fg + Fm_1 \quad (5)$$

$$Fk_2 = Fg + Fm_2 \quad (6)$$

Having for each study the following muscular forces:

$$Fm_1 = (0.1678 * 2 + 0.1768 + 0.1528 + 0.0097 + 0.0561 + 0.2354) * BW$$

$$Fm_2 = (0.446 * 2 + 0.2909) * BW$$

With equations (5) and (6) the total three-dimensional force generated on the knee (Fk) is:

$$Fk_1 = 220.05\ [N]$$

$$Fk_2 = 225.74\ [N]$$

Finally, polar angles of the resultant force in the knee are calculated and with equations (7), (8) and (9), the components of each plane of Fk are obtained:

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (7)$$

$$\phi = \cos^{-1}\left(\frac{F_z}{F}\right) \quad (8)$$

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right) \quad (9)$$

$$Fk_{1z} = 219.45\ [N]$$

$$Fk_{2z} = 223.59\ [N]$$

$$Fk_{1y} = 15.24\ [N]$$

$$Fk_{2y} = 29.86\ [N]$$

$$Fk_{1x} = 5.35\ [N]$$

$$Fk_{2x} = 8.71\ [N]$$

To perform the analysis of momentums around the x-axis, the forces of the planes 'y' and 'z' are required. Then, with the equations (5) and (6), the values of GRF and Fk are replaced in each orthogonal component. We obtained the components of muscle strength, as described below:

$$Fm_z = Fk_z - Fg_z$$

$$Fm_{1z} = 28.57\ [N]$$

$$Fm_{2z} = 32.70\ [N]$$

$$Fm_y = Fk_y - Fg_y$$

$$Fm_{1y} = -22.74\ [N]$$

$$Fm_{2y} = -8.13\ [N]$$

Fig. 3 shows a free body diagram for the maximum momentum applied to the knee:

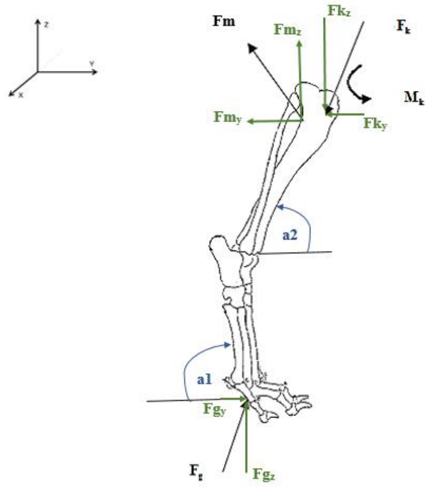

Figure 3. Free body diagram of the forces and angulations considered for the calculation of knee moment.

The angles made by the foot and tibia-fibula to the ground for the instant of the application of maximum strength are:

$$a1 = 77°$$

$$a2 = 53°$$

The sum of momentums at the moment of the application of the maximum force in the hind limb is:

$$Mk = -Fm_y * \left[\frac{1}{8} * L_{tp} * \sin(a2)\right] - Fm_z * \left[\frac{1}{8} * L_{tp} * \cos(a2)\right] - Fg_z * \left[L_{tp} * \cos(a2) - L_m * \cos(a1)\right] + Fg_y * \left[L_{tp} * \sin(a2) + L_m * \sin(a1)\right] \quad (10)$$

$$Mk_1 = -4.23\ [Nm]$$

$$Mk_2 = -4.63\ [Nm]$$

IV. Results and Future Work

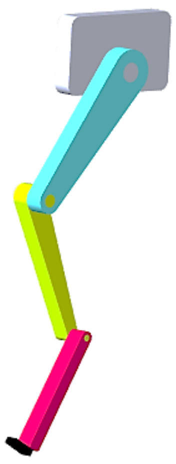

Figure 4. Three-dimensional simulation of the hind limb for mechanical analysis software.

To verify the results obtained through the calculation, the analysis explained above was taken to a mechanical simulation software. Firstly, CAD software was used to perform a three-dimensional assembly of links that simulate the canine hind limb, as shown in Fig. 4, and then import it into a Mechanical Analysis Software.

The mechanism can be represented by a block diagram, as show in Fig. 5, where properties and parameters of the joints and solids can be established to simulate the normal movement of the leg. For the articulated joints of hip, knee and ankle, parameters were obtained from a study that provides data angles of a complete phase of contact with the ground of the hind limb during the trot [1]. The data is presented in a simulation time of 10 seconds to better observe the results.

Knowing the maximum value of the force applied to the limb, the mass value is obtained.

$$W_g = \frac{F_g}{g}$$

$$W_g = \frac{194.63\ [N]}{9.81\ [m/s^2]} = 19.84\ [kg]$$

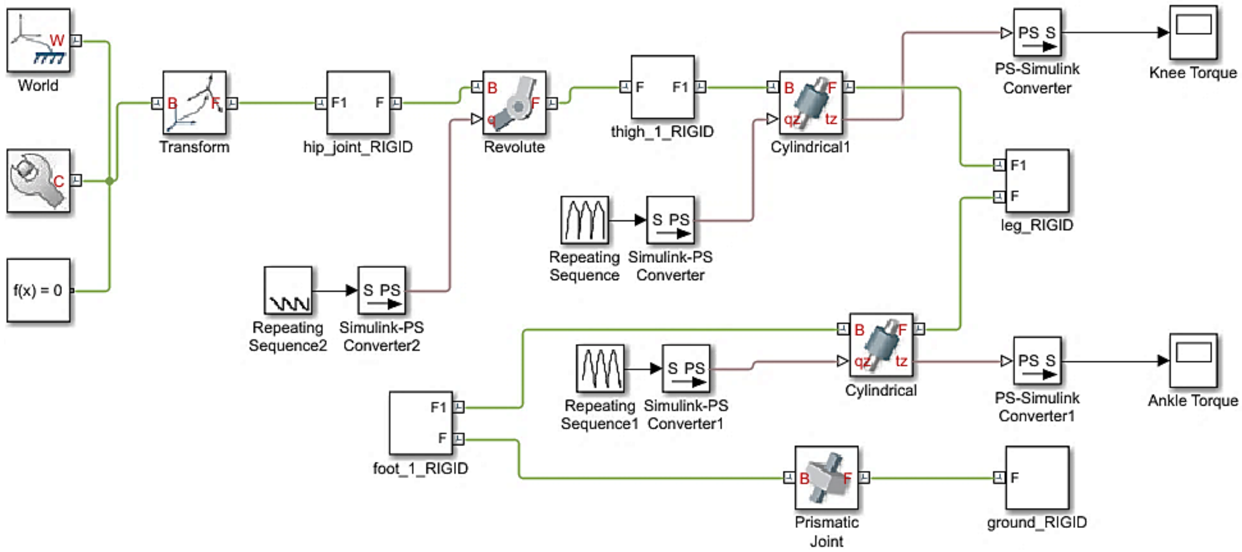

Figure 5. Block diagram of the 3D model in mechanical analysis software.

The distribution of the total weight obtained was distributes in each segment for the mechanical simulation, as shown in Fig. 6, according to [19].

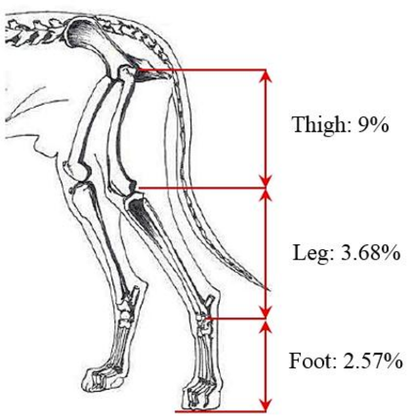

Figure 6. Percentage of weight distribution of areas of the canine hind limb [20].

Fig. 7 shows the results of torque of the knee in simulation, and the stance phase was simulated during a walking cycle to compare simulated data with the torque values obtained theoretically.

The results obtained in an analytical way were compared with those obtained by means of the simulation of the movement are presented in Table II and Table III as follows.

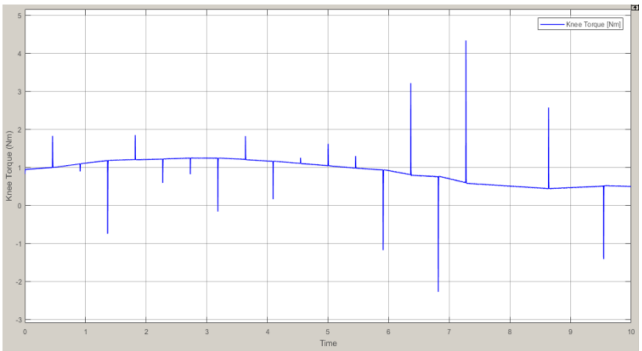

Figure 7. Graph in the time of torque on the knee during the trot.

TABLE II. COMPARISON OF ANALYTICAL AND SIMULATED RESULTS FOR ANKLE ANGLE

Percentage of BW [%]	Ankle angle [°]		Error [%]
	Analytical	Simulated	
20	140	140	0
56	150	130	13,33
74	130	140	7,69
16	150	150	0
10	155	160	3.23

TABLE III. COMPARISON OF ANALYTICAL AND SIMULATED RESULTS FOR KNEE TORQUE

Percentage of BW [%]	Knee torque [Nm]		Error [%]
	Analytical [opt.1- opt.2]	Simulated	
20	1,44	1,82	20,88
	1,30		28,57
56	3,29	3,21	2,49
	3,64		13,40
74	4,22	4,33	2,54
	4,63		6,93
16	2,34	2,57	8,95
	2,55		0,78
10	1,35	1,41	4.96
	1,54		8.44

Errors produced in torque, due to they are obtained as forces by meters, will not generate a considerable difference in the results of an application with actuators for rehabilitation purposes. However, further studies are required in applications with motors to determine the rating of error generating while applying the mathematical or simulated model.

A standardization of the reviewed Force Plates studies is recommended, due to the different parameters considered in each one of them to explain relation against variables or parameters of the canine hind limb movement.

V. CONCLUSIONS

Analytical calculation was performed with complete and normalized information for any dog during the trot, according to their body weight.

The use of software for mechanical simulation provides a better analysis of results; in addition, it allows manipulating all internal and external variables for a complete and reliable calculation.

An analysis of difference against the studies provides a worst case error of 13% for the ankle and 28% for knee, this because the studies, in order to simplify the calculation, assume certain information, while the simulation considers all aspects.

The simulated model provides a more realistic model to analyze the variables and parameters to consider for a canine hind limb.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] R. Carrier, C. S. Gregersen and N. A. Silverton, "Dynamic gearing in running dogs," Salt Lake City, 1998.

[2] R. Shahar and L. Banks-Sill, "The Veterinary Journal," June 2002. [Online]. Available: https://www.researchgate.net/publication/11284458_Biomechanical_Analysis_of_the_Canine_Hind_Limb_Calculation_of_Forces_During_Three-legged_Stance. [Accessed 7 January 2019].

[3] C. E. DeCapm, "Kinetic and kinematic gait analysis and the assessment of lameness in the dog," *Veterinary Clinics of North America: Small Animal Practice*, vol. 27, no. 4, pp. 825-840, 1997.

[4] R. M. McLaughlin, "Kinetic and kinematic gait analysis in dogs," *Veterinary Clinics of North America: Small Animal Practice*, vol. 31, no. 1, pp. 193-201, 2001.

[5] J. P. Weigel and D. Millis, "Biomechanics of physical rehabilitation and kinematics of exercise," in *Canine Rehabilitation and Physical Therapy*, St. Louis, Missouri, Elsevier Inc., 2014, pp. 401-430.

[6] Y. C. Fu, B. T. Torres, and S. C. Budsberg, "American journal of veterinary research," *Evaluation of a Three-dimensional Kinematic Model for Canine Gait Analysis,* vol. 71, no. 10, pp. 1118-1122, 2010.

[7] P. J. Holler, V. Brazda, B. Dal-Bianco, E. Lewy, M. C. Mueller, C. Peham, and B. A. Bockstahler, "Kinematic motion analysis of the joints of de forelimbs and hindlimbs of dogs during walking exercise regimens," *American Journal of Veterinary Research*, vol. 71, no. 7, pp. 734-740, 2010.

[8] K. Voss, L. Galeandro, T. Wiestner, M. Haessig, and P. M. Montavon, "Relationships of body weight, body size, subject velocity, and vertical ground reaction forces in trotting dogs," in *Veterinary Surgery*, Sydney, 2009, pp. 863-869.

[9] K. Söhnel, E. Andrada, M. H. E. de Lussanet, H. Wagner and M. S. Fischer, "db-thueringen," 15 September 2017. [Online]. Available: https://www.db-thueringen.de/servlets/MCRFileNodeServlet/dbt_derivate_00039329/ilm1-2017iwk-041.pdf. [Accessed 29 November 2018].

[10] A. A. Biewener, "Allometry of quadrupedal locomotion: The scaling of duty factor, bone curvature and limb orientation to body size," *The Journal of Experimental Biology*, no. 105, pp. 147-171, 1983.

[11] R. M. Walter and D. R. Carrier, "Rapid acceleration in dogs: Ground forces and body posture dynamics," *The Journal of Experimental Biology*, no. 212, pp. 1930-1939, 2009.

[12] K. Foss, P. Rajala-Shultz, R. Da Costa, and M. Allen, "Force plate gait analysis in doberman pinschers with and without cervical spondylomyelopathy," *Kinetic Gait Analysis of Wobbler Syndrome*, no. 27, pp. 106-111, 2013.

[13] D. L. Millis, R. A. Taylor, and M. Hoelzler, "Orthopedic and neurologic evaluation," in *Canine Rehabilitation Physical Therapy*, St. Louis, Missouri, Elsevier Inc., 2014, pp. 179-200.

[14] D. L. Millis, A. Lewelling, and S. Hamilton, "Range-of-motion and stretching exercises," in *Canine Rehabilitation and Physical Therapy, St. Louis, Missouri*, Elvesier Inc., 2014, pp. 228-243.

[15] S. M. Nacy, S. S. Hassan, and M. Y. Hanna, "A modified dynamyc model of the human lower limb during complete gait psycle," *International Journal of Mechanical Engineering and Robotics Research*, vol. 2, no. 2, pp. 8-19, 2013.

[16] O. R. Barclay, "Some aspects of the mechanics of mammalian locomotion," *Journal of Experimental Biology*, no. 30, pp. 116-120, 1953.

[17] T. Pfau, A. Garland de Rivaz, S. Brighton, and R. Weller, "Kinetics of jump landing in agility dogs," *The Veterinary Journal*, no. 190, pp. 278-283, 2011.

[18] G. Silva, M. Trés Cardoso, T. P. Gaiad, M. P. Brolio, V. C. Oliveira, A. Assis Neto, D. S. Martins, and C. E. Ambrósio, "Kinematic gait analyses in healthy Golden Retrievers," *Pesquisa Veterinária Brasileira*, vol. 34, no. 12, pp. 1265-1270, 2014.

[19] L. G. García, C. R. García, I. G. Fuentes and N. P. Victoria, "Articulación de la rodilla y su mecánica articular," *MEDISAN*, vol. 7, no. 2, pp. 100-109, 2003.

[20] G. L. Contreras, "Análisis numérico y experimental de un prototipo de," México D.F., 2016.

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