A Model Based Velocity Study of Walking and Trotting Horses

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1 Motivation

Animals adapt their way of moving as their locomotion speed changes. Strong correlations between velocity, kinematic, and kinetic parameters have been demonstrated in many studies of equine locomotion [1], [2]. In our work, we are seeking to understand what is driving these changes. In particular, we are investigating simplistic models that could potentially explain these adaptations in a fundamental way. This approach could be interpreted as a variational study, in which changes in a parameter (i.e., velocity) allow us to draw conclusions about the underlying nature of a process (i.e., locomotion).

To this end, we developed a quadrupedal model that is able to reproduce a wide range of horse gaits [3] and implemented methods to match this model in order to correctly explain experimentally recorded ground reaction forces of horses at Walk, Trot, and Tölt [4]. In the present study, we extend these methods to a data set of vertical ground reaction forces recorded for walking and trotting of horses at different velocities [5]. We investigate which model parameters and states are sensitive to changes in velocities. As most interesting result, stiffness does not need to change to explain changes in kinetics. This is in contrast to previous work [6]. Beyond understanding locomotion of horses, the results provide potential insights into the design and control of legged robotic systems moving with different gaits at different speeds.

2 State of the Art

The effects of changes in walking and trotting velocities on real horses have been investigated in a number of experimental studies [1], [2], [5]. In these experiments, kinematic data was collected by analyzing the motion of reflective markers and force data were recorded simultaneously by either a force platform or an instrumented treadmill. By running inverse kinematics and dynamics on this data, joint angles, velocities, and torques can be computed. More complex properties, such as the stiffness of the legs, are harder to obtain. To estimate these, simple models have been used in the past to estimate the values of kinematic variables. Farley et al. [6], for example, used a spring loaded inverted pendulum model to match the experimental results of dogs, goats and horses while trotting at different velocities. This single-leg model can explain changes in stiffness during trotting (were two legs are always touching down and lifting off the ground at almost the same time). An equivalent analysis for other gaits is not possible with this model.

3 Own Approach

In this project, we employ a simple passive quadrupedal model with a single rigid body and four massless legs [7]. With proper initial conditions, a large variety of different gaits can be found; -including walking, trotting, and galloping. During the simulation of a stride, simulated GRFs can be computed as $\mathrm{F}_{sim}(t, \mathbf{X}, \mathbf{p})$. They are a function of time t and depend on a set of model parameters $\mathbf{p}$ and on the states at the beginning of a stride (defined by the vector $\mathbf{X}$). $\hat{\mathrm{F}}(t)$ denotes the experimentally obtained GRFs that were recorded from actual horses. The residual c_i quantifies how well the model predicts the experimentally obtained GRFs at velocity i:

$$\mathrm{c}_i(\mathbf{X}_i, \mathbf{p}) = \int_0^1 \left\| \mathrm{F}_{sim}(s, \mathbf{X}_i, \mathbf{p}) - \hat{\mathrm{F}}(\hat{s}) \right\|^2 dt. \quad (1)$$

A set of data recorded by an instrumented treadmill of a Warmblood horse walking at six different velocities are normalized and ranged from 0.3 - 0.45 $\sqrt{gl}$ and trotting at nine different velocities ranged from 1.0 - 1.6 $\sqrt{gl}$ was used in this research [5]. We defined the cost function as the summation of all these residuals and the value of this cost function is minimized as a constrained optimization problem:

$$\begin{aligned} \mathrm{C}_{total} &= \min \left\{ \sum \mathrm{c}_{i,opt}(\mathbf{X}_i,\ \mathbf{p}) \right\} \\ s.t. \quad & \mathrm{P}(\mathbf{X}_i, \mathbf{p}) - \mathbf{X}_i = 0 \end{aligned} \quad (2)$$

Note that only a single set of parameters $\mathbf{p}$ is used for all velocities i.

4 Current Results

Figure 1 compares the simulated GRFs to the experimental data for walking and trotting. The curves of the walking gait gradually change from single humped at slower speeds to double humped at faster speeds. The general shape of the GRF trajectories for trotting remains the same over a range of velocities, yet force magnitudes increase as speed is increasing. This is a consequence of an extended flight phases (with no force) at faster speeds. Forces of both gaits could be explained reasonably well with the simplistic model.

We used the same value of spring stiffness for both front legs and another value for hind legs. After optimization, the values of these parameters remain almost the same at all these velocities. For the trotting gait, the spring stiffness are almost identical for front and hind pair of legs but at walking gait the front legs' stiffness are always larger than the hind legs (Fig. 2, top).

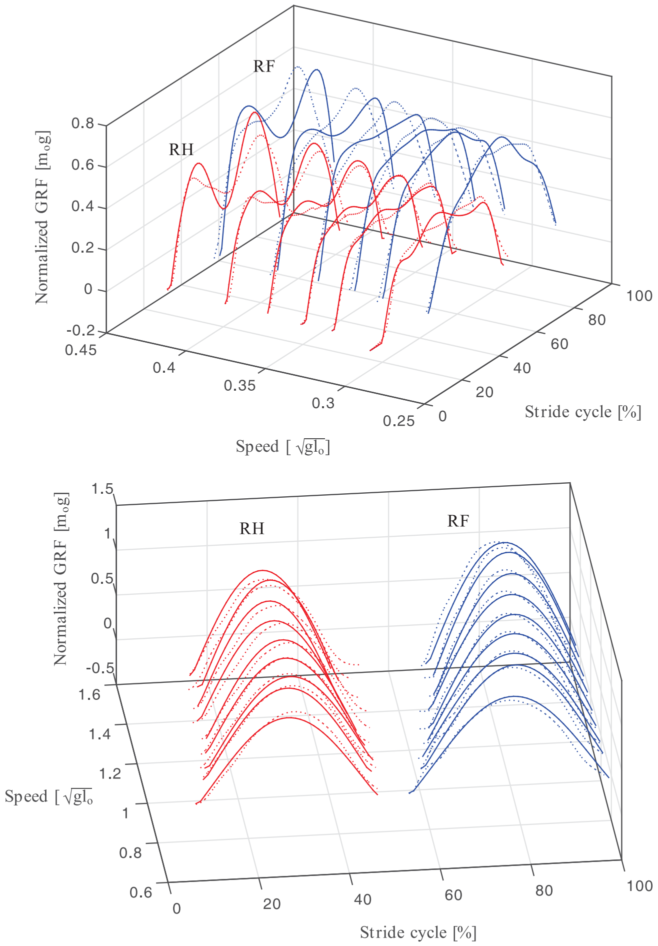

Figure 1: A simple passive dynamic quadrupedal model with massless elastic legs can reasonably well explain the vertical ground reaction forces of horses walking (top) and trotting (bottom) at different velocities. Shown are experimental (dotted) and model predicted (solid) forces for the right hind (RH) and fore (RF) limbs.

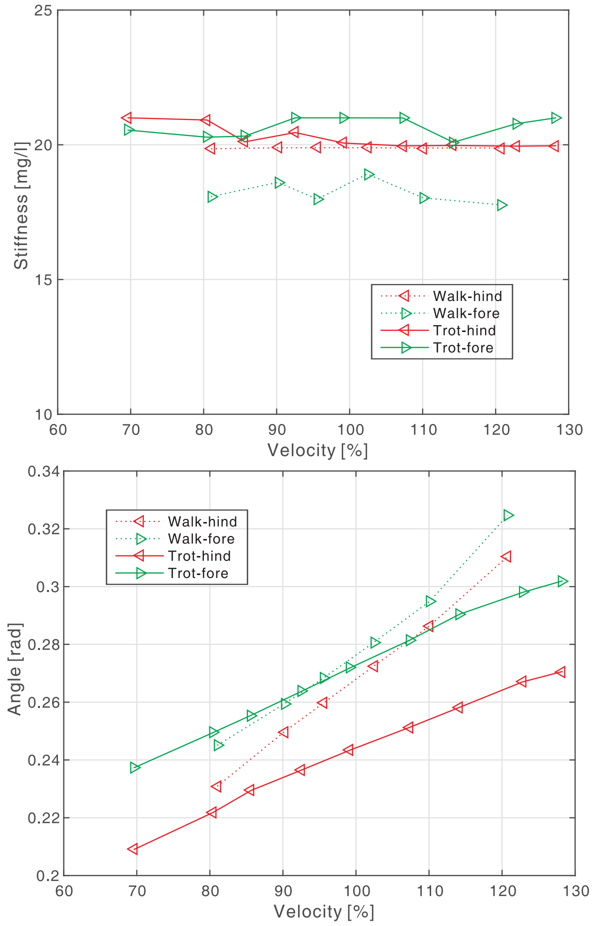

Figure 2: For both, walk and trot, leg stiffness of the model was not found to change when matching experimentally recorded GRFs across different velocities (top). The main adaption in the model was a change of the angle of attack (bottom), which increased linearly with velocity. All velocities are expressed as percentages of variations with respect to their mean values to better demonstrate the differences of trotting and walking.

In contrast, a strong dependency on locomotion velocity was found for the angles of attack for both fore and hind limbs. Values increased nearly linearly with faster speeds. In our model, these changes and an increase in system energy were the main drivers of velocity adaptation (Fig. 2, bottom).

References

[1] S. Khumsap, H. Clayton, J. Lanovaz, and M. Bouchey, "Effect of walking velocity on forelimb kinematics and kinetics," *Equine Veterinary Journal*, vol. 34, no. S34, pp. 325–329, 2002.

[2] P. Van Weeren, A. Van den Bogert, W. Back, G. Bruin, and A. Barneveld, "Kinematics of the standardbred trotter measured at 6, 7, 8 and 9 m/s on a treadmill, before and after 5 months of prerace training," *Cells Tissues Organs*, vol. 146, no. 2-3, pp. 154–161, 1993.

[3] Z. Gan and C. D. Remy, "A passive dynamic quadruped that moves in a large variety of gaits," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, pp. 4876–4881, IEEE, 2014.

[4] Z. Gan and C. D. Remy, "Passive dynamics explain quadrupedal walking, trotting, and tölting," *Journal of computational and nonlinear dynamics*, (under review),2015.

[5] M. Weishaupt, H. Hogg, J. Auer, and T. Wiestner, "Velocity-dependent changes of time, force and spatial parameters in warmblood horses walking and trotting on a treadmill," *Equine Veterinary Journal*, vol. 42, no. s38, pp. 530–537, 2010.

[6] C. T. Farley, J. Glasheen, and T. A. McMahon, "Running springs: speed and animal size," *Journal of experimental Biology*, vol. 185, no. 1, pp. 71–86, 1993.

[7] Z. Gan and C. D. Remy, "A simplistic model for quadrupedal walking and trotting," *Dynamic Walking*, 2013.