ISOLATING FUNCTIONAL DEGREES OF FREEDOM IN LIMBS DURING LOCOMOTION

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The pattern of limb movements characteristic of a given vertebrate during locomotion is, at least in part, reflected in its osteology. The limbs, working in concert, produce an efficient (hence smooth) forward movement of the body. Candidate movements for a given limb can be formalized as trajectories within a configuration space defined by all possible combinations of joint deflection angles, to within some given angular resolution. This space can then be explored using Genetic Algorithms (GA) techniques, where a candidate movement is evaluated on how well it transports the body while minimizing angular and translational deviations during the forward path. This application focuses on the pectoral girdle and forelimbs of the sauropod *Apatosaurus*, to determine how the limb might have functioned during locomotion. The wrist, elbow, shoulder, and pectoral girdle are provided appropriate functional degrees of freedom (FDOFs) per joint (e.g., flexion/extension at the elbow; flexion/extension plus abduction/adduction and medial- and lateral-rotation at the shoulder). By selectively adding and removing specific FDOFs it possible to isolate the relative contribution of each towards the locomotion task. This is particularly important in examining the potential mobility of the pectoral girdles, for which no strong constraint on their position and range of motion is provided by their osteology.

Joint flexibility is represented by a Range of Motion (ROM). ROMs describe limits of flexibility using FDOFs. FDOF estimation is based on anatomical and physiological constraints. Each configuration within the ROM specifies all 6 geometric DOFs (3 rotational, 3 translational). The *Apatosaurus* forelimb model has 7 FDOFs at 4 articulation points: scapulothorax (rotation, elevation), shoulder (flexion/extension, abduction/adduction, medial/lateral rotation), elbow (flexion/extension), and wrist(flexion/extension). Figures 1 and 2 show the *Apatosaurus* articulation points.

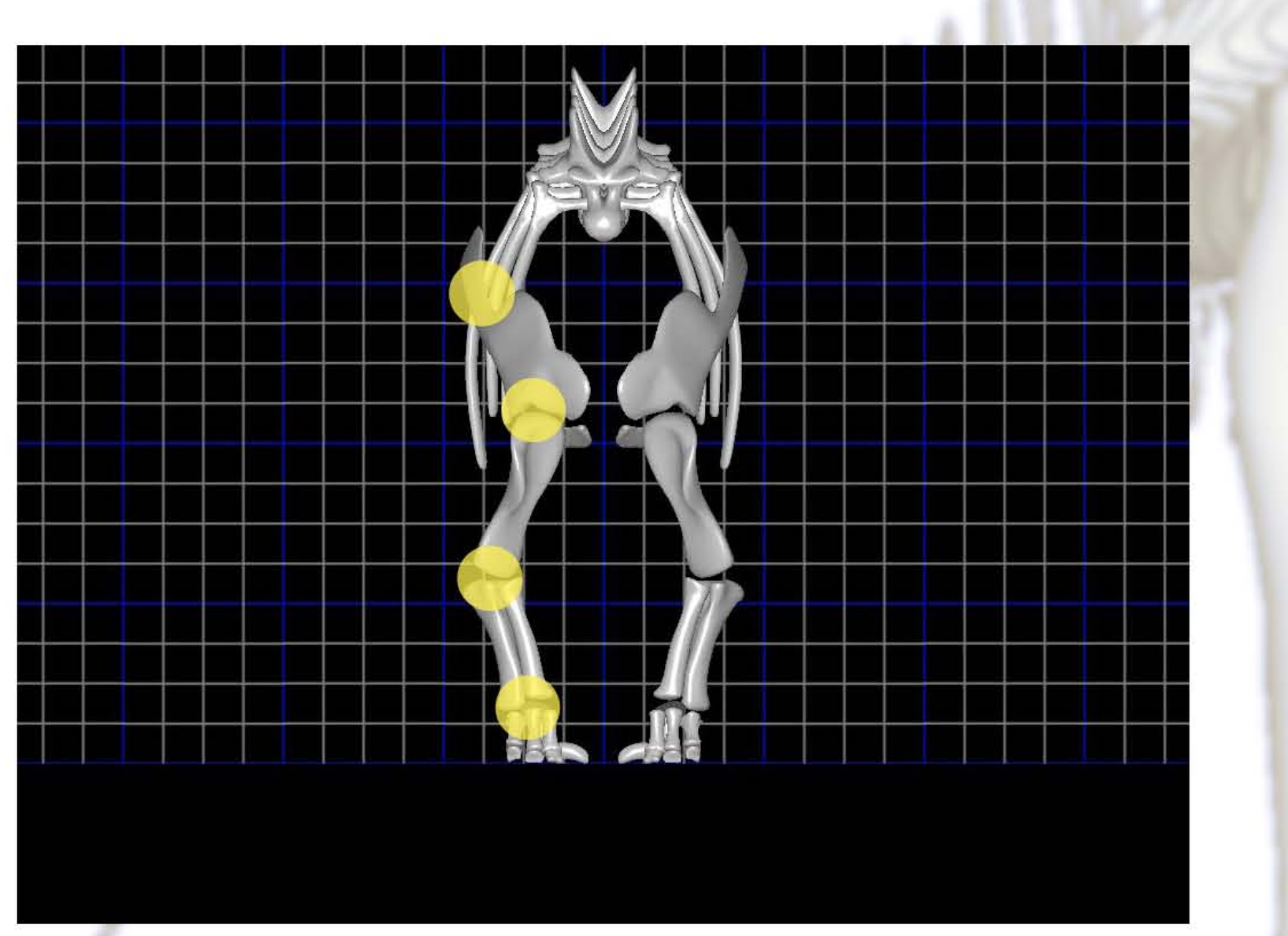

Figure 1

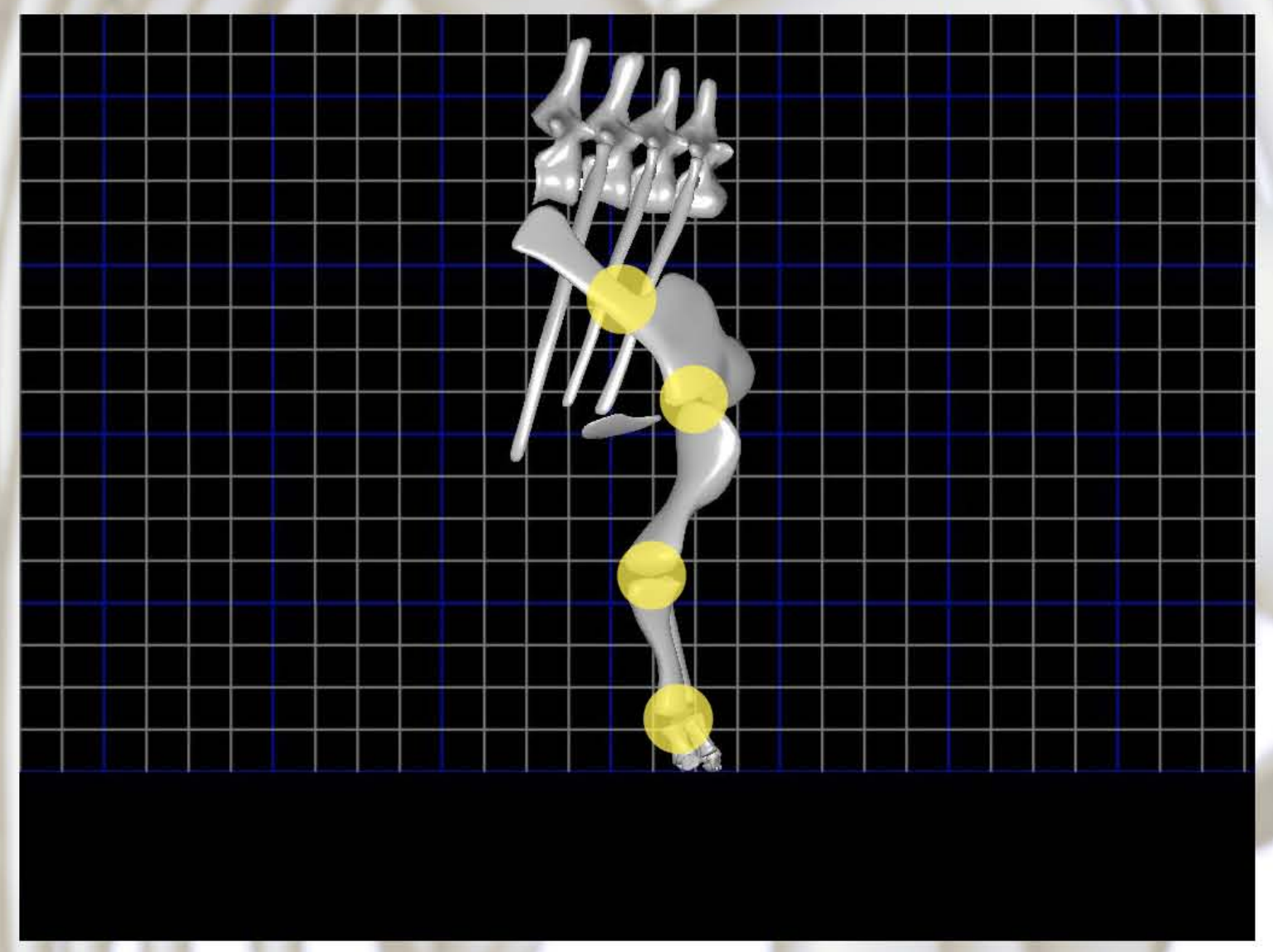

Figure 2

To determine the effect of FDOFs on body position and orientation, the right manus is first positioned and oriented on the ground based on trackways. All combinations of FDOFs are then evaluated at 4˚ resolution (5cm resolution for translation-only FDOFs). Manus position and orientation is maintained fixed throughout the evaluation process. Resulting thorax positions and orientations (measured at the 3rd dorsal) are stored. Figure 3 shows the resulting Limb ROM (LROM) space. Colors represent the minimum change in thorax orientation necessary to reach each position (green for least, red for most).

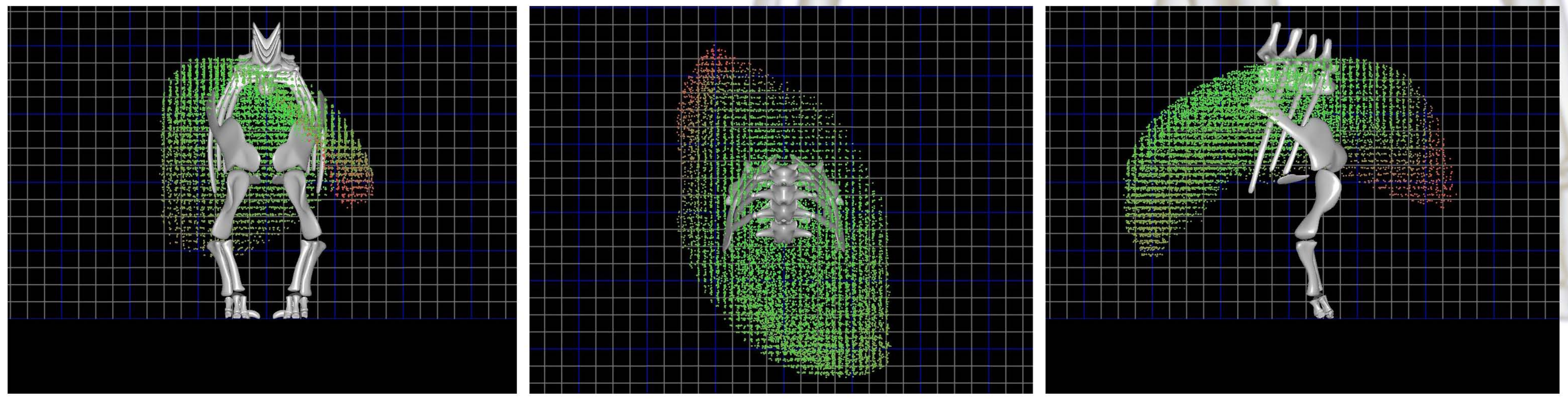

Figure 3

Left and right side LROMs are combined to constrain forward locomotion. During the Dual Support phase, both limbs are in contact with the ground, so the thorax positions and orientations predicted by the LROMs must be consistent. To satisfy this constraint, 4 events are identified for the right limb: Right Down (RD), Right when Left Down (RLD), Right when Left Up (RLU) and Right Up (RU). Equivalent events are also identified for the left limb. Figure 4 illustrates the relationships between these events, the Duty Factor, and the Dual Support phase. Limb trajectories are assumed to be symmetrical across the parasagittal plane and be 180˚ out of phase for forward locomotion.

The limb trajectories are mirrored across the parasagittal plane and 180˚ out of phase, so the LROM configuration at RLD should be equal to the LROM configuration at RD but mirrored across the parasagittal plane (and further along the direction of travel). Consistency between the left-and-right-side LROM thorax predictions is achieved by only selecting LROM configurations for RD such that a mirrored LROM configuration exists for RLD. Similarly, a mirrored LROM configuration must exist for RU with respect to RLU. Figure 5 illustrates these relationships.

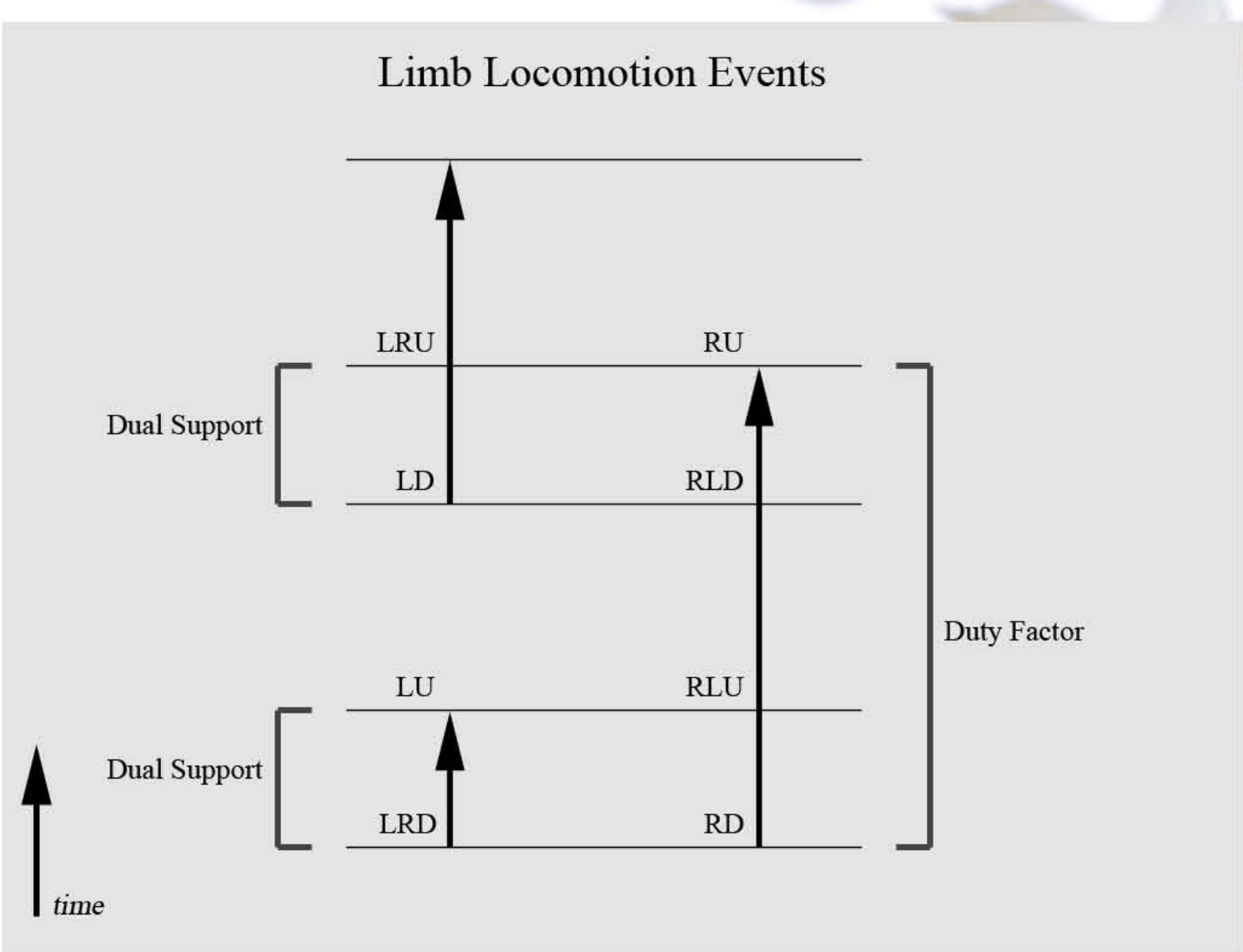

Figure 4

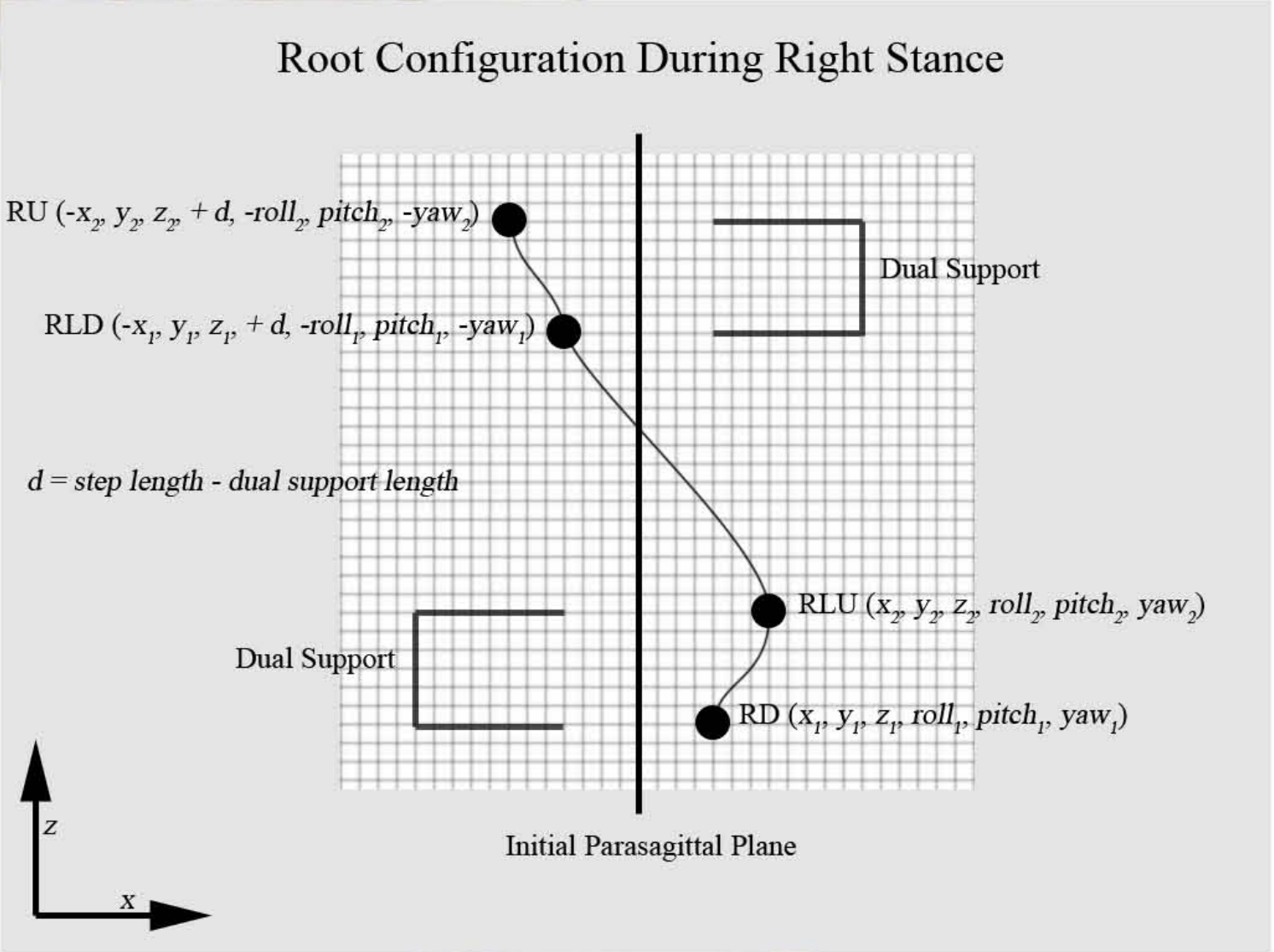

Figure 5

The GA selects sets of LROM configurations that generate forward locomotion. The GA encourages lateral/vertical smoothness of the thorax trajectory and discourages pitching, yawing, and rolling of the thorax. Table 1 shows the effect of selectively disabling FDOFs (averaged over 10 GA runs each).

Table 1

	Error (summated over 100 trajectory samples)				
FDOFs utilized	Pitch (˚)	Yaw (˚)	Roll (˚)	Lateral (cm)	Vertical (cm)
All FDOFs (7 FDOFs)	256 ± 91	415 ± 234	187 ± 110	176 ± 100	227 ± 74
Missing shoulder abduction/adduction FDOF, with scapulothorax FDOFs (6 FDOFs)	127 ± 13	374 ± 89	99 ± 29	240 ± 26	263 ± 71
Missing shoulder abduction/adduction FDOF, without scapulothorax FDOFs (4 FDOFs)	346 ± 0	529 ± 0	203 ± 0	249 ± 0	215 ± 0
Missing shoulder medial/lateral rotation FDOF, with scapulothorax FDOFs (6 FDOFs)	197 ± 36	446 ± 61	163 ± 11	204 ± 128	279 ± 29
Missing shoulder medial/lateral rotation FDOF, without scapulothorax FDOFs (4 FDOFs)	95 ± 0	429 ± 0	381 ± 0	828 ± 0	232 ± 0

Disabling medial/lateral rotation at the shoulder causes considerable body roll and lateral sway during forward locomotion. Disabling abduction/adduction at the shoulder introduces additional body pitching and yawing. Allowing scapulothorax rotation and elevation partially compensates for these effects in both cases. Figure 6 shows frames from an *Apatosaurus* walk cycle generated using these methods.

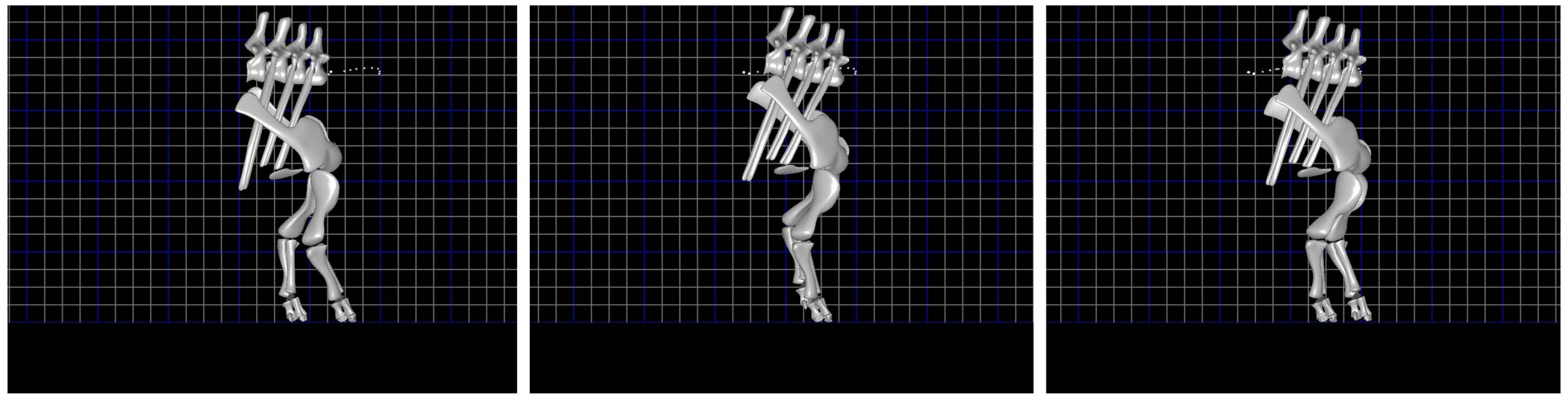

Figure 6