Long-axis rotation (LAR): a missing degree of freedom in avian bipedal locomotion

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1 Introduction

The hind limbs of ground-dwelling birds have traditionally been characterized as restricted to planar motion by hinge-like hip, knee, and ankle joints. Yet bird limbs must be able to deviate from parasagittal in order to maneuver, balance during single support, and correct instability. 2-D analyses from a lateral perspective are effective for measuring flexion-extension movements and moments, but what is being missed when joints are not treated in 3-D during locomotion? Here we present high-resolution kinematic data for the hip, knee, and ankle in a chicken-like bird, the helmeted guineafowl (*Numida meleagris*).

2 Methods

We quantified motion using marker-based XROMM: X-ray Reconstruction of Moving Morphology [1, 2]. This method combines biplanar x-ray videos with CT-scans of the same individual to create accurate 3-D animations of skeletal elements (Fig. 1).

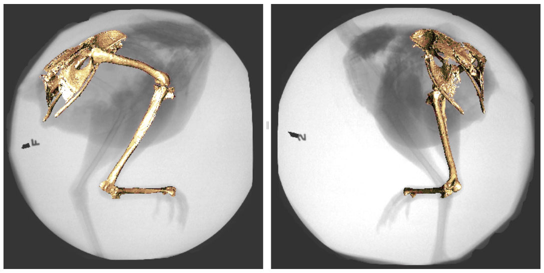

Figure 1: XROMM analysis of skeletal motion

Clusters of surgically implanted carbide markers were tracked to calculate rigid body kinematics and animate polygonal bone models at 250 fps. Unlike efforts to measure 3-D motion with surface markers [3, 4], x-ray imaging is unaffected by soft tissue artifact, eliminates marker occlusion, and allows the fidelity of reconstructed motion to be visually checked. Six degree of freedom data were extracted using explicit Joint Coordinate Systems [5, 6] during treadmill walking, maneuvering, jumping, and sit-stand behaviors (Fig. 2).

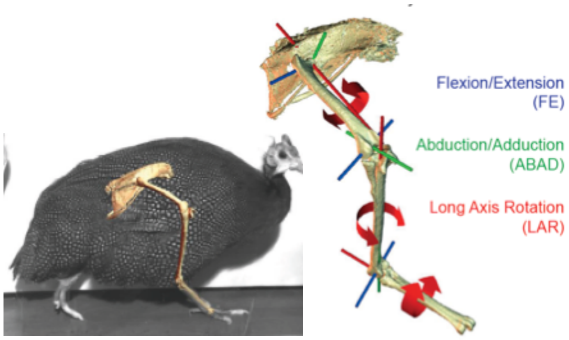

Figure 2: Joint Coordinate Systems for the right leg

3 Results

Joint flexion-extension patterns are concordant with those reported for guineafowl and related taxa from 2-D analyses [7]. The ankle (intertarsal) joint acts relatively hinge-like with minimal abduction-adduction or long-axis rotation (LAR). Most striking, however, is the prevalence of LAR at the hip and knee. During one maneuver, a bird pivoted its entire body about the stance phase knee using internal tibiotarsal LAR of 67°. In a side-step maneuver, lateral displacement of a swing foot was accomplished by external tibiotarsal LAR of 50°.

LAR is always present during treadmill walking (Fig. 3). In “steady” locomotion performed with a slightly yawed pelvis, femoral LAR can exceed hip extension. LAR of the femur and tibiotarsus increases with degree of yaw; elements counter-rotate to skew the path of the foot relative to the body. Pelvic yaw requires kinematic asymmetry, creating an intriguing coordination in which the alternating left and right limbs flex-extend out-of-phase while undergoing in-phase LAR.

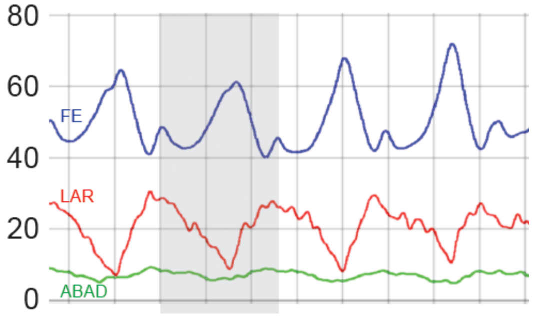

Figure 3: Hip rotation angles for four strides of fast walking locomotion

4 Discussion

LAR is central to avian bipedal locomotion in even the most parasagittal of species. Given that abduction-adduction is highly restricted at all three joints, the ability to "spin" the femur and tibiotarsus provides the flexibility to reposition and reorient the foot in 3-D. Despite the limb's superficially planar appearance, motion and loading about long bone axes are critical to both avian locomotor mechanics today as well as to the evolution of bipedalism in the dinosaurian lineage leading to birds.

5 Open questions

Is LAR currently being used for legged robots, and if not, why not? Are there benefits to spinning limb segments rather than ab/adducting them? Does a biped with bicondylar joints capable of both flexion/extension and LAR make good sense from an engineering perspective?

References

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