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Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Foot-Ground Contact Modelling of Quadruped Robot

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ARTICLE INFO

Article history:
Received 27 March 2025
Received in revised form 18 August 2025
Accepted 29 September 2025
Available online 10 October 2025

Keywords:
Quadruped robots; Dynamic modeling; MATLAB; Simmechanics^{TM}; Simulation; Friction

ABSTRACT

A lot of studies have focused on legged robots, and the goal is to create machines with features similar to those that exist in biological living things. However, this goal remains relatively distant, and construction of models for such studies is costly as well as time consuming, which leads to the design models that can facilitate the research by using software. The fundamental characteristics of biological creatures that are relevant to locomotion investigations should be included in these models. This study described the details of constructing a four-legged robot model in MATLAB/ Simmechanics^{TM} software. A simulation model for a multi-legged locomotion mechanism with two degrees of freedom for each leg was presented. The foot-ground contact is represented by a non-linear spring dashpot system, which the parameters were obtained from soil mechanics investigations using the theoretical model given in the literature. Finally, the generated simulation model's performance is tested by a series of trials, while the robot leg joints are controlled using fractional order algorithms. A configuration file that comes with the model allows you to simply adjust the robot's parameters. This study also discusses the robot model with a flexible body, legs, hip, and knee joints.

1. Introduction

Currently, there has been a significant increase in robotics research, and development of legged locomotion has been the main interest due to its advantages compared to the other robot vehicles [1-3]. The expenses and the time spent on developing automated prototype are considerably high, and this encourages the search for innovative working ways which facilitate the improvement, and experimenting these machines to be conducted more rapidly, and conveniently. There are numerous tools in the marketplace that make it possible to build, develop, and test mechanical components. These programs aid in the design of structural components by providing a real-time state of the equipment, which aids in the detection of any potential issues that might arise. These programs not only make the design step easier, but they also help with the testing process of the machines. In most circumstances, robots may be tested in a 3-D virtual environment [4].

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https://doi.org/10.37934/ard.145.1.165174

Despite that, it cannot entirely remove the requirement to construct functional model, but it helps to reduce possibility of an error, as a result of the multiple testing that been performed before building a real prototype. Because of the capabilities for describing, as well as implementing many kinds of systems with varying levels of complexities, the dynamic systems simulation programs are employed in a variety of industries, with special attention regarding to robotic studies. Many applications for three-dimensional simulation of mechanical systems are available in the market, including Adams - Multibody Dynamics Simulation [5], Simpack [6], VisSim [7], and Webots [8]. Each of these applications can analyze and simulate the dynamical systems. Those combined with more appealing graphical user interface, as well as those that rely only on code, all of them offer the capabilities that comparable to $\mathrm{Simmechanics}^{TM}$. The advantage of utilizing $\mathrm{Simmechanics}^{TM}$ is that it has an easy interface, which allows to add model features straight from CAD designs, also the variables can be imported and exported straight to and from MATLAB software. This is a fairly comprehensive tool with very simple functions because of the ability to communicate with other Simulink tools, making it easy to build on. Furthermore, MATLAB includes not only simulation instruments such as Simulink, but it also includes a numerical program. The purpose of this work is to demonstrate a contact ground quadruped robot modelling in the $\mathrm{Simmechanics}^{TM}$ environment, and to provide a tool for optimizing quadruped legged robot characteristics.

This model is distinguished by the use of soil mechanics based on non-linear foot ground interaction model research, as well as a flexible body with backbone-like properties [9-11]. The model that was built allows various locomotion patterns by directly introducing the knee and hip joint angular positions. Multiple characteristics can also be changed in the model quite simply by M.file.

2. Simmechanics Modelling of Walking Robot

$\mathrm{Simmechanics}^{TM}$ is a 3-D modelling tool for simulating multibody systems involving robotics, automobiles, in addition to plane landing gear. Its interface is made up of blocks that represent body "links", joints, motion restrictions, forces, and torques. The numerous elements are connected by lines that indicate the signals transferred from one block to the next. $\mathrm{Simmechanics}^{TM}$ has already been used in previous robotics research, particularly those involving legged robots. Zhao and Liu [12] implemented this program's tool to create a computer simulation of a bipedal robot, then simulate its entire movement. Through simulation, the authors were able to demonstrate the model's logicality, but the effect of contact with the ground is not explored, and it was unclear how the robot stays on the ground and travels. $\mathrm{Simmechanics}^{TM}$ was also used by Ponticelli and Armada [13] within the deeper framework setting for the dynamic simulation of the bipedal “SILO2”. The authors' major goal is to establish a virtual model in order to conduct measures of indices and gait controls studies for bipedal that were physically consistent and equivalent to an actual robot. The ground contact model is accomplished using a spatial contact force between the foot and the ground, and this type of contact block activated based on the contact phase. The developed system, according to the author's conclusions, meets the intended objectives. In the $\mathrm{Simmechanics}^{TM}$ environment, Naf [14] developed a three-dimensional model of a trot robot. The work constructed a quadruped model, emphasis on production of the ground contact model. A touch technique with a “linear spring-damper” structure was adopted, and a trotting gait controlling has also been developed. At last, Woering [15] developed a hexapod simulator using MATLAB $\mathrm{Simmechanics}^{TM}$. The hexapod simulation is divided into two sections; the first is the kinematic simulation of “graphical visualization” of hexapod with much fewer mass points obtained. Moreover, the “dynamic simulation” is utilized to figure out the effect of gravity and mass of a hexapod. In terms of ground interface with foot, this study successfully simulated the ground contact as a spring-damper, allowing the constructed model to possess at zero level. Friction was included to allow the robot to move in a specific direction, also, the impacts experienced once foot strike ground.

3. Overview of The Model

This study considers a walking system with four legs, each with two rotating joints (hip joint, and knee joint) that provide angular motion along z-axis. A spring-damper included in one degree of freedom joints that connects each two adjoining parts of the body, providing more flexibility to the body's motion [16]. A foot-ground contact techniques was built to improve the simulated model through the use of reaction forces equations in x-axis and y-axis respectively. Every element comes with its "inertia matrix" based on its form. The constructed model weight is 4 kg in total. "Fig. 1" displays the Simmechanics^{TM} robot model. A schematic model of the body, legs, and foot-ground systems is illustrated in "Fig. 2". A ground block (GND) is also included in the diagram in order to supply the model with a position in reference to GND [17-18].

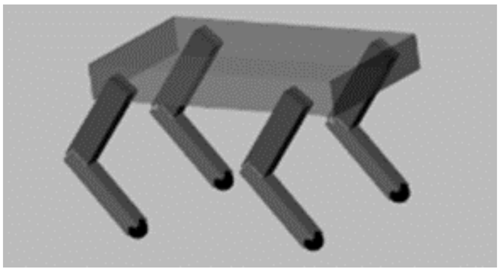

Fig. 1. Model of the four-legged robot

3.1 Robot Body Subsystems

This section describes the methods to model the quadruped robot in Simmechanics^{TM}, as shown in "Fig. 2". The body is seen as a single uniform rectangular block. Because of its symmetry around the coordinated axis, the inertia matrix I_b with mass m_b is represented in "(1)". The robot body dimensions are shown as follows; width = 30 cm, depth = 50 cm, and height = 20 cm.

$$I_b = \frac{1}{12}\begin{bmatrix} m_b(h_b^2 + d_b^2) & 0 & 0 \\ 0 & m_b(w_b^2 + d_b^2) & 0 \\ 0 & 0 & m_b(w_b^2 + h_b^2) \end{bmatrix} \tag{1}$$

The density of the material used are 0.625 g/〖cm〗^3 for legs and 2.72 g/〖cm〗^3 for the body, as it was built using aluminum. It is possible to adjust both the dimensions and the density of the robot model using the configuration of the program in Simmechanics^{TM}. Different CS with inertia matrix allows the legs to be connected to model body, as well as joints that connect the two links of each leg from the robot.

Once the inertia matrix being calculated, the effects of forces and torques operating on the model can be estimated. By using MATLAB, it can automatically define the inertia matrix of a particular body respecting to COM. In addition, various blocks are required to connect body elements in order to determine the final body form. These blocks connect joint or body actuator with a sensor. Several methods are found in Simmechanics^{TM} for defining the positions of components with relation to one another. The reference could be either relative or absolute. Whatever the robot's elements references, it is essential to keep a certain standardization in its definition.

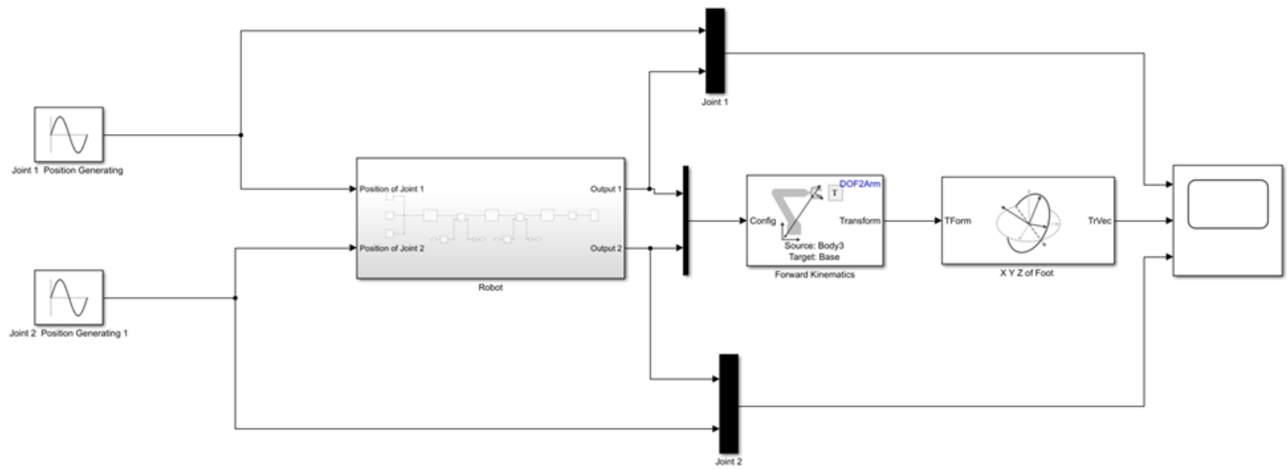

Fig. 2. Full Body scheme of the four-legged robot in Simmechanics^{TM}.

Once simulation initiates, MATLAB/Simulink verifies that every component's body and joints comply to the Assembly Tolerances. Considering the model is being emulated, restrictions can be modified in the “Machine Environment" menu options. It is important to recall in relative reference, and one of body components must always linked to a "GND block”, whose referring must be absolute. On all the robots shown here, relative references were employed. To set the initial position of robot body, it was linked to a "Six Degrees of Freedom" joint type. Individual joints will determine the initial positions of the arms, legs, or other body components. This allows the robot to move about in three dimensions.

3.2 Robot Leg Subsystems

The initial stage is to establish the leg's constitution. The limbs are linked to model via the hip joint. Every limb consists of upper part referred to as "Link 1", and the bottom one is known as "Link 2" and it is connected to the Link 1 through a revolute joint named knee joint. Thus, each leg of the robot has two 1 DF rotating joints for "hip and knee joint". Also, the model was chosen with backward legs as shown in "Fig. 3". The hip angle being calculated starting from the line of horizontal body position, while knee angle being calculated relative to extended line starting from Link 1. This angular connection is equivalent to Simulink even widely used in robots since it allows members' positions to be visualized [16]. One of the model's goals was to allow for the implementation and testing of various gaits.

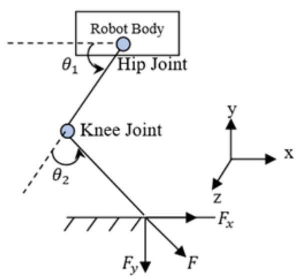

Fig. 3. Robot leg constitution scheme

Two blocks in Simmechanics^{TM} provide the starting angle of each simulated joint, as shown in "Fig. 4". The subsystem linked to the relevant body block on the left and the foot-ground block on the right. The “inertia matrix” comes with the foot spherical block that has radius r = 2 cm and mass m_f = 0.06 kg. The top joint is intended to simulate the hip rotation, while the lower joint is intended to simulate knee rotation. Hip joint rotates around z-axis. The center of gravity of Link 1 and Link 2 segments are both defined as point masses. The arrangement of knee rotated joint is same as that of the hip. In addition, the Link 1 segment's CG configuration is similar to that of Link 2.

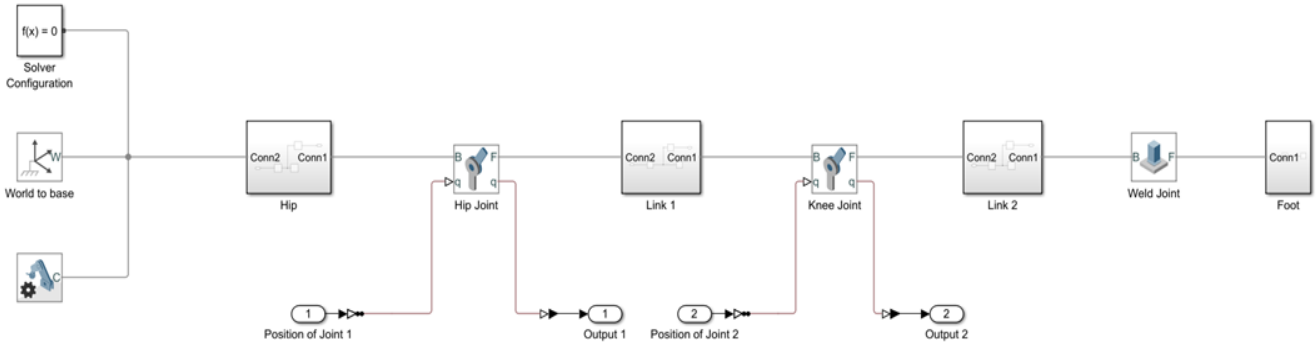

Fig. 4. Model of a robot’s leg

3.3 Robot Foot-Ground Subsystems

The model of ground interaction is a key element of the robot. Once robot's foot contacts the ground, it will exert force on the foot at same magnitude and opposite direction based on Newton's third law. This action-reaction pair is responsible for a body's mobility on a particular surface. It involves a contact point on the lower end of leg to simplify the model. When this point makes interaction to specific point, a 3D force is applied to the ground, as well as a force that has same magnitude, but in a reverse direction of robot foot [19]. When a rectilinear force is separated into its components, one will go along the x-axis and another one along the y-axis, as shown in "Fig. 3". Two main techniques for simulation to contact with the ground are rigid and flexible contacts. The rigid contact models lack any sort of collision energy dissipation and may be applied to simulate interaction of two rigid bodies. In fact, it does not make any sense to employ rigid contact since the model is designed to simulate the robot's foot's touch with the ground. As a result, the method utilized to compute normal and tangential forces using an approximation model of the ground based on models gained from soil mechanic, based on Eq. 2 and Eq. 3 respectively. A contact model of “spring-damper” type is illustrated in "Fig. 5".

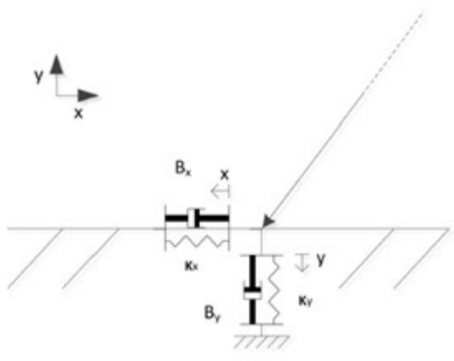

Fig. 5. Ground contact model

The foot-ground subsystems have been implemented in the model to simulate a real quadruped robot, and "Fig. 6" shows its architecture. Sensors will analyze the velocity and position of the robot's foot to determine the frictional force and normal force transmitted by the robot to ground. Applied forces are estimated using "(2)" and "(3)", which occur only when the foot touches the ground.

$$F_x = -K_x(x - x_o) - B_x\dot{x} \tag{2}$$

$$F_y = -K_y y - B_y(-y)^m \, \dot{y} \tag{3}$$

The equation of friction force is used based on a linear "smooth spring damper system", where F_x is acting in x-axis, K_x is the spring's elastic constant, x and x_o represent current position and previous position at x-axis related to the ground, while B_x is the constant of the damper and $\dot{x}$ is the velocity indicated in x-axis. A "non-linear spring-damper equation" was chosen to estimate the normal force because it gives better results in tests [16]. In this case, F_y is the applied as a normal force, K_y is spring's elastic constant, y is the current position in y-axis, B_y is "damper constant", m is a factor that affected by soil conditions and finally, $\dot{y}$ is the velocity in y-axis. In this study, only two contact components will be taken into account; normal force that exerted in the y direction and tangential force which exerted in the x direction. The normal component of the force is to control keeping the robot above ground, while the tangential component causes the robot to move forward.

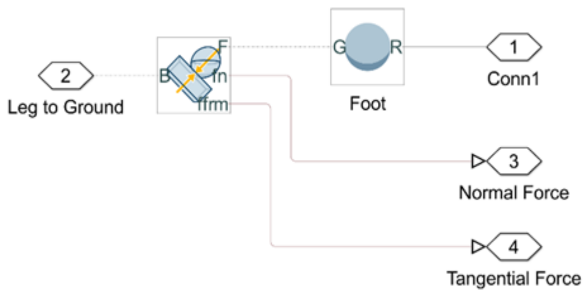

Fig. 6. $\mathrm{Simmechanics}^{TM}$ foot-Ground contact

The ground was represented as a surface formed by the coordinate axes x and z, and the origin located at coordinate zero of the y-axis, and ground contact was predicted to occur only at the bottom of the leg. The spatial contact force block connected to the foot is used to allow the ground model to know the contact signal, separation distance, normal and tangential force magnitude, location, velocity, and acceleration of the feet in all time samples. When the system senses contact between the foot and the ground, two subsystems are triggered to determine the tangential and normal contact forces. The forces calculated as a result of these computations are then combined into two signals, with zero being the force value in the z-axis.

1) Frictional Force (F_x): Eq. 2 calculates the tangential force of robot to move ahead on ground and is dictated by the model shown in "Fig. 6". The foot's position and velocity are the input parameters for this model. After that, the vectors are sorted, one block is in control of specifying whether or not the foot is in contact with the ground. If the foot hasn't yet made contact with the ground, the force applied to block's output is 0, and if the foot makes contact to the ground, then "Friction Force" block, as illustrates in "Fig. 6" is activated. Blocks used to implement Eq. 2 are found within the "Friction Force" subsystem. The tangential force signal is subjected to saturation, allowing the user to insert a limit of soil intensity values. This saturation parameter's limits are set to inf and -inf, respectively. in the default configuration. This saturation was deemed to be interesting for minimizing the tangential force exerted by the ground on the robot's foot if necessary.

2) Normal Force (F_y): The normal force ensures that the robot remains above the ground throughout simulation. It can be determined using the model presented in "Fig. 6" and is calculated using Eq. 3. The foot's position and velocity are the input parameters for this model. A block, similar to the one responsible for computing the tangential force, determines whether or not the foot has already made interaction with the ground. If the foot remains on the ground, the force delivered to the block's output is 0. When foot makes interaction with the ground, the block of Normal Force gets activated. The normal force signal undergoes the saturation point, giving the user the option to adjust the soil intensity values. The lower limit has been put to zero by default, and the upper limit is set to infinity (inf). This method ensures that the ground model always exerts a negative force on the robot foot. Table I shows several parameters for various soil types.

Table 1
Young Modulus and Ground Model Settings for Various Soil Types [20]

Soil Type	Young's Modulus (kNm^{-2})	K_{xF} (Nm^{-1})	B_{xF} (Nsm^{-1})	K_{yF} (Nm^{-1})	B_{yF} (Nsm^{-1})
Concrete	30000000	2604304130	153097	3410398265	175196
Wood	13000000	1128531790	100781	1477839248	115328
Gravel	100000–200000	17362028	12500	22735988	14305
Sand	10000–80000	6944811	7906	9094395	9047
Compact Clay	3000–15000	1302152	3423	1705199	3917
Loose Clay	500–3000	260430	1531	341040	1752
Peat	100–500	43405	625	56840	715

4. Simulation Results and Discussions

The Simulink model was built in the MATLAB/Simulink 2022b software, and the dynamic modelling of the quadruped is carried out by taking into account multiple factors such as the robot's body and legs' masses, density, friction, stiffness, damping, type of contact force, and so on. According to Table I, different parameters and environments can be used in the simulation. The simulation was carried out in the condition of robot is walking. "Fig. 7" shows the variation of position in the hip joint horizontal movement of the body and limbs throughout time. It indicates that the reference axis has been taken as the right back leg tip of the hip joint position, which is 7 mm in x direction and 2.323 mm in the negative y direction. "Fig. 8" shows the variation in the position of knee joint about 11 mm in the x direction and 1.583 mm in y direction. The error signal is generated by subtracting the actual position from the desired position. By determining the gait profile and spring stiffness, it was found that the maximum torque required at the hip for swaying the leg forward for the next stride is about 15 N.cm ("Fig. 9"), whereas there is a little higher of torque generated at the knee joint as shown in "Fig. 10". The robot considered walking on level terrain. When the robot's leg meets the ground, a smooth spring-damper is applied, and a smooth stick-flip mechanism is employed to impart frictional force with friction coefficient of μ=0.5, to produce dependable and smooth landing contact. "Fig. 11" shows the tangential force change curve. Tangential force fluctuation increases to about 58 N when the robot's leg touches the ground and decreases to zero during flight. As shown in "Fig. 12", the estimated normal foot force in a robot is about 122 N, which gradually decreases as the leg enters the flying phase again.

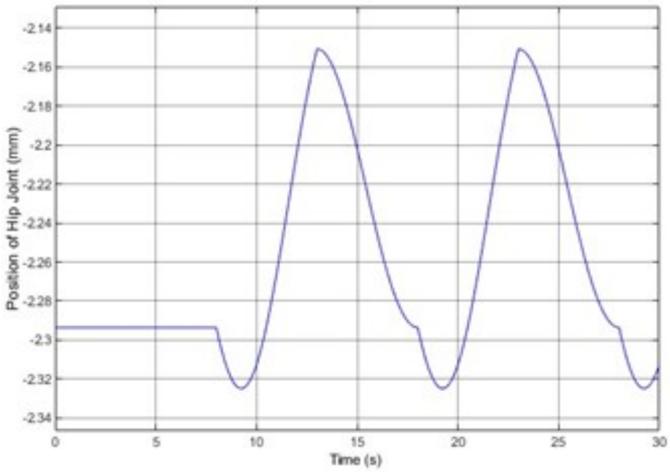

Fig. 7. Position of hip joint

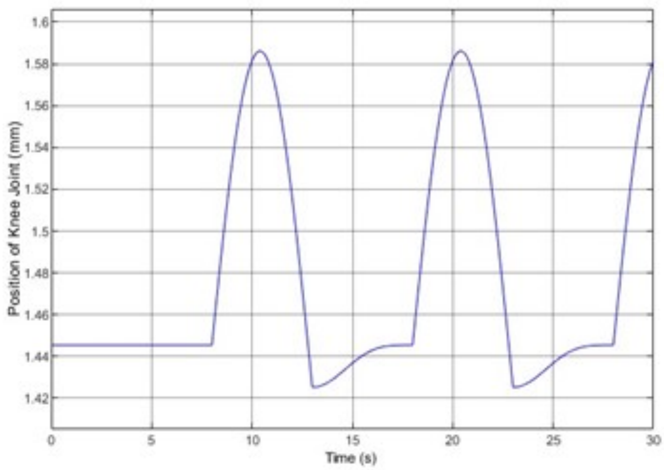

Fig. 8. Position of knee joint.

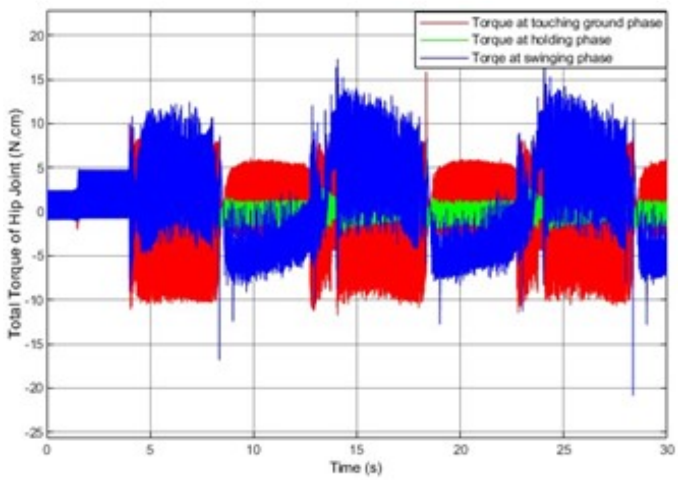

Fig. 9. Total torque of hip joint.

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Volume 145, Issue 1 (2026) 165-174

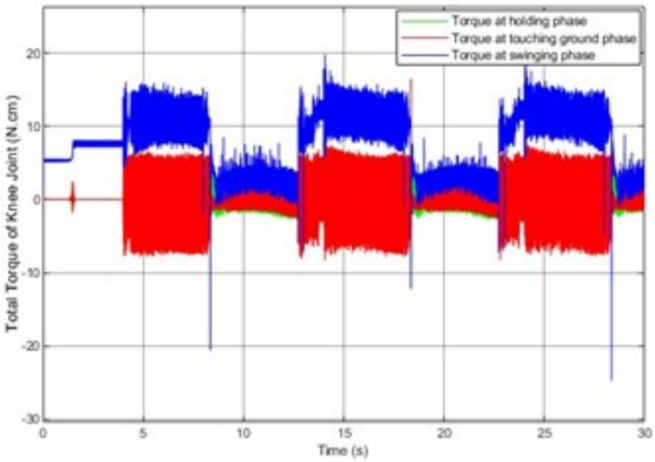

Fig. 10. Total torque of knee joint.

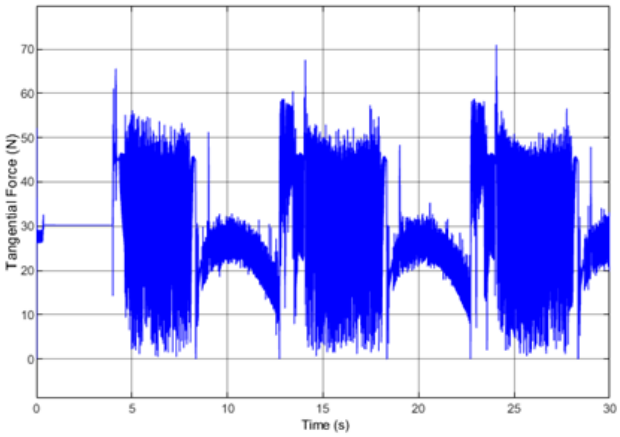

Fig. 11. Ground and reaction force (Tangential force).

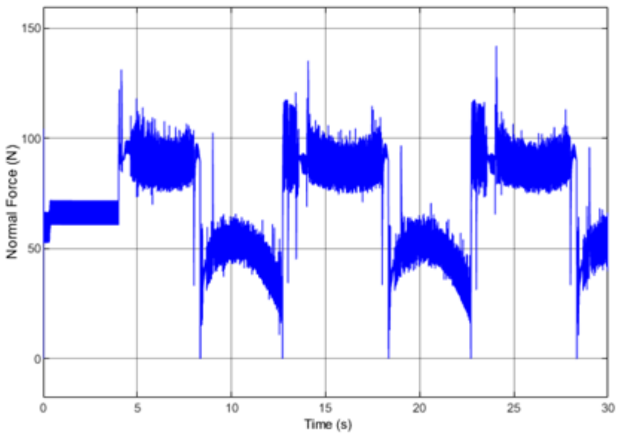

Fig. 12. Ground and reaction force (Normal force).

5. Conclusions

This paper presents a study of foot-ground interaction using Simmechanics^{TM} modelling for four-legged robots, by adopting a model based on soil mechanics studies. By directly introducing the angular positions of the knee and hip joints, the model additionally allows to implement different gaits. The configuration file is included with the model and allows the user to simply adjust the robot's parameters. The authors intend to expand this model further, so that it can be used to test different gaits and locomotion in three dimensional environments as well as along rough terrains.

Acknowledgement
The authors would like to acknowledge Ministry of Higher Education Malaysia for awarding the Fundamental Research Grant Scheme (FRGS) with Project Code: FRGS/1/2021/TK0/USM/03/6.

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