Generalized Dog Motion Measurements to Support a Simple Model of Rotary Galloping Locomotion

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The gallop is the preferred gait by mammals for agile traversal through terrain. This motion is intrinsically complex as the feet are used individually and asymmetrically. Experimental data for the gallop are limited due the large workspace needed because of the gait's speed and long traversal. A generalized motion measurement strategy is adopted based on high-speed, motion capture with a reduced marker set and an emphasis on body and leg kinematics and with limited ground reaction force measurement. This allows for an extension of the workspace and allows for markers to be placed in locations with reduced tissue compliance. This is sufficient for capturing the principal motion and for making kinematic comparisons to a previously developed approximating impulse model framework. A series of gallops were measured in a large gait laboratory (18 m^2 principal working area) from three canine subjects (ranging from 8 to 24 kg) galloping down a 15 m runway. Normalized results show a correlation with motions suggested by the impulse model and are in keeping with insights from previous animal and legged robot studies.

Keywords: gallop; locomotion; impulse model; gait measurement; canine.

1. Introduction

Legged platforms offer unparalleled adaptation and obstacle traversal over rough terrain. Rapid field motion requires the adoption of dynamic gaits that, unlike walking, are statically unstable, but agile. For quadrupeds this is manifest in the trot and gallop, with the gallop achieving higher speeds and greater energetic efficiency through the asymmetric extension of the flight phase.[1]

A gallop is intrinsically different from the other dynamic gaits in that the feet are used individually, and the footfall timing lacks any apparent symmetry.[2] Experimental measurement is complex and requires large infrastructure. Consequently, experimental data against which gallop models can be validated are quite sparse. Prior efforts have included both active and passive measurement. Active measurement with instrumented subjects (such as horses[3] and large dogs[4]) require a complex processing and are limited to large subjects such that the dynamics of the sensor payload are negligible. Passive measurement using reflective markers and motion capture (such as that applied to dogs[5]) generally focuses on motion kinetics and ground reaction forces and is limited by the joint camera workspace, camera resolution, and force plate dimensions.

This is in contrast to more general kinematic relationships suggested by simple models in robotics, such as those proposed most recently by the authors[6] and by others including Raibert,[7] Herr and McMahon,[8] Schmiedeler and Waldron[9] and Poulakakis *et al.*[10] These models approximate away some effects and subtle interaction to provide deep insights and approximate solutions that are in keeping with the hierarchical controllers employed by these robots. This paper suggests a simplification of the experimental approach to align it to the overall insights suggested by these models. That is a focus on the general body motion and instead of the musculoskeletal forces central to biomechanics analysis. This abstracts details, but still provides a mechanism to assess important assumptions used by simple models. In particular, this paper makes comparison against a dynamic impulse model[6] through the measurement of the galloping motion of three dogs (of varying size) by tracking key leg and body locations using a twelve-camera, synchronized high speed motion capture system optimized for range. The results are in accordance with insights from previous legged robot and animal studies, such as those from recent force plate experiments with galloping dogs[5] and dynamic legged robots, such as KOLT.[1]

2. Galloping Dynamic Model

The galloping gait can be modeled in the impulse-momentum domain with an impulse balance considered over the entire stride period, T. This views the gallop as being an asymmetric bound in which the front and rear leg pairs “skip”. The advantage of splitting out the legs at each stance in this way is that the impulse impelling each hop is halved. This assumption is in keeping with lower observed costs of transport[11] as the vertical energy loss in a gallop is approximately one quarter of that of a bound.

When combined with simplifying assumptions, such as small roll and pitch angles and negligible leg mass (compared to body inertia), some predications about the gallop can be drawn. For full details and derivations the reader is drawn to previously published analysis.[6] Some notable conclusions from this include: (1) that the two durations of gathered and spread double support/flight phase are the same; (2) that changes in angular velocity occur in two steps instead of one; (3) that body motion is independent of the distribution of forces during contact and hence that these forces can be integrated over time and treated as a resultant; and (4) that speed at which the first foot impacts the ground is equal speed at which the second foot leaves the ground.

3. Experiments

A series of motion capture experiments was conducted to experimentally validate the assumptions underlying the impulse model approach. In particular, the impulse model gives general predictions for the center of mass motion. Thus it is not necessary to compute inverse dynamics and hence motion analysis can focus on kinematics.

The approach taken was to adjust passive marker motion capture for greater range and a larger workspace by simplifying the marker-set so that the there was less chance of self-occlusion and marker observation loss, which allowed for the cameras to be placed further apart and yet maintain the necessary three camera views per marker throughout the workspace. A Vicon MX high speed (400-fps) video motion capture system using 12 cameras was setup with a $6m$ long by $6m$ wide by $2.5m$ high reconstruction volume as verified through system software and validation during calibration. Four markers were placed in a rectangular perimeter around the force plate to define a $5.4m$ by $3.3m$ principal region (in which 4 or more cameras could see the marker). A $15m$ long runway was outlined to pass through this region (see also Figure 1).

Three canine subjects weighing 7.6 kg, 19.2 kg, and 24 kg respectively were tested. The subjects were fitted with passive spherical motion markers around key joints in the leg (i.e., on the toe, the foot [near the ankle], and the lower leg [next to the knee]), around the collar, and on the head (see also Figure 2). All of the subjects were given plenty of time to warm up and practice before being instructed by their owner to gallop down the runway as quickly as possible. Trials were repeated between 8 to 10 times (see also Figure 3).

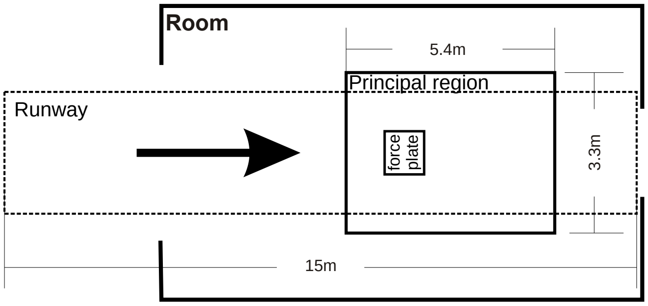

Fig. 1. Gait lab schematic showing the general layout for experiments. The runway was designed with a wide corridor for experimental simplification as the subject does not need to land with a single contact on the force plate.

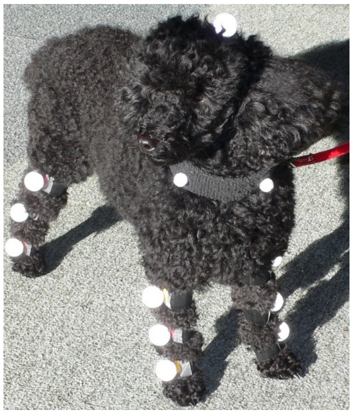

Fig. 2. A subject as outfitted with a simplified passive reflective markers set with three on each leg, a four around the collar, and one on the head.

4. Discussion

It is attractive to assume that the left and right legs of a pair generate identical impulses since they are constructed identically. The force plate data[5] indicate that although there are differences between the magnitudes of the force components, and in the durations of the stances of the legs of each pair the resultant impulses of each lateral pair of legs are very nearly identical, supporting the above assumption.

Fig. 3. In this picture a subject is galloping down the runway at 6.2 m/s. The gathered flight phase is clearly visible. Note the location of the marker poles for the convenience of the owner to have the subject gallop down the principal region of interest.

The variations in the velocities, vertical position, and angular velocities are shown schematically and compared to normalized experimental measurements for the galloping runs detailed in the previous section (see also Figure 4). A notable difference is the relatively large roll excursions of the rotary gallop. This results from the feature of this gait of having a single roll oscillation in every stride, as compared to a double oscillation for the transverse gallop. It is apparent from high-speed photographs that some fast running animals that use rotary gallops exhibit large pelvic rotations, notably cheetahs and greyhounds. This may be an adaptation to reduce the effects of these large roll excursions.

The experimental measurements show supporting evidence for some of the main assumptions. For example, the duration equal duration of flight phases is evident in both translational and rotational measurements. The data also shows a slight variation in upward vertical velocity components before and after stance, which is more consistent with the impulse model than the SLIP model.

Noise, soft-tissue flexure, and approximations in determining difficulty the center of mass location remain evident as seen by the small discrepancies present in the results. For example, the measurements of minimum position ($z_{\min}$) do not exactly align with the zero of the vertical velocity (u) as is obviously the case in true nature. There is variance beyond that of the motion capture system. As detailed in 6, efforts are being investigated to address this matter. Also, the current process of averaging gait cycles with their stochastic nature and noise could be biasing the result, in particular the rapid change in angular during gathered flight might be due to other effects such as cross-coupling and gait variation.

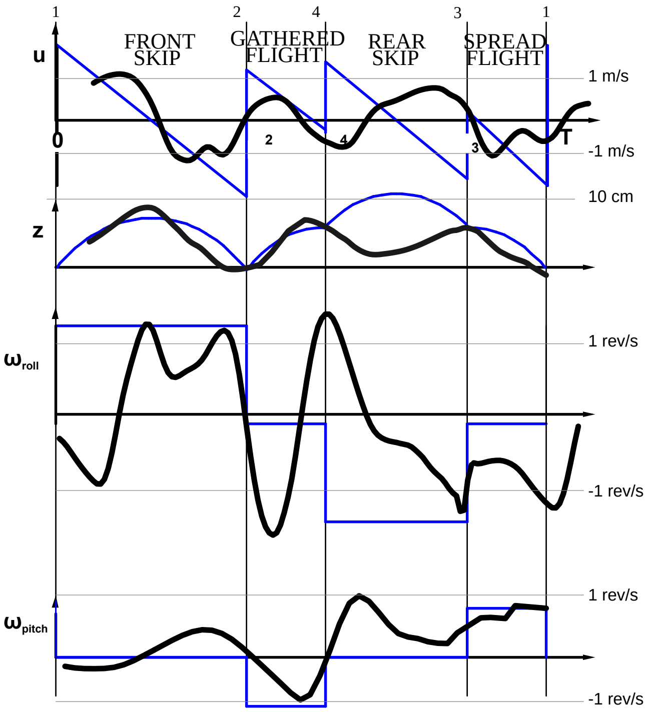

Fig. 4. Graphical representation of variations of velocity (u) and position (z) through a rotary gallop stride. Notable is the extension of the roll (x) axis angular velocities and angular positions. Superimposed on the graph (black line) is a normalized plot of results averaged over several cycles from the trails conducted. The units indicated are for the experimental (black line) as the theoretical results are given to scale.

5. Conclusions

The theory presented here predicts behaviors that resemble those observed in galloping mammals, and also in robotic experiments in dynamic legged locomotion. However, it also raises many questions that will require more comprehensive measurements for their resolution.

In order to produce a mathematically workable, and reasonably transparent model, we have made a number of assumptions about the system. Most of these can be shown to be approximately valid. However, the assumption that the principal moments of inertia of the system are aligned with the chosen body reference frame, and are constant through the stride cycle is questionable. Also, there is an implicit assumption that the body is rigid. This runs counter to the observation that galloping mammals employ spinal flexure in the sagittal plane to lengthen their flight phases. It does have the effect of changing the hip to shoulder distance, and of varying the moments of inertia. The results of this study also point out the importance of comprehensive empirical observation of dynamic biological systems.

6. Future Work

A limiting issue with this work is the need for a structured gait laboratory with extensive experimental infrastructure. Even considering that one of the largest and most advanced rooms available was used for these experiments, strides could only be analyzed over short distances (6 m). Thus as an alternative to use of force-plate data, inertial sensors mounted on the body are be used to estimate the changes in momentum, and angular momentum resulting from the leg impulses.[4] This is similar to localization of a dynamic robot using inertial sensing. It has the advantage of providing data continuously over an indefinite number of strides, and does not require placement of the feet in specific locations, as is necessary for force-plate readings, and can be operated in less structured environments. This would also allow for measurements of the lateral forces associated with agile operations such as turning and weaving.

Future work is investigating mechanisms for extended measurement by both field vision systems and by treadmill study. The former tends to be limited by camera resolution. The later is limited by evidence that suggests a variation between overground and treadmill ground reaction forces;[12] however, such experiments might have reduced levels of experimental noise and variation.

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