EVALUATION OF PLANAR RECONSTRUCTION ACCURACY FOR TWO TECHNIQUES INCORPORATING CAMERA TILT

Mark Brewin[1], David Kerwin[1] and Paul McCombie[2]
[1]Department of Sport & Exercise Science, University of Bath, Bath, UK
[2]Department of Architecture & Civil Engineering, University of Bath, Bath, UK

Planar analyses of sporting activities routinely employ scaling techniques with the camera elevated above the activity. An alternative technique for planar reconstruction can be derived from the DLT. This study compared reconstruction accuracy for scaling with 2D-DLT for a large field of view as camera tilt increased. Four calibration and 30 reconstruction markers on a vertical plane were recorded at tilt angles from 0° to 6°. Locations for the reconstruction markers were estimated using both techniques and compared to their known values. The smallest reconstruction errors were obtained using 2D-DLT and were unaffected by tilt angle ($P<0.01$). An increased tilt angle produced significantly larger errors ($P<0.01$) for scaling than 2D-DLT. 2D-DLT provided accurate reconstruction data over a range of tilt angles and should be adopted for planar analyses of sporting activities.

KEY WORDS: two-dimensional, direct linear transformation, scaling, 2D-DLT, tilt correction.

INTRODUCTION: For two-dimensional analyses of sporting activities, where motion is considered to be constrained to a single plane, many studies adopt a linear scaling technique to reconstruct image coordinates into real-space coordinates. In the technique's simplest form the camera is horizontally levelled and located perpendicular to the plane of motion with a scaling object of known length positioned in the same plane. In competition arenas the camera is often elevated above the activity and the orientation of the camera, typically defined by three successive rotation angles; pan, roll and tilt, must be measured or estimated. When investigating vaulting in gymnastics, Takei and colleagues used an elevated camera location and accounted for the camera's tilt by using simple trigonometry to adjust the vertical scale factor (Takei et al., 2000). In such cases the camera is carefully orientated, negating the need to account for the camera angles pan and roll. While this pinhole-camera approach suggests that camera tilt may be accounted for without affecting reconstruction accuracy, empirical data supporting this view is currently unreported. One reason for using the scaling technique is its uncomplicated mathematical treatment of image data to obtain real-space coordinates. While this factor may have contributed to its widespread use, the technique should not be selected at the expense of reconstruction accuracy. Weaknesses include the difficulty in locating the optical axis of the camera's lens perpendicular to the plane of motion (pan angle) and, when necessary, obtaining estimates of the camera's tilt. The Direct Linear Transformation (DLT) (Abdel-Aziz & Karara, 1971) is a reconstruction technique used extensively in three-dimensional analyses of sporting activities. The 11 DLT parameters are functions of six geometric parameters defining the location (x_0, y_0, z_0) and orientation (, ,) of the camera and the five internal characteristics of the digitiser system, comprising the centre of the image (u_0, v_0), two scale factors ($_1$ and $_2$) and a shear factor (k). Adopting the direct linear transformation, but considering planar motion where only horizontal (y) and vertical (z) locations are of concern, the following relationship between image coordinates (u, v) of calibration markers on a plane and the DLT parameters is formed (Walton, 1981 op. cit. Kwon, 1999):

$$u = \frac{L_1 y + L_2 z + L_3}{L_7 y + L_8 z + 1} \qquad v = \frac{L_4 y + L_5 z + L_6}{L_7 y + L_8 z + 1}$$

A minimum of four calibration markers is required to produce the eight equations from which the eight DLT parameters are calculated. This modified version of the DLT, termed 2D-DLT, permits two-dimensional reconstruction of markers considered to be on a plane. The technique has been used with theoretical data to investigate reconstruction accuracy underwater (Kwon, 1999), and in analyses of vaulting skills (Yeadon et al., 1998). While the theory underpinning 2D-DLT indicates that reconstruction accuracy should be unaffected by camera tilt, there is currently limited empirical data to substantiate this. The purpose of this study therefore was to determine the influence of camera tilt on reconstruction accuracy for both techniques from empirical data. The manner in which reconstruction accuracy varied throughout the field of view was also explored. A 6 m horizontal field of view was selected since many sporting activities cover such a distance.

METHODS: Four calibration and 30 reconstruction markers were placed on a vertical plane 6.0 m wide by 4.5 m high (Fig. 1). Reconstruction markers were allocated to one of three subsets; inner, mid and outer, based on the distance from the centre of the calibration markers.

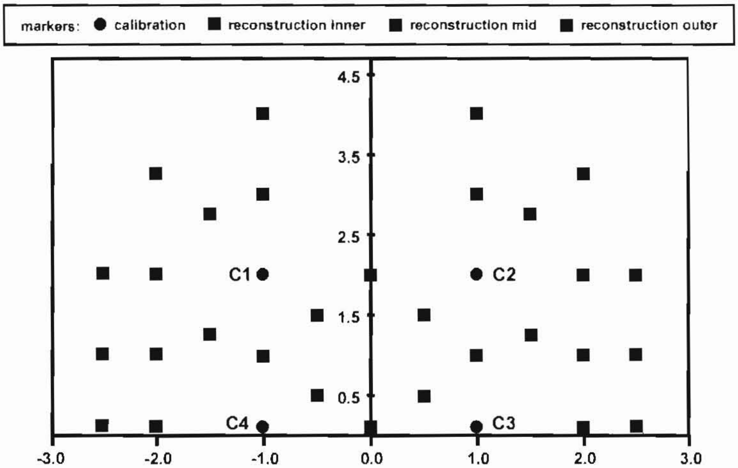

Figure 1. Location of calibration markers (closed circles) and reconstruction markers in the inner (black squares), mid (grey squares) and outer sections (open squares) on the vertical plane.

Markers were surveyed using a 7" digital theodolite (Sokkia DT600) to provide criterion horizontal and vertical locations. A 3 CCD mini-DV digital camera (Sony DCR-TRV900E) was mounted on a digital inclinometer with in-built laser level (SOLA LASER – Lasertronic) to measure the tilt of the camera. Tilt was defined as the angle between a horizontal plane perpendicular to the calibration plane and the optical axis of the lens. Positive values indicated the camera was elevated above calibration markers C1 and C2. The combined camera-inclinometer unit was initially mounted on a tripod 2.00 m above the floor and 11.13 m from the calibration plane directly opposite the central markers. The optical axis of the camera was perpendicular to the plane and the location of the laser on the plane was recorded to ensure the pan angle remained at zero throughout the data collection. The shutter speed was set to 1/215 s with zero electronic gain and optical zoom selected. Camera height was systematically adjusted for tilt angles from 0° to 6° in 1° intervals while ensuring the centre of the image altered minimally throughout the range of tilt angles. The calibration plane was video-recorded at each tilt angle. All digitising was conducted using PEAK Motus 6. At each camera angle four calibration markers (C1 to C4) and 30 reconstruction markers were digitised over five consecutive fields. Estimates of digitising precision were determined from the raw image coordinates over the five fields and at each tilt angle. A two-way ANOVA with repeated measures ($P<0.01$) indicated that digitising precision did not differ statistically between tilt angles or digitised fields. Consequently, at each tilt angle fields 1 to 4 were used for calibration purposes while field 5 was used to assess reconstruction accuracy. Only four calibration markers were used in order provide parity between the calibration methods for the two techniques. Calibration markers C1 to C4 were used to calculate independent horizontal and vertical scale factors for the scaling technique. The tilt of the camera was accounted for by dividing the uncorrected vertical scale factor by the cosine of the measured tilt angle. Estimates of the real-space locations of the 30 reconstruction markers were made in the same absolute coordinate system as the surveyed data through the use of additional vertical and horizontal offsets. For the 2D-DLT technique, calibration markers C1 to C4 were used to determine the eight DLT parameters representing the camera-digitiser system. The real-space locations of the reconstruction markers in field 5 were calculated using 2D-DLT reconstruction. Estimates of overall resultant reconstruction accuracy for both techniques were determined by comparing the surveyed real-space locations of the reconstruction markers with the reconstructed estimates. For an individual marker reconstruction error was calculated as the square root of the sum of the squared horizontal and vertical differences between the known and reconstructed locations. For both techniques estimates of resultant reconstruction accuracy for each subset were also calculated. The reconstruction error data were logarithmically transformed to reduce the heteroscedasticity evident in the data. A two-way ANOVA with repeated measures was used to determine if statistical differences existed in overall reconstruction accuracy between the techniques and across the range of tilt angles. A two-way ANOVA with repeated measures was also used to determine whether differences existed between the techniques at different locations across the field of view and throughout the range of tilt angles. Post-hoc Tukey tests were used to evaluate any statistical differences and the level of significance was set at $P<0.01$ for all analyses.

RESULTS: Overall resultant reconstruction errors for both techniques at each tilt angle are provided in Table 1. Overall errors were statistically larger for the scaling technique ($F_{1,210}=274.46$, $P<0.01$) than 2D-DLT. When expressed at a percentage of the horizontal field of view, the minimum and maximum overall reconstruction errors were 0.14% and 0.47% for scaling and 0.05% and 0.11% for 2D-DLT, respectively. Although not significant ($F_{6,60}=2.81$, $P=0.011$), differences in the reconstruction errors throughout the range of tilt angles was observed. Overall resultant reconstruction error was found to increase as tilt angle increased for the scaling technique, while no such trend was observed for 2D-DLT.

Table 1. Overall reconstruction errors for scaling and 2D-DLT for all tilt angles.

	tilt angle [°]						
technique	0	1	2	3	4	5	6
scaling [mm]	10.9	8.5	11.9	15.4	18.6	22.8	28.3
± s.e. (n = 30) [mm]	0.7	1.0	1.2	1.9	2.5	3.3	4.1
2D-DLT [mm]	3.9	6.5	3.7	3.0	4.2	3.3	4.6
± s.e. (n = 30) [mm]	0.4	0.9	0.5	0.3	0.4	0.4	0.6

Fig. 2 provides more detailed information highlighting the disparities between reconstruction techniques throughout the field of view and range of tilt angles. Statistical differences existed between the techniques in the three sub-sections ($F_{5,70}=117.59$, $P<0.01$) and across the camera tilt angles ($F_{6,60}=4.09$, $P<0.01$). Reconstruction errors for 2D-DLT showed trends of larger errors for markers positioned further away from the centre of the image at most tilt angles (Fig. 2) but, with the exception of the outer sub-section at 1° and 6° of tilt, were not statistically different. For the scaling technique, with the exception of 0° and 1°, reconstruction errors were statistically larger in the mid and outer-subsections at all tilt angles, and the magnitude of the errors increased as tilt angle increased. These results are likely to be symptomatic of symmetrical lens distortion (Hatze, 1988).

DISCUSSION: While the errors presented are concerned with easily identifiable points in an image, and not body-landmarks, the protocol used provides an appropriate method to assess the accuracy of the reconstruction techniques. The greater accuracy observed for 2D-DLT is due to the parameterisation of the geometrical external and internal camera-digitiser parameters, which includes tilt. Since the effects of roll and pan are also incorporated in this technique, any camera misalignment is automatically accounted for. However, this is not the case in scaling, where camera misalignment is likely to result in larger reconstruction errors. With this in mind, it is interesting to note the smallest errors for the scaling technique occurred at 1° of tilt and not the expected 0°. Although every attempt was made to ensure zero camera roll or pan at each tilt angle, the lack of any estimates and subsequent corrections for these angles may have led to this unexpected result. Lens distortion may account for the larger errors observed in both techniques for markers positioned closer to the edge of the image (Fig. 2). Incorporating additional terms into the 2D-DLT transformation to account for symmetrical lens distortion, in a manner analogous to that used in 3D DLT (Nigg et al., 1999), may enhance reconstruction accuracy and warrants attention.

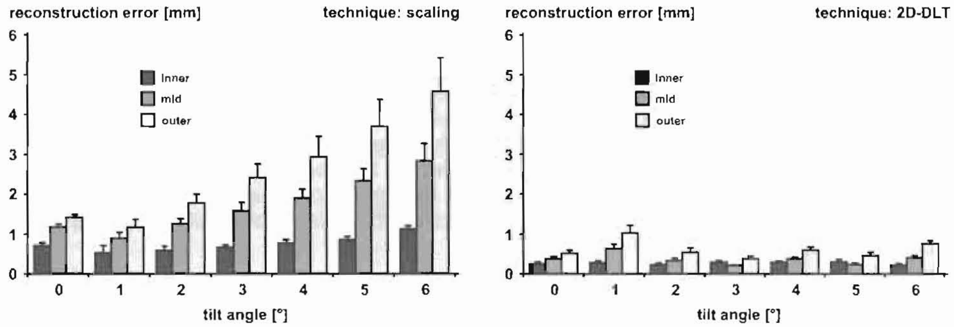

Figure 2. Variations in reconstruction accuracy for both techniques throughout the field of view. Standard errors about the means are also presented (n = 10).

CONCLUSION: The 2D-DLT technique provided significantly more accurate reconstruction data than scaling for planar video analyses. As expected, camera tilt did not adversely affect reconstruction accuracy for 2D-DLT. However, contrary to expectations, reconstruction accuracy for scaling decreased as camera tilt increased when using the simple trigonometric approach to account for camera tilt. Researchers investigating technique-dominated sports, where reconstruction accuracy is paramount, would therefore be advised to use 2D-DLT.

REFERENCES:

Abdel-Aziz, Y.I. and Karara, H.M. (1971). Direct linear transformation from comparator coordinates into object space coordinates in close-range photogrammetry. In: *ASP Symposium on Close Range Photogrammetry*. American Society of Photogrammetry, Falls Church.

Hatze, H. (1988). High-precision three-dimensional photogrammatic calibration and object space reconstruction using a modified DLT-approach. *Journal of Biomechanics*, **21**, 533-538.

Kwon, Y-H. (1999). Object plane deformation due to refraction in two-dimensional underwater motion analysis. *Journal of Applied Biomechanics*, **15**, 396-403.

Nigg, B.M., Cole, G.K. and Wright, I.C. (1999). Measuring Techniques: Optical Methods. In: Nigg, B.M. and Herzog, W (Eds.) *Biomechanics of the Musculo-skeletal System (2nd Edition), (pp.302-313)*. Chichester: Wiley & Sons.

Takei, Y., Dunn, J.H., Blucker, E.P., Nohara, H. and Yamashita, N. (2000). Techniques used in high- and low-scoring Hecht vaults performed at the 1995 World Gymnastics Championships. *Journal of Applied Biomechanics*, **16**, 180-195.

Yeadon, M.R., King, M.A. and Sprigings, E.J. (1998). Pre-flight characteristics of Hecht vaults. *Journal of Sports Sciences*, **16**, 349-356.