Technical Note: Out-of-Plane Angular Correction Based on a Trigonometric Function for Use in Two-Dimensional Kinematic Studies

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ABSTRACT In two-dimensional (2D) kinematic studies, limb positions in three-dimensional (3D) space observed in lateral view are projected onto a 2D film plane. Elbow and knee-joint angles that are less than 20° out-of-plane of lateral-view cameras generally exhibit very little measurable difference from their 3D counterparts (Plagenhoef [1979] Environment, Behavior, and Morphology; New York: Gustav Fisher, p. 95–118). However, when limb segment angles are more than 20° out-of-plane, as is often the case in locomotor studies of arboreal primates, elbow and knee angles can appear significantly more extended than they actually are. For this reason, a methodology is described that corrects 2D out-of-plane angular estimates using a series of trigonometric transformations. Am J Phys Anthropol 000:000–000, 2006. ©2005 Wiley-Liss, Inc.

The use of kinematic analytical techniques has greatly advanced the understanding of primate functional morphology (e.g., Rollinson and Martin, 1981; Jouffroy, 1989; Vilensky and Larson, 1989). Kinematic studies offer insights into locomotor behavior and anatomy by documenting the sequence and timing of touchdown and lift-off events (e.g., Hildebrand, 1967; Alexander and Maloiy, 1984; Cartmill et al., 2002), in addition to permitting the quantification of aspects of limb movements throughout the stride cycle (e.g., Demes et al., 1990; Schmitt and Larson, 1995; Larson et al., 2000; Krakauer et al., 2002; Stevens, 2003; Larney and Larson, 2004). Yet kinematic studies are not without limitations, and it has long been recognized that out-of-plane movements can confound two-dimensional (2D) analyses (Plagenhoef, 1979). Limb segments that are rotated toward or away from the camera appear shorter than they actually are. Joint angles measured between such out-of-plane limb segments can appear significantly larger than their actual values. This poses a potentially serious problem for obtaining accurate data in kinematic studies that are limited to lateral-view camera setups. Accuracy is the degree to which a given measurement resembles its actual value (Sokal and Rohlf, 1995; Spencer and Spencer, 1995), and is clearly an important consideration in any locomotor study. Some researchers avoid this reduced accuracy in the laboratory setting by using multiple cameras in a calibrated space, in combination with software packages that employ three-dimensional (3D) kinematic algorithms to record XYZ coordinates for each point of interest (e.g., Polk, 2001). Yet these approaches can be prohibitively expensive, and may not always be feasible in studies conducted in naturalistic settings that exclude optimal positioning for multiple camera views. This study offers an alternative solution, by outlining trigonometric out-of-plane corrections for 2D data sets that reduce out-of-plane measurement errors to less than 5% (Chan, 1997; Schmitt, 1995; Stevens, 2003).

METHODS

In order to use this out-of-plane correction, a few basic requirements need to be met. First, precise limb dimensions (actual segment lengths) must be recorded for each study subject. Animals may then be filmed using a stationary camera set at a sufficient distance from the moving subjects to reduce the effects of parallax (Spencer and Spencer, 1995). Finally, measurements between landmarks in the study space are required for calibration of apparent limb segment lengths.

To test the accuracy of the proposed trigonometric angular correction method, a wire calibration object of known dimensions was designed to resemble a primate forelimb (Fig. 1, Table 1a). A video camera was placed 4 m away from the object in lateral view, and the object was filmed. This position represents the case of a limb in perfect lateral view (0° out of the film plane), whereby the camera is able to "see" the actual elbow-joint angle. The object was then rotated both toward and away from the camera and filmed 45° and 90° out of the film plane, in both directions. Video clips at each position were

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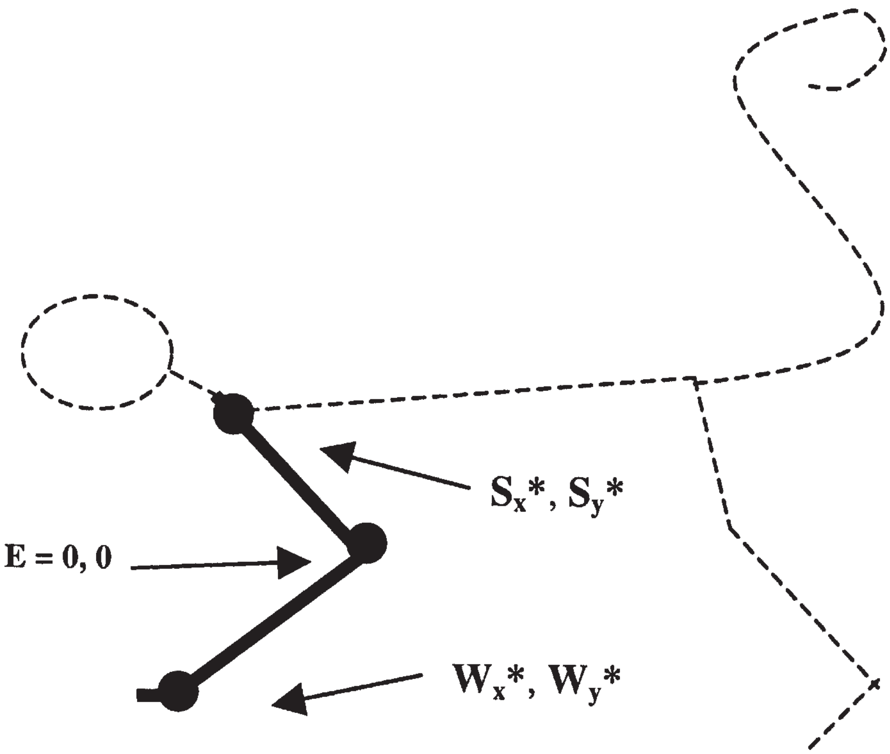

Fig. 1. Schematic of calibration object (heavy line), simulating primate forelimb. XY coordinates for joint of interest (elbow) are set at (0, 0). Coordinates for shoulder and wrist are expressed in relation to their distance from elbow.

exported into Peak Motus software (version 5.1.6), and the calibration object was digitized. XY coordinate data and calibration object segment lengths were then exported from Peak Motus into Microsoft Excel (version 2002). Recorded angles were combined with actual and recorded segment lengths for the calibration frame, in order to permit estimates of actual angles at the simulated elbow joint. To do so, a coordinate system was generated for each simulated joint involved in calculating the angle (i.e., shoulder, elbow, and wrist). Calculations are briefly outlined here to demonstrate angular corrections for the elbow (Table 1a). Knee-joint angular corrections may be made in a similar manner.

The observed XY coordinates for all joints were transformed so that the XY coordinates of the joint of interest (elbow) were translated to the origin (0, 0) (Fig. 1), such that:

$$S_x^* = S_x - E_x \qquad S_y^* = S_y - E_y$$
$$E_x^* = E_x - E_x = 0 \qquad E_y^* = E_y - E_y = 0$$
$$W_x^* = W_x - E_x \qquad W_y^* = W_y - E_y$$

where S_{xy}, E_{xy}, and W_{xy} represent the XY coordinates of the shoulder, elbow, and wrist joints, respectively. Coordinates with an asterisk represent transformed XY coordinates (Table 1b).

Next, out-of-plane angles were calculated for each segment, using 2D *apparent* limb segment lengths measured by the Peak Motus program and *actual* limb segment lengths measured on the calibration object. For example, the out-of-plane angle of the "arm," θ_{arm}, can be represented by the following equation:

$$\theta_{arm} = \cos^{-1}(arm_{apparent}/arm_{actual})$$

where $arm_{apparent}$ is the apparent 2D "arm" segment length or absolute distance between the simulated shoulder and elbow markers measured in the Peak Motus program, and arm_{actual} is the actual "arm" segment length measured on the calibration object. The out-of-plane angle for the "forearm" segment was derived in the same way (Table 1c).

Next, these angles were used to generate Z coordinates to reflect the 3D joint positions of the shoulder and wrist joints (keeping the joint of interest, the elbow, at the XYZ origin 0, 0, 0):

$$S_z^* = arm_{apparent}(\tan \theta_{arm})$$
$$W_z^* = forearm_{apparent}(\tan \theta_{forearm})$$

where $arm_{apparent}$ and $forearm_{apparent}$ represent the apparent lengths of the arm and forearm segments, θ_{arm} and $\theta_{forearm}$ represent the out-of-plane angles of each of the segments, and S_z^* and W_z^* represent the Z coordinates for the shoulder and wrist joints, respectively (Table 1c).

Finally, XYZ coordinates were converted into the 3D angle between arm and forearm:

$$\Omega_{elbow} = \cos^{-1}\frac{(S_x^*W_x^* + S_y^*W_y^* + S_z^*W_z^*)}{arm_{actual}\,forearm_{actual}}$$

where Ω_{elbow} represents the true elbow angle, reconstructed from transformed shoulder and wrist XYZ coordinates and actual arm and forearm segment lengths (Table 1d).

RESULTS AND DISCUSSION

Comparisons of the actual, apparent, and corrected angular estimates are summarized in Table 1d. Without the trigonometric correction described above, calibration segment angles recorded from lateral-view cameras were

TABLE 1. Accuracy of out-of-plane calculations[1]

a) Dimensions of calibration tool, and XY coordinates for joints involved in angle

Degrees out of plane of camera view	Actual elbow angle	Actual arm length[2]	Actual forearm length[2]	S_x	E_x	W_x	S_y	E_y	W_y
0.00	90.00	6.00	7.00	17.44	20.93	15.15	20.03	15.05	11.01
45.00	90.00	6.00	7.00	17.59	19.83	15.79	19.93	15.20	11.11
90.00	90.00	6.00	7.00	15.25	15.15	15.10	19.93	15.15	11.16
−45.00	90.00	6.00	7.00	16.35	18.90	15.35	18.40	13.80	9.45
−90.00	90.00	6.00	7.00	14.55	14.60	14.55	18.48	13.80	9.17

b) Measured segment lengths, and transformed XY coordinates

Degrees out of plane of camera view	Apparent elbow angle	Apparent arm length[2]	Apparent forearm length[2]	S_x^*	S_y^*	W_x^*	W_y^*	E_x^*	E_y^*
0.00	89.93	6.00	7.00	−3.49	4.98	−5.78	−4.04	0.00	0.00
45.00	110.01	5.24	5.74	−2.24	4.73	−4.04	−4.09	0.00	0.00
90.00	180.48	4.78	3.99	0.10	4.78	−0.05	−3.99	0.00	0.00
−45.00	111.78	5.26	5.61	−2.55	4.60	−3.55	−4.35	0.00	0.00
−90.00	178.77	4.68	4.63	−0.05	4.68	−0.05	−4.63	0.00	0.00

c) Segment out-of-plane angles, and transformed Z coordinates

Degrees out of plane of camera view	θ_{arm} (radians)	$\theta_{forearm}$ (radians)	θ_{arm} (degrees)	$\theta_{forearm}$ (degrees)	S_z^*	W_z^*
0.00	0.00	0.00	0.00	0.00	0.00	0.00
45.00	0.51	0.61	29.15	34.92	2.92	4.01
90.00	0.65	0.96	37.19	55.25	3.63	5.75
−45.00	0.50	0.64	28.76	36.73	2.89	4.19
−90.00	0.68	0.85	38.74	48.59	3.75	5.25

d) Comparison of actual angle, with measured angle before and after out-of-plane corrections

Degrees out of plane of camera view	Actual angle	Apparent angle	Corrected angle
0.00	90.00	89.93	89.93
45.00	90.00	110.01	88.06
90.00	90.00	180.48	87.56
−45.00	90.00	111.78	88.46
−90.00	90.00	178.77	92.67

[1] Positive out-of-plane angles indicate rotation of calibration frame toward camera, whereas negative angles denote rotation away from camera.
[2] Segment lengths in cm.

overestimated by as much as 100% of the actual value when the calibration frame was out-of-plane of lateral view. In contrast, the trigonometric corrections described in this study retrieved highly accurate limb-segment angles, differing by less than 2° from the actual value when the object was rotated 45° toward or away from the plane perpendicular to the camera view, and by less than 3° from the actual value even when the object was 90° out of plane in either direction (Table 1d). Although we do not recommend this correction method for reconstructing joint angles in which a proximal or distal reference point (e.g., shoulder or wrist) also exhibits a high degree of out-of-plane displacement, this method clearly corrects well for single elbow or knee joints that are simply rotated out-of-plane, as commonly seen in animals traveling along narrow arboreal supports.

CONCLUSIONS

This study demonstrates a convenient method to correct for out-of-plane limb segment angles in 2D studies, retrieving values that fall well within acceptable 5% accuracy limits (e.g., Polk, 2001). It is important to recognize that potential sources of error in applying this method are similar to those in laboratory experimental approaches, and include the calibration of the study space, the accuracy of limb-segment lengths directly measured on study subjects, the subsequent identification of those landmarks on fur-covered animals, and less significantly, digitizing errors once those landmarks have been identified. We do not recommend the use of this correction for limb angles that are less than 20° out of the film plane, as in this range, relatively small changes in the cosine function result in apparent and actual angles that are not significantly different from one another (Plagenhoef, 1979); hence, application of this method could reduce the accuracy of angular estimates by amplifying the effects of any measurement error. Nonetheless, such kinematic correction approaches may be particularly useful when collecting locomotor data on elbow and knee joint angles in natural settings that prohibit ideal filming conditions using multiple cameras.

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