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Short communication

Automated approximation of center of mass position in X-ray sequences of animal locomotion

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ABSTRACT

A crucial aspect of comparative biomechanical research is the center of mass (CoM) estimation in animal locomotion scenarios. Important applications include the parameter estimation of locomotion models, the discrimination of gaits, or the calculation of mechanical work during locomotion. Several methods exist to approximate the CoM position, *e.g.* force-plate-based approaches, kinematic approaches, or the reaction board method. However, they all share the drawback of not being suitable for large scale studies, as detailed initial conditions from kinematics are required (force-plates), manual interaction is necessary (kinematic approach), or only static settings can be analyzed (reaction board). For the increasingly popular case of X-ray-based animal locomotion analysis, we present an alternative approach for CoM estimation which overcomes these shortcomings. The main idea is to only use the recorded X-ray images, and to map each pixel to the mass of matter it represents. As a consequence, our approach is surgically noninvasive, independent of animal species and locomotion characteristics, and neither requires prior knowledge nor any kind of user interaction. To assess the quality of our approach, we conducted a comparison to highly accurate reaction board experiments for lapwing and rat cadavers, and achieved an average accuracy of 2.6 mm (less than 2% of the animal body length). We additionally verified the practical applicability of the algorithm by comparison to a previously published CoM study which is based on the kinematic method, yielding comparable results.

1. Introduction

The instantaneous position of an animal's center of mass (CoM) during locomotion is of basic interest in comparative biomechanical research. Amongst various applications, assessing this parameter is necessary for the analysis of global parameters used in minimalistic models of animal and human locomotion. These models use “virtual legs” with spring-like or pendulum-like behavior that are “anchored” between the center of pressure of ground contact and the animal's CoM (*e.g.* Cavagna et al., 1977; Blickhan, 1989). Also, the derivative of the CoM position is needed to calculate the mechanical work during locomotion (Cavagna et al., 1977), and, relatedly, mechanical energy fluctuations of the CoM are widely used to discriminate gaits in legged locomotion (*e.g.* Biewener, 2006).

Ideally, the instantaneous position of the CoM is found by double integration of the forces exerted onto force-plates during steady-state locomotion and subsequent combination of this data with simultaneously recorded motion capture data (*e.g.* Cavagna, 1975; Maus et al., 2011). However, a fundamental problem in comparative biomechanics of locomotion in small animals is the difficulty to obtain steady-state locomotion in trackway experiments. In those cases, kinematically determined CoM position estimates are necessary to minimize drift based errors in force-plate measurements (*e.g.* Daley et al., 2006). Periodic locomotion is more readily accomplished by animals trained to walk and run on treadmills. While treadmills instrumented with several force-plates to register single limb ground reaction forces are available (*e.g.* Dierick et al., 2004; Brebner et al., 2006; Abdelhadi et al., 2012), these devices appear more applicable for studies of larger and more easily trainable animals such as dogs or horses.

Alternatively, the instantaneous CoM position can be determined by combining detailed kinematic data of all moving body segments and knowledge of each of these segments' mass and CoM position (*e.g.* Nyakatura et al., 2012). High-speed fluoroscopy of small, rapidly moving animals allows a highly detailed kinematic analysis of all skeletal elements hidden under fur or feathers and other tissue (*e.g.* Gatesy, 1999; Fischer et al., 2002), but noninvasive, automated kinematic analysis for fluoroscopy is still in its infancy (You et al., 2001; Miranda et al., 2011; Haase et al., 2011). To date,

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obtaining the kinematic data from X-ray recordings is achieved through manual digitization of landmarks resulting in substantial time needed for the analysis of the CoM. Here, we present a novel technique to estimate the instantaneous position of the CoM on X-ray recordings for small animals locomoting on a treadmill. It uses a fully automated computer vision approach, allows the analysis of large datasets, and does not necessarily depend on steady-state locomotion, facilitating larger scaled comparative studies of CoM position and mechanics between different species and/or differing locomotor tasks. To assess the accuracy of our approach, we perform a comparison of results for a lapwing and a rat to reaction board measurements which provide a highly accurate reference CoM approximation. We additionally apply our method to the terrestrial locomotion of lapwings and test its practical applicability through comparison to previously published CoM movements obtained using the kinematic method.

2. Methods

2.1. Automated CoM estimation

To achieve our goal of a surgically noninvasive method which is able to approximate the position of the CoM without any kind of user interaction, we solely base the estimation on the images of a given X-ray sequence. The main idea of our approach is to relate each pixel of an image to the mass of matter it represents. The theoretical basis for this process is the *Beer–Lambert law* (Kak and Slaney, 2001; Buzug, 2008, also supplement Section A.1), which describes the absorption of electromagnetic waves traversing an arbitrary material. To resolve ambiguities arising from the fact that only one X-ray view is available (*cf.* Tuy, 1983; Buzug, 2008), we have to assume volumic mass and X-ray absorption coefficients to be identical for all materials. It can then be shown that the approximate mass $m_{x,y}$ corresponding to each pixel (x, y) of an X-ray image $\boldsymbol{I}$ is proportional to the logarithm of its [0, 1]-normalized gray scale value $\boldsymbol{I}_{x,y}$ ($0 \hat{=}$ black, $1 \hat{=}$ white). The 2D CoM $\boldsymbol{\mu} = (\mu_x, \mu_y)^\top$ can then simply be computed as the centroid of $\boldsymbol{I}$, weighted by the mass corresponding to each pixel, *i.e.*

$$\boldsymbol{\mu} = \frac{\sum_{(x,y)} \ln(\boldsymbol{I}_{x,y}) \cdot \binom{x}{y}}{\sum_{(x,y)} \ln(\boldsymbol{I}_{x,y})}. \tag{1}$$

Note that $\boldsymbol{\mu}$ is inherently represented within the image's coordinate system. To obtain the 2D CoM position in millimeters or even in 3D for a biplanar camera setup, a calibration of the camera system is necessary (Hartley and Zisserman, 2003; Stevens et al., 2006; Hedrick, 2008).

As the CoM calculation is solely based on image gray values, it is crucial to remove all background information from the images. Based on the Beer–Lambert law, a known background component (*e.g.* obtained by recording an empty sequence) can be removed from an image via a pixel-wise division by the background image (see Supplement Section A.2). However, in many cases such as for previously recorded datasets, the background is not known and thus has to be estimated from the image sequence itself. Because this is an ill-posed problem (*i.e.* an infinite set of solutions exists), we regularize the estimation to maximize the information explained by the background. The regularized problem has a unique solution which can efficiently be computed as the pixel-wise maximum over all images of a sequence. Artifacts in the background estimation may appear when the animal remains relatively static over the course of an entire sequence, but can easily be corrected using inpainting techniques (*e.g.* Bertalmío et al., 2001).

A more detailed derivation and discussion of our algorithm is given in the supplementary material. An implementation of the algorithm is provided for MATLAB® and C++ free for use under http://www.inf-cv.uni-jena.de/locomotion.

2.2. Experimental evaluation of our approach

To reliably assess the accuracy of our approach, we performed a comparison to the highly accurate reaction-board method for CoM estimation (Özkaya and Nordin, 1999, Chapter 4) using frozen cadavers of a lapwing (*Vanellus vanellus*) and a rat (*Rattus norvegicus*). Each cadaver was placed on a rigid equilateral triangular plate with an edge length of 0.38 m, whereas each vertex rested on a weighing scale (Fig. 1a). The three scales were calibrated beforehand and had an accuracy of 0.1 g. For each animal, ten trials comprising a variety of poses (*lateral*, *dorsoventral*, varied positions of body parts) were acquired. The weights measured at the three scales were used to derive the reference position of the CoM within the

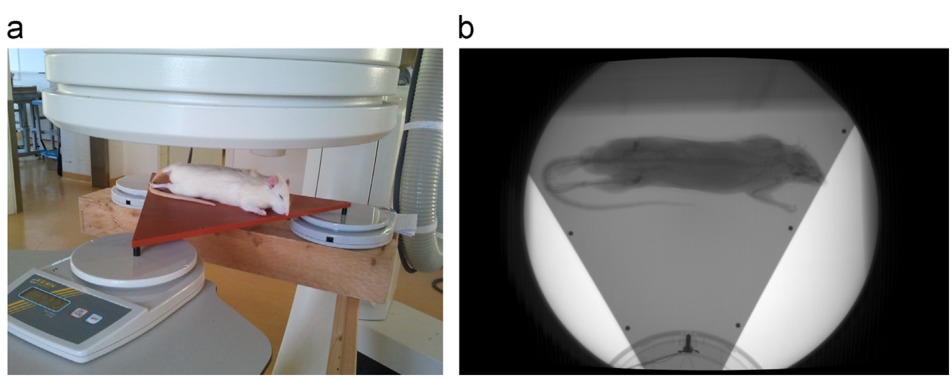

Fig. 1. Experimental setup (a) and corresponding X-ray image (b) used to assess the accuracy of the presented image-based CoM estimation approach.

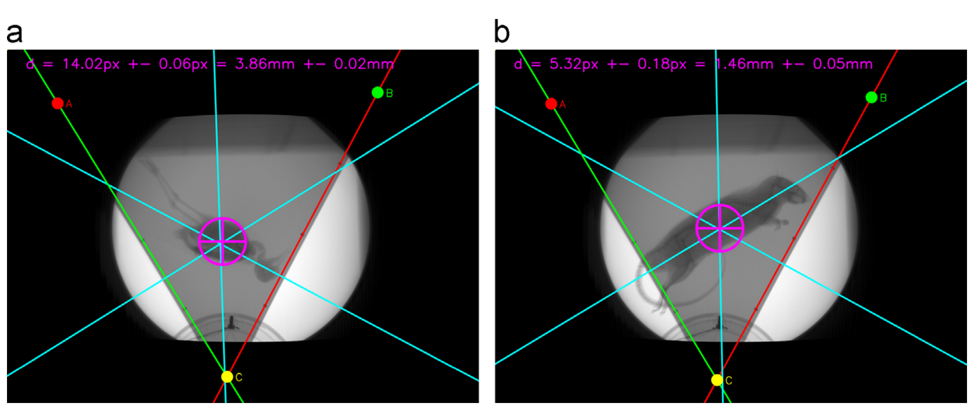

Fig. 2. Qualitative results of the comparison between our approach (magenta cross hairs) and the reaction board method (cyan lines) for the trial with (a) the largest error (lapwing, trial 1, 3.86 mm) and (b) the smallest error (rat, trial 9, 1.46 mm). Automatically reconstructed contact points between the reaction board and the scales are denoted by A, B, and C. Qualitative results for all 20 trials are included in the supplementary material. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)