Design and Scaling of Versatile Quadruped Robots

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The rough terrain mobility of legged robots is expected to exceed the performance of their wheeled or tracked counterparts. To fully take advantage of the legs, such robots need to be versatile by achieving highly dynamic motions at the same time as careful navigation over rough terrain. Highly dynamic robots need to be designed to be fast and strong enough to run and jump. A dynamic robot needs to be light and powerful at the same time. Two requirements that are conflicting and therefore have to be traded off. In this work we present a tool that helps quadruped robot designer to better select and size joint actuators for various robot sizes. We use the squat jump as characteristic motion of a highly dynamic robot and estimate required joint torque and velocity in relation to maximum jump height, body mass and leg segment length.

Keywords: Quadruped Robot Design; Scaling; Actuator Sizing; Jump.

1. Introduction

Legged machines promise higher mobility in difficult terrain in comparison to more traditional vehicles with wheels or tracks. Nature shows that legged animals including humans are able to navigate through challenging grounds by putting their limbs on suitable footholds to support their body. Depending on the difficulty of the terrain, this may not only include climbing but also highly dynamic maneuvers such as jumping where static equilibrium is temporarily lost.

Today's legged robots lack the ***versatility*** to perform both highly dynamic motions **and** rough terrain walking. Only few examples exist, e.g. *Boston Dynamic's BigDog*.[1] Whether such machines will ever reach the above-mentioned higher mobility, and therefore open up a vast range of applications in dangerous and difficult terrain, largely depends on the robot designers' abilities to construct truly versatile machines of various sizes.

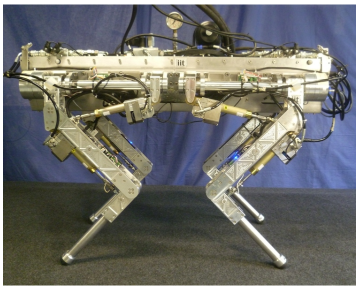
A crucial part of the design process of versatile legged robots is the careful sizing and selection of actuators. A highly dynamic robot needs to be light-weight and powerful at the same time. The higher the required robot performance, the higher the required joint torque and speed, and the higher the actuator weight. A heavier robot requires higher joint torques and thus heavier actuators. To come up with a good compromise, most robot designers go through several iterations before finding a suitable actuator.

The aim of this work is to create a useful tool for designers of versatile legged robots that allows them to make good decisions about the size and type of joint actuators. For this study we selected the *squat jump* as characteristic motion for highly dynamic robots to obtain peak values of joint speed and torque in relation to robot mass, leg segment lengths and desired jump height. We use the leg segment length as a measure of the robot's size, as the leg length usually scales in accordance to overall size. The tool should be straight-forward and intuitive to provide a rough estimate with the least amount of parameters that need tuning. Experiments with a highly dynamic quadruped robot performing squat jumps confirm the validity of our simulation. As a result, we present plots that show required joint torque and velocity for various robot weights, leg segment lengths and jump heights.

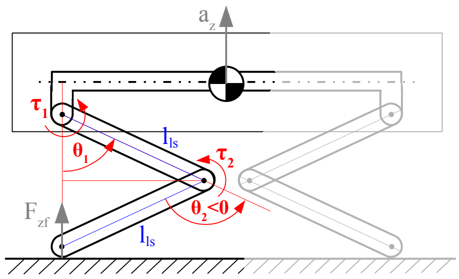
Related Work Similar studies were conducted for the electric DC motor sizing of a bounding robot,[2] hopping monopod robot[3] and a vertical climbing robot.[4] A genetic algorithm was used by Smith *et al.*[5] to obtain design parameters including joint torque for statically stable walking robots. Alexander[6] summarized and compared the jumping capabilities of animals ranging from bushbabies to frogs and fleas. In an earlier study he compared the maximum forces exerted by animals in relation to their body weight.[7] Similar animal studies were conducted by Fedak *et al.*[8] and Heglund *et al.*[9]

2. Experimental Platform: HyQ robot

The experimental platform used in this study is the versatile, quadruped robot HyQ,[10,11] Fig. 1(a), a hydraulically and electrically actuated machine that weighs $70kg$, is $1m$ long and has a leg segment length of $0.35m$. The robot's legs have three degrees of freedom each, two hydraulic joints in the sagittal plane (hip and knee flexion/extension) and one electric joint for hip adduction/abduction. Each joint has $120°$ range of motion and is controllable in torque and position. The maximum joint torque is 145Nm for the hydraulic and 152Nm for the electric joints. Semini *et al.*[11] describe HyQ's design and specifications in detail.



(a)



(b)

Fig. 1. HyQ: Hydraulic Quadruped robot. **(a)** picture and **(b)** sketch of side view of robot in squat posture, defining the centre of mass (COM) acceleration vector a_z; joint angles $\theta_{1,2}$ and torques $\tau_{1,2}$ of the hip and knee joint, respectively; leg segment lengths l_{ls} and ground reaction force vector at the foot F_{zf}.

3. Squat jump Simulation

As mentioned above we selected the squat jump as a characteristic motion for a highly dynamic robot. Such a *squat jump* is composed of several phases: first, a vertical **acceleration phase** from a squatting posture until **lift-off** (when the feet loose contact with the ground); then, a parabolic **flight phase** with the legs moving to a suitable landing posture.

To reduce the amount of tunable parameters, we made several assumptions: the legs are massless, all weight is equally distributed in the robot's torso, and the vertical acceleration is constant during the whole acceleration phase. Furthermore, the lengths of the upper and lower leg segment (distance between the hip and knee axis (upper); knee axis and foot (lower)) are equal and the hip joint axes are always vertically above the contact point of their corresponding feet, as shown in Fig. 1(b). This leads to the following relationship between the hip and knee joint angles θ_1 and θ_2:

$$\theta_1 = -\frac{\theta_2}{2} \tag{1}$$

Furthermore, these assumptions lead to ground reaction force vectors F_{zf} that intersect (or *point through*) the hip axes during the whole acceleration phase, resulting in zero required hip torque. Section 5 will address the consequences of these assumptions and discuss the limitations of this approach.

The jump height is the crucial input to our simulation and is measured as the vertical distance that the COM travels from the time the body lifts off the ground to the end of the upward motion. The maximum jump height

h_{max} of any object undergoing a parabolic flight phase is directly related to its lift-off velocity v_{lo}:

$$v_{lo} = \sqrt{2gh_{max}} \tag{2}$$

and can be obtained by equating the kinetic energy E_{kin} at lift-off with the potential energy E_{pot} at the maximum jump height:

$$E_{kin} = \frac{1}{2}mv_{lo}^2 = mgh_{max} = E_{pot} \tag{3}$$

where g is the gravity constant and m_{robot} the robot mass. Note that v_{lo} is independent from m_{robot}.

The next step is to calculate the constant vertical acceleration a_z necessary to reach the velocity v_{lo}. To further reduce the number of input parameters, we defined the distance z_{ap} of vertical travel of the COM before lift-off to be equal to the length of the leg segments l_{ls}.

$$a_z = \frac{1}{2}\frac{v_{lo}^2}{z_{ap}} = \frac{1}{2}\frac{v_{lo}^2}{l_{ls}} \tag{4}$$

This results in the required vertical force F_{ap} during the acceleration phase:

$$F_{ap} = (a_z + g)m_{robot} \tag{5}$$

This force should be equally spread over the four legs and therefore results in a vertical ground reaction force of $F_{zf} = \frac{1}{4}F_{ap}$ at each foot. The required torque in the knee joint depends on the momentary joint angles during the motion and is obtained as follows:

$$\tau_2 = \frac{1}{4}F_{ap}l_{ls}\sin(-\theta_1(t)) = \frac{1}{4}F_{ap}l_{ls}\sin(\frac{\theta_2(t)}{2}) \tag{6}$$

with the joint angles and torques as defined in Fig. 1(b). The joint angle trajectories are obtained through the foot trajectory in Cartesian coordinates and the leg Jacobian.[11] Using (2), (4)-(6) we get the following result

$$\tau_2 = \frac{1}{4}gm_{robot}l_{ls}\sin(\frac{\theta_2(t)}{2})(\frac{h_{max}}{l_{ls}} + 1) \tag{7}$$

4. Experimental Results

We performed several squat jump experiments with HyQ. Figure 2(a) and 3(a) show the results of a jump with $0.2m$ jump height that can be seen in a *youtube* video[12] at minute 1:06.

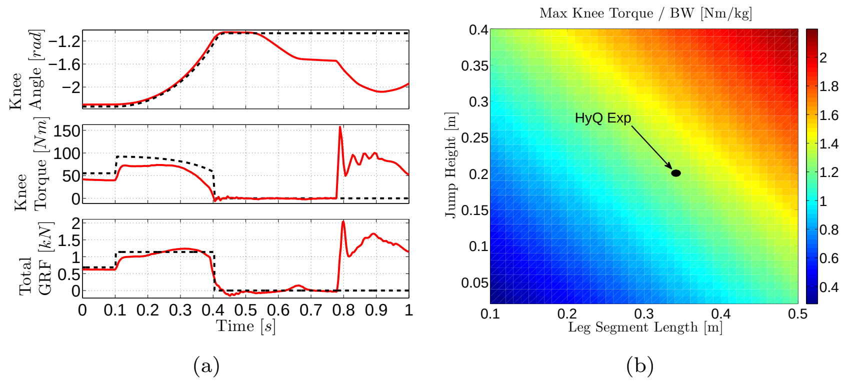


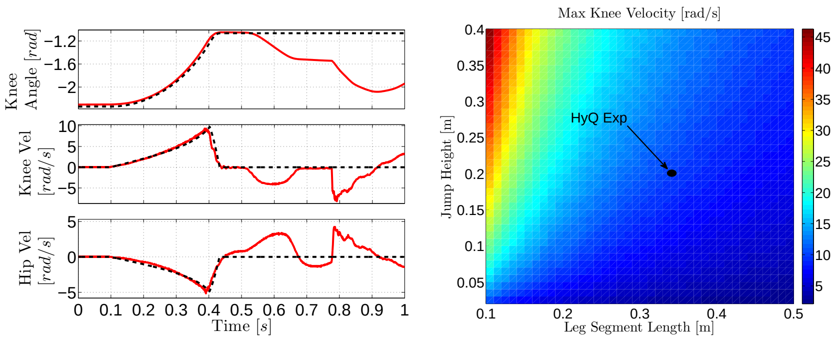
Fig. 2. **(a)** Plot of experimental data (red solid) and simulated data (black dashed) for a squat jump motion of 0.2m jump height. *Top:* knee joint angle θ_2; *middle:* knee torque τ_2; *bottom:* total ground reaction force $4F_{zf}$. **(b)** plot of maximum knee joint torque scaled by the robot's body weight (BW) for different leg segment lengths and jump heights. The arrow marked with *HyQ Exp* shows the experimental results obtained with HyQ as an example.

The three subplots of Fig. 2(a) show the data of the experiment (red solid line) and of the simulation (black dashed line) for the knee joint angle (top), knee joint torque (middle) and vertical ground reaction force (bottom). The acceleration phase starts at $0.1s$ and lasts till $0.4s$ when the torques go to zero. The robot touches down again at $0.78s$. The simulation calculates values only during the acceleration phase.

Similarly, the three subplots of Fig. 3(a) report again the data for the knee joint angle on the top (to facilitate the comparison of the plots), and the knee and hip joint velocities in the middle and bottom plot, respectively.

The plots show that the simulation results match well for joint position, joint velocities and ground reaction forces. The simulated knee torques are slightly higher due to the above mentioned assumptions. See Section 5 for a discussion about these assumptions and their effect on the results.

Based on the simplified squat jump simulation presented in Section 3 we created three 3D plots illustrating estimations of knee joint torque, velocity and power for a selection of leg segment lengths between $0.1m$ and $0.5m$ and jump heights ranging from $0.02m$ to $0.4m$. Figure 2(b) shows a plot of the maximum knee joint torques scaled in relation to body weight (BW). Figure 3(b) shows a similar plot for the maximum knee joint velocities. As the jump height mentioned in (2) is independent of body weight and only related to the lift-off velocity, this plot does not need to be scaled by



(a) (b)

Fig. 3. **(a)** Plot of experimental data (red solid) and simulated data (black dashed) for a squat jump motion of $0.2m$ jump height. *Top:* knee joint angle θ_2; *middle:* knee joint velocity $\dot{\theta}_2$; *bottom:* hip joint velocity $\dot{\theta}_1$. **(b)** plot of maximum knee joint velocity for different leg segment lengths and jump heights. The arrow marked with *HyQ Exp* shows the experimental results obtained with HyQ as an example.

body weight. Finally, Fig. 4 shows the product of the knee joint torque and velocity plots resulting in the maximum required knee joint power scaled in relation to body weight.

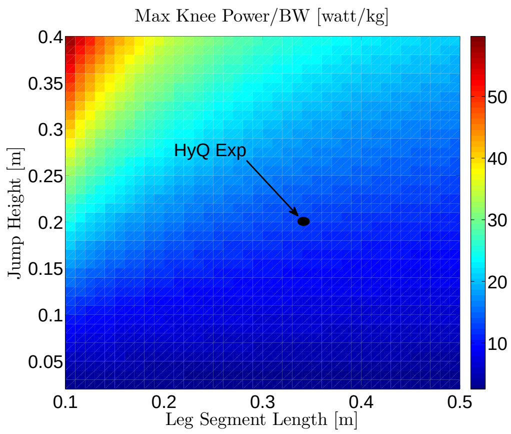


Fig. 4. Plot of maximum knee joint power scaled by body weight BW for different leg segment lengths and jump heights. The arrow marked with *HyQ Exp* shows the experimental results obtained with HyQ as an example.

As a reference we added the results of the squat jump experiment with HyQ presented in Section 4 to each of the plots with an arrow marked

HyQ Exp. A jump height of $0.2m$ and leg segment length of $0.35m$ results in a value of $1.3Nm/kg$ for the maximum knee torque. Multiplied by HyQ's weight of $70kg$, this results in $91Nm$, matching the peak value of the simulated torque shown in Fig.2(a). In terms of joint velocities we obtain $10rad/s$. Figure 4 shows an estimated maximum knee joint power of 910W for HyQ ($13W/kg * 70kg$).

5. Discussion

In this section we discuss the limitations of our method and evaluate the consequences of the assumptions mentioned in Section 3. *Massless legs:* If the mass of the legs is small with respect to the torso's weight, this first assumption does not significantly influence the results. However, Alexander[6] showed that increasing leg mass reduces the jump height, especially if the additional mass is located in the lower leg segment. *Equally distributed body weight:* If the body weight is not equally distributed, the joint torques in the four legs are not equal, however the average will match our simulation. A wise rule for the design of versatile, quadruped robots is an equal distribution of body mass, since it simplifies balancing during locomotion. *Constant vertical acceleration:* In reality the acceleration and thus the pushing force does not follow the step input as shown in Fig. 2(a), this leads to a smaller jump height. *Hip joint axes vertically above feet:* In reality, it is difficult to achieve perfectly synchronized motions of the hip and knee joints. Thus, the ground reaction forces will not always be only vertical, but non-zero tangential components result in internal forces that might lead to foot slippage if the foot-ground friction coefficient is low. For this reason, the hip torque during the experiment is not zero. The torque plot of Fig. 2(a) shows that our simulation results in an overestimation of required joint torques.

A major limitation of our approach is that it currently only considers the squat jump as characteristic motion of a versatile robot. It does not provide any information about leg workspace and thus joint range of motion, neither does it take running at different speeds into consideration.

6. Conclusion and Future Works

This paper presented a simple method to estimate maximum joint torques and velocities for the design of highly dynamic quadruped robots with articulated legs. A jumping motion out of a squat posture was used as characteristic motion of dynamic robots. The maximum jump height, the body mass and the leg segment length were the input parameter for the simulation. Maximum joint torques, velocities and power were the output. Our method should provide robot designers with a useful tool helping them in correctly sizing and selecting joint actuators.

Future Works The presented method only looks at one aspect of versatile robots. We will therefore extend it by a similar estimation of maximum joint torques and velocities for running with forward speed, body mass and leg segment length as input parameters. We are currently working on the design of a smaller version of HyQ, whose actuators will be sized and selected based on these estimations.

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