THE EFFECT OF CAMERA PAN ON THE TWO-DIMENSIONAL DIRECT LINEAR TRANSFORMATION AND SCALAR RECONSTRUCTION TECHNIQUES WHEN APPLIED TO ERGOMETER ROWING

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Changes in camera pan may affect reconstruction accuracy of two-dimensional (2D) kinematic data collected in on-water rowing testing. The 2D direct linear transformation (2D-DLT) may assist in improving reconstruction accuracy of rowing kinematics when a perpendicular camera changes position. Accuracy of the 2D-DLT and scalar reconstruction techniques was compared using coefficient of multiple correlations (CMCs), range of motion difference (ROM_{Diff}) and root mean square error (RMSE). 2D-DLT was found to have significantly greater accuracy (CMC and RMSE; $p<0.05$) for the ankle and knee. 2D-DLT also had significantly greater accuracy ($p<0.05$) for the knee and hip in ROM_{Diff}. However, offset errors were found for the hip (CMCs and RMSE) and are potentially due to kinematic offsets derived from out-of-plane location of markers.

KEY WORDS: 2D-DLT, scaling, kinematics, panning, calibration.

INTRODUCTION: Accurate body kinematics is necessary for enhancing rowing performance (Soper & Hume, 2004). Three-dimensional (3D) opto-reflective systems are impractical in hydrodynamic sports such as rowing (Kersting, Kurpiers, Darlow, & Nolte, 2008). As a consequence, 2D video-based kinematic models in accordance with the scalar reconstruction technique are used to assess kinematic performance in on-water rowing (Lamb, 1989). The scalar reconstruction (or scaling) protocol involves recording a calibration object of known horizontal and vertical dimensions for one frame of video within the calibration plane (Brewin & Kerwin, 2003). Previous rowing studies using 2D kinematic models have involved a single camera being mounted to a motor boat moving approximately parallel to the rower (Lamb, 1989). However, potential marker reconstruction errors increase when applying the scalar technique on-water, due to inconsistencies in angle between the rower and the motor boat resulting in the camera being panned.

The two-dimensional direct linear transformation (2D-DLT) (Walton, 1981) allows for two-dimensional reconstruction based on motion occurring in a single plane. Accuracy of the 2D-DLT has been assessed in the reconstruction of static 2D marker sets in varying camera positions (Brewin & Kerwin, 2003) and in functional kinematic trials in gymnastics (Irwin & Kerwin, 2001). The 2D-DLT works regardless of the camera angle to the plane of motion (Kwon & Casebolt, 2006) and therefore may be beneficial in rowing where video is captured from a separate boat travelling alongside the rower which results in a constantly changing viewpoint. The purpose of this study is to compare reconstruction accuracy of the scalar and 2D-DLT techniques when applied to lower-extremity kinematics of ergometer rowing at varying levels of camera pan. Although camera panning would never be used to analyse kinematics on a rowing ergometer as the camera could be fixed, the use of an ergometer and a panning camera is used in this study as a simulation of the applied on-water environment. All panned camera positions will be compared to a standard 2D planar (90º) camera. It is hypothesised that the 2D-DLT will be significantly more accurate in kinematic reconstruction when compared to the traditional scalar reconstruction technique at all levels of camera pan across all body joints measured.

METHODS: Data collection: Eleven (two females, nine males) novice rowers (age = 24.5 ±4.4 years; mass = 83.9 ±9.5 kg; height = 1.82 ±0.9 m) participated in this study. Markers were placed on five anatomical locations (derived from the 3D opto-reflective model Plug-in-Gait or PGM from pilot research): second metatarsal head of the left foot, lateral malleolus of left foot lateral femoral epicondyle for left leg, greater trochanter of left leg and sagittal orientation of the pelvis. Markers were used to derive absolute ankle, knee and hip sagittal joint angles. Four static calibration markers were used for the 2D-DLT reconstruction.

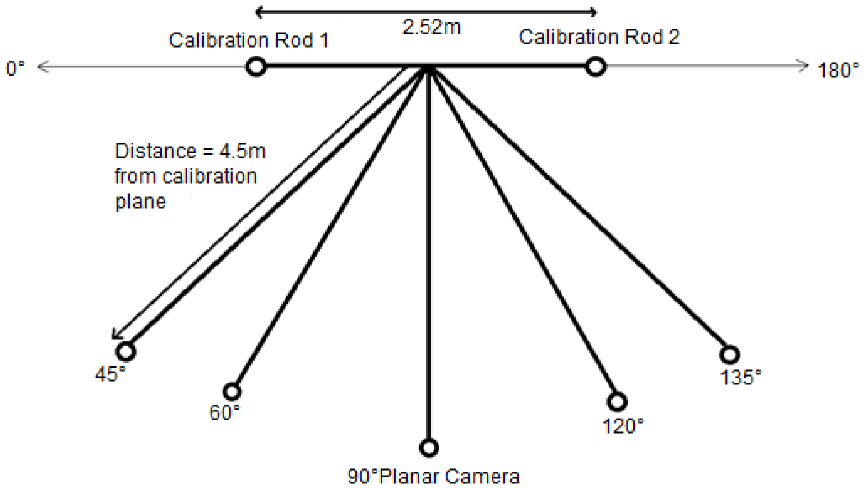

Figure 1: Diagram of testing setup as viewed from above.

Five digital video cameras (Canon MD 225) simultaneously recording at 50Hz were positioned at panning angles of 45°, 60°, 90°, 120° and 135° relative to the calibration (and motion) plane. Each camera was placed 1.2 m high and 4.5 m from the calibration plane (Figure 1). Participants rowed on a Sport-Op R600 rowing ergometer at 20 strokes per minute. Kinematic data for three complete stroke cycles of the lower body relative to the left limb were collected following a 1-min familiarisation period. Markers were digitised in Peak Motus (v9.0, Peak Performance Technologies, Inc.). For the scalar reconstruction the 90° camera was used for each panning camera to resemble violations to a perpendicular camera position. A residual analysis was performed on all markers for two participants from every camera position to determine the optimum cut-off frequencies for a 4th order dual pass Butterworth filter. For the scalar reconstruction method, data were filtered and sagittal plane angles calculated for each joint within Peak Motus. 2D-DLT reconstruction of the 2D coordinates from Peak Motus was performed in MatLab version R2010b (Mathworks, Massachusetts, USA) then sagittal plane angles calculated for each joint. The present study used the minimum point of knee joint displacement as events for the start and finish of each kinematic waveform. The rowing stroke cycle was normalised to 101 data points using an interpolating cubic spline.
Data Analysis: Overall shape of the kinematic waveform patterns was compared using the coefficient of multiple correlations (CMC). Differences in the amplitude of the kinematic curves were estimated by calculating range of motion difference (ROM_{Diff}) and errors due to kinematic offsets were assessed by calculating the average root mean square error (RMSE) between the two curves. CMCs, ROM_{Diff} and RMSE were compared between reconstruction techniques for each joint using two-way ANOVAs with repeated measures (p <0.05), after being logarithmically transformed. Bonferroni corrections were applied to matched samples t-tests to isolate significant differences at each level of camera pan (p <0.00625).

RESULTS: CMCs for ankle and knee kinematics using the 2D-DLT were significantly higher ($F_{1,10}$=54.860 and $F_{1,10}$=51.251 respectively, both p<0.05), with Posthoc testing revealing significance at every level of camera pan for both angles (p<0.00625). This was similar with RMSE results, where the ankle and knee were also significantly more accurate when using the 2D-DLT ($F_{1,10}$=539.746 and $F_{1,10}$=1013.952 respectively, both p<0.05) at every level of pan (0.00625). ROM_{Diff} of the knee and hip was significantly lower for the 2D-DLT

($F_{1,10}$=62.173 and $F_{1,10}$=43.013 respectively, both p<0.05) with Posthoc testing revealing significance across all levels of camera pan (p<0.00625). Despite no significant finding between reconstruction techniques, results for ankle ROM_{Diff} also demonstrated a trend for the 2D-DLT to be lower than the scalar technique at three of the four panned cameras (Table 1).

Table 1: Mean difference and standard deviation (CMC, ROM_{DIFF}, RMSE) for each camera position compared to the 90° camera position.

		Ankle		Knee		Hip	
Position		**Scalar**	**2D-DLT**	**Scalar**	**2D-DLT**	**Scalar**	**2D-DLT**
45˚	**CMC**	0.60 (0.18)	0.87 (0.19)	0.96 (0.02)	0.99 (0.01)	0.70 (0.19)	0.80 (0.21)
	ROM_{DIFF}	5.41 (3.08)	3.63 (2.86)	8.40 (3.59)	1.91 (1.59)	17.82 (7.91)	7.64 (5.46)
	RMSE	10.27 (4.15)	3.14 (.099)	4.09 (1.21)	1.40 (0.77)	6.83 (2.72)	3.36 (1.65)
60˚	**CMC**	0.69 (0.19)	0.95 (0.08)	0.98 (0.01)	0.99 (0.01)	0.87 (0.09)	0.91 (0.10)
	ROM_{DIFF}	6.10 (3.64)	2.80 (2.11)	4.15 (2.15)	1.13 (1.53)	9.59 (4.64)	4.39 (3.67)
	RMSE	5.23 (1.94)	2.02 (0.68)	2.30 (0.71)	1.40 (0.87)	3.70 (1.61)	1.97 (1.19)
120˚	**CMC**	0.38 (0.18)	0.97 (0.03)	0.95 (0.02)	0.99 (0.01)	0.95 (0.04)	0.91 (0.09)
	ROM_{DIFF}	3.75 (1.89)	2.81 (2.03)	12.58 (4.07)	1.09 (1.44)	10.16 (3.13)	3.78 (2.12)
	RMSE	4.92 (2.00)	1.58 (0.61)	5.44 (1.72)	0.96 (0.83)	4.11 (1.11)	1.73 (0.83)
135˚	**CMC**	0.59 (0.18)	0.93 (0.08)	0.92 (0.04)	0.99 (0.01)	0.93 (0.06)	0.81 (0.20)
	ROM_{DIFF}	4.06 (1.52)	4.85 (3.81)	15.12 (7.35)	1.80 (1.56)	12.65 (4.76)	6.55 (3.54)
	RMSE	6.44 (2.71)	2.45 (0.98)	7.07 (2.16)	1.19 (0.98)	5.58 (1.56)	2.75 (1.25)

DISCUSSION: Results from this study support the hypothesis the 2D-DLT provides more accurate kinematic reconstruction when compared to the scalar reconstruction for the ankle and knee joints, across all levels of camera pan, but further investigation is needed for the hip joint. Strong CMC measures in the present study, particularly for the knee should be interpreted with caution as activities involving much larger joint ROM, such as rowing, are susceptible to over-reporting of CMC results (McGinley, Baker, Wolfe, & Morris, 2009). Inaccuracies found for the hip joint when using the 2D-DLT may have been affected by a number of factors. It is possible soft tissue artifact may have affected accuracy in reconstruction hip kinematics particularly at maximum flexion by contributing to inaccuracies in marker centroid tracking (Karduna, McClure, Michener, & Sennett, 2001). RMSE results for the 2D-DLT are also potentially affected by markers moving out-of-plane. Offsets in horizontal coordinate location have been shown in research evaluating the accuracy of the 2D-DLT when applied to static markers that lie outside of the calibration plane (Hinrichs, Morrison, Vint, DeWitt, Mitchell, & Mclean, 2005). In the present study it is possible that out-of-plane movement of the knee, hip and pelvis markers may have contributed to hip angle error offsets increasing RMSE results and also decreasing CMC results. Ferrari et al. (2010) has identified that CMC measures are adversely affected by consistent kinematic offsets despite waveform shape between two data sets being similar. It is also possible novice rowing sample in the present study may have been more susceptible to out-of-plane movement given research demonstrating increased variability in novice rowers in oar angle consistency measures (Smith & Spinks, 1995). As a consequence of this, a larger stroke profile may be needed to identify stroke-to-stroke inconsistencies in planar movement of the lower extremities, and be captured at a range of stroke rates (Greene, Sinclair, Dickson, Colloud, & Smith, 2009). There is limited empirical evidence to support a specific tendency for novice rowers to demonstrate increased lower extremity out-of-plane movement during the ergometer rowing stroke cycle (Soper & Hume, 2004). Despite this it would be useful to examine the effectiveness of both reconstruction techniques used in the present study when applied to a sample of elite athletes, as there are benefits for use of a 2D kinematic model in an elite athlete servicing environment when measuring the rowing stroke cycle. The use of an experimentally reliable ergometer such as a Concept II should also be used in any validation of the reconstruction techniques, particularly if elite athletes are involved (Soper & Hume, 2004).

CONCLUSION: The accuracy of the 2D-DLT and scalar techniques was assessed to measure rowing kinematics from cameras panned up 45˚ away from perpendicular position to the plane of motion, simulating a panning camera. The results of this study demonstrated that the 2D-DLT had greater accuracy than the scalar technique in reconstructing a sagittal ankle and knee joint displacements during ergometer rowing. However, the 2D-DLT method had offset errors for the hip joint angle for panned camera positions. Therefore, before the 2D-DLT is explored further in any context, inclusive of an on-water setting, research should focus on quantifying and account for offset errors present for the hip joint angle.

REFERENCES:

Brewin, M., & Kerwin, D.G. (2003). Accuracy of scaling and DLT reconstruction techniques for planar motion analyses. *Journal of Applied Biomechanics,* 19, 79-88.

Ferrari, A., Cutti, A.G. & Cappello, A. (2010). A new formulation of the coefficient of multiple correlation to assess the similarity of waveforms measured synchronously by different motion analysis protocols. *Gait & Posture,* 31, 540-542.

Greene, A.J., Sinclair, P.J., Dickson, M.H., Colloud, F. & Smith, R.M. (2009). Relative shank to thigh length is associated with different mechanisms of power production during elite male ergometer rowing. *Sports Biomechanics,* 8, 302-317.

Hinrichs, R.N., Morrison, B., Vint, P.F., DeWitt, J.K., Mitchell, J. & Mclean, S.P. (2005). Predicitng out-of-plane point locations using the 2D-DLT. In: *ASB Annual Symposium*. American Society of Biomechanics, Cleveland.

Irwin, G. & Kerwin, D.G. (2001). Use of '2D-DLT' for analysis of longswings on high bar. In: *Scientific Proceedings of the XIXth International Symposium on Biomechanics in Sports*. International Society of Biomechanics in Sports, University of Sanfrancisco.

Karduna, A.R., McClure, P.W., Michener, L.A. & Sennett, B. (2001). Dynamic measurements of three-dimensional scapular kinematics: a validation study. *Journal of biomechanical engineering,* 123, 184.

Kersting, U.G., Kurpiers, N., Darlow, B.J.S. & Nolte, V.W. (2008). Three-dimensional assessment of on-water rowing technique: A methodological study. In: *Scientific Proceedings of the XXVIth International Symposium on Biomechanics in Sports*. International Society of Biomechnics in Sport, Seoul.

Kwon, Y. & Casebolt, J.B. (1989). Effects of light refraction on the accuracy of camera calibration and reconstruction in underwater motion analysis. *Sports Biomechanics,* 5, 315-340.

Lamb, D.H. (1989). A kinematic comparison of ergometer and on-water rowing. *American Journal of Sports Medicine,* 17, 367-373.

McGinley, J.L., Baker, R., Wolfe, R. & Morris, M.E. (2009). The reliability of three-dimensional kinematic gait measurements: a systematic review. *Gait & Posture,* 29, 360-369.

Smith, R.M. & Spinks, W.L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of Sports Sciences,* 13, 377-385.

Soper, C. & Hume, P.A. (2004). Towards an ideal rowing technique for performance: the contributions from biomechanics. *Sports Medicine,* 34, 825-848.

Walton, J.S. (1981). Close-range cine-photogrammetry: A generalized technique for quantifying gross human motion*.* Unpublished Doctoral Thesis, Pennsylvania State University, USA.

Winter, D.A. (1990). Biomechanics and motor control of human movement. *Wiley, 6*, 1.