THE APPLICATION OF FUNCTIONAL DATA ANALYSIS TECHNIQUES FOR CHARACTERIZING DIFFERENCES IN ROWING PROPULSIVE-PIN FORCE CURVES.

John Warmenhoven[1], Richard Smith[1], Conny Draper[1], Stephen Cobley[1], Andrew Harrison[2], Norma Bargary[3].
Exercise and Sports Science, University of Sydney, Sydney, Australia.[1]
Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland.[2]
Department of Mathematics and Statistics, University of Limerick, Limerick, Ireland.[3]

The pattern of propulsive force (measured at the pin), represented by force-time and force-angle graphs, typically differs among rowers. How the pattern differs according to competition level and gender has not been identified. Functional data analysis (FDA) techniques were used on force-time and force-angle data to identify the main modes of variance in curves representing thirty eight rowers of different competition levels (domestic, underage international and open international) and different gender. Stepwise discriminant function analysis showed strong classification of rowers using force-time and force-angle graphs and strong classification of female rowers. Male rowers, Underage rowers and Open International rowers showed weaker classification. Despite this, FDA provided useful information for the assessment of rowing performance.

KEY WORDS: principal components analysis, shape, waveform, on-water.

INTRODUCTION: The idea of a rowing technique 'signature' was first proposed by researchers in the nineteen seventies, and was associated with execution of the pulling force on the oar handle (Ishiko, 1971). A force signature is usually represented graphically with force either plotted against time (Smith & Spinks, 1995) or against the horizontal angle of the oar (Spinks, 1996); and rowers have been qualitatively identified by their distinctive shape on such graphs. However, empirical research analysing the specific importance of shape characteristics and their relationship with performance is currently limited. Yet the use and manipulation of 'signatures' to enhance performance is feasible. Two strategies for investigating differences in the shape of force-time and force-angle profiles are 'Functional Principal Components Analysis' (*f*PCA) and 'Bivariate Functional Principal Components Analysis' (*bf*PCA), from the Functional Data Analysis (FDA) family of statistical techniques (Ramsay, 2006). The benefits of *f*PCA and *bf*PCA for assessing trends in biomechanical variables have already been highlighted for use on vertical jump performance (Ryan, Harrison & Hayes, 2006; Harrison, Ryan & Hayes, 2007). In rowing the shape of the force-time curve could be analysed using *f*PCA, and the force-angle profile could be analysed using *bf*PCA. In the present study, data obtained on thirty eight athletes were processed to assess whether force trends in continuous data can be used to discriminate between rowers, and whether they can predict competition level and gender.

METHODS: Subjects: Following institutional ethical approval, data from thirty eight subjects were analysed (11 male, 27 female). The rowers consisted of highly trained heavyweight and lightweight scullers. Athletes were classified as Domestic (D) (n = 20), Australian International Underage (IU) (n = 7) or Australian International Open (IO) (n = 11) athletes.
Testing and Data Processing: Athletes were directed to row at four stroke rates in 250m steps (20, 24, 28, 32 Str min^{-1}), separated by one minute of light rowing. Ten strokes from the 32 Str min^{-1} data only were analyzed. The drive and recovery phases were identified using the horizontal angle of the oar (Smith & Loschner, 2002), and only the drive phase was analysed for this study. A linear length normalization strategy using an interpolating cubic spline was applied, normalizing each curve to 100% of the drive phase. An amplitude normalization (AN) technique was also applied, ensuring that variability described in the curves was only reflective of shape characteristics independent of amplitude. For AN, force was converted to a percentage relative

to each curve's maximum value. Similarly, horizontal oar angle was normalized to a percentage relative to the length of each drive phase. Both normalization formulas are below:

$$Force_{Norm(i)} = \left(\frac{Force_{(i)}}{Force_{(Maximum)}}\right) \times 100(\%) \qquad Angle_{Norm(i)} = \left(\frac{Angle_{(i)}}{Angle_{(Maximum)} - Angle_{(Minimum)}}\right) \times 100(\%)$$

The horizontal oar angle normalization strategy is expressed as a relative percentage of the drive phase length, but still preserves important information on where the oar is relative to the boat. An average curve created from each participant's ten strokes was used for further analysis.

***f*PCA and *bf*PCA**: For *f*PCA, B-spline basis functions were used for creation of force-time curves. The smoothing parameter was selected using a generalized cross validation (GCV) procedure and from these curves the functional principal components were derived. Each force-time curve was weighted by each of the first five functional principal components (*f*PCs), with resulting scalar averages referred to as *f*PC scores. For *bf*PCA, B-spline basis functions were used for force-time and angle-time curves. The smoothing parameter was again selected using a using a GCV procedure. A composite function was derived from the inner product of the bivariate functions. The composite function was then used to extract a set of bivariate functional principal components (*bf*PCs) and corresponding *bf*PC scores (Ramsay, 2006).

Discriminant Analysis: *f*PC and *bf*PC scores were input to separate stepwise discriminant function analyses (SDFA) for classification according to competition level and gender. The smallest Mahalanobis distance (D2) procedure was used in each case using prior allocation probabilities to account for the different sample sizes in each comparison.

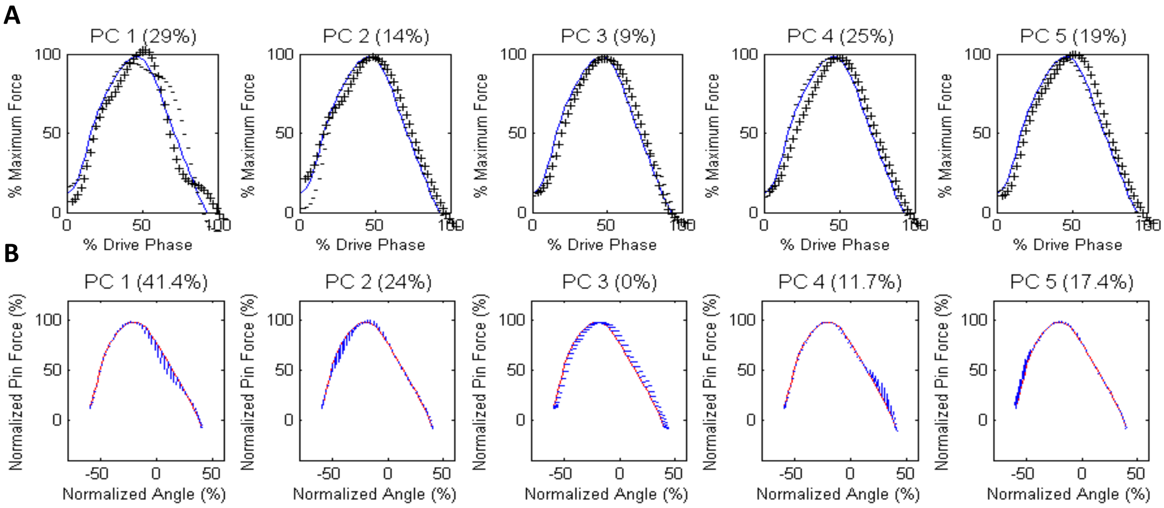

Figure 1. The first five varimax rotated *f*PCs (A) and *bf*PCs (B). For *f*PCs, the blue line represents mean force-time, the '+' line represents positive scorers who are +2SD and the '-' line represents negative scorers who are -2SD from the mean function. For *bf*PCs, the red line represents the mean force-angle function and the blue lines represent positive scorers +2SD from the mean function.

RESULTS: The corresponding percentage contribution for each *f*PC and *bf*PC to the total variability in all curves are shown in Figure 1. Mean scores for *f*PCs and *bf*PCs are in Table 1.

SDFA for competition levels using *f*PCA: *f*PC2 had the greatest discriminating power for the first step ($p < 0.001$), demonstrating a change in the pattern of force production in the first half of the drive phase. In the second step, *f*PC4 was identified ($p = 0.017$) showing a greater rate of force development early in the drive phase for negative scorers, and in the third step *f*PC3 was identified (p = 0.017), showing greater force production leading into the finish.

SDFA for competition levels using *bf*PC: Scores on *bf*PC2 had the greatest discriminant power for the first step (p = 0.002), demonstrating a lower rate of force development leading into maximum force, but a better ability to maintain a higher force closer to square-off for positive scorers. In the second step, *bf*PC4 was also identified (p < 0.001), showing a greater ability to produce force at the end of the drive phase.

SDFA for gender using *f*PCA: *f*PC5 (p < 0.001), *f*PC3 (p < 0.001) and *f*PC4 (p < 0.001) were discriminating variables for classification, with each identified in separate steps.

SDFA for gender using *bf*PC: *bf*PC1 (p < 0.001) and *bf*PC4 (p < 0.001) were discriminating variables for classification, with each identified in separate steps. *bf*PC1 showed a reduction in force production after reaching maximum force for positive scorers. The results of the discriminant analyses using *f*PC and *bf*PC scores for force-time and force-angle data as predictors of competition level and gender are shown in Table 1.

Table 1. *f*PCA and *bf*PCA mean (SD) scores for competition level and gender (A). Percentages of correct classification of *f*PCA (B) and *bf*PCA (C) for competition and gender.

(A) Competition Level *f*PCA and *bf*PCA scores

		*f*PCA	*bf*PCA
D	PC1	-3.4 (43.4)	-7.5 (52.1)
	PC2	-10 (26.9)	-2.4 (37.5)
	PC3	0.2 (19.6)	-6.5 (24.1)
	PC4	3.6 (35)	-2.3 (21.1)
	PC5	4.7 (31.1)	-10.7 (31)
IU	PC1	8.2 (24)	15.6 (35.3)
	PC2	24.4 (27.2)	-25.3 (32.4)
	PC3	-15.5 (16.2)	-2 (23.1)
	PC4	-26.3 (28.9)	13.8 (19.9)
	PC5	-13.6 (27.8)	27.9 (28.5)
IO	PC1	1 (41.9)	3.76 (53.1)
	PC2	2.6 (17.9)	20.5 (39.2)
	PC3	9.5 (24)	13.1 (19)
	PC4	10.1 (38.7)	-4.6 (27.9)
	PC5	0 (36.6)	1.8 (22.1)

Gender *f*PCA and *bf*PCA scores

		*f*PCA	*bf*PCA
F	PC1	9.2 (34.8)	14.9 (43.7)
	PC2	2.7 (24.1)	-6.6 (38.9)
	PC3	-5.1 (21.1)	0.7 (24.5)
	PC4	-6.8 (34.3)	4.5 (22.5)
	PC5	-11.3 (29.8)	3.6 (26.8)
M	PC1	-22.6 (43.2)	-36.4 (46.3)
	PC2	-6.6 (34.5)	16.2 (38.2)
	PC3	12.5 (18.8)	-1.8 (22.8)
	PC4	16.6 (39.1)	-11.1 (23.5)
	PC5	27.8 (20.1)	-8.9 (39.9)

(B) Competition Level *f*PCA - % Classified

	D	*IU*	*IO*
D	**87.5**	2.5	10.0
IU	50.0	**35.7**	14.3
IO	36.4	9.1	**54.5**

Gender *f*PCA - % Classified

	F	*M*
F	**90.7**	9.3
M	27.3	**72.7**

(C) Competition Level *bf*PCA - % Classified

	D	*IU*	*IO*
D	**85.0**	5.0	10.0
IU	42.9	**57.1**	0.0
IO	45.5	9.1	**45.5**

Gender *bf*PCA - % Classified

	F	*M*
F	**92.6**	7.4
M	27.3	**72.7**

DISCUSSION: The purpose of this paper was to see if FDA-analysed force-time and force-angle data from single scullers could be used to discriminate between their competition level and gender. If the analysis was successful it could be a method of identifying the ‘ideal’ force-angle shape characteristic of competition-winning scullers. Knowing the shape of the force-angle profile is critical for the development of strength and conditioning strategies (Korner and Schanitz, 1987). In the present study *f*PCs and *bf*PCs discriminated best between domestic and international open rowers. These results initially suggested that increased force near the start and the end of the drive phase may not be as important as increased force when the horizontal oar angle is closer to zero degrees, especially indicated by *bf*PC2. Despite this, both *f*PC and *bf*PC scores provided high correct classification percentages for domestic rowers but comparatively weaker percentages of classification for international underage and open rowers. It is possible that the skill in applying force to the oar is quite similar at lower performance levels, but international underage and open rowers have subsequently learned to adapt the shape of their force signatures with experience and potentially 'individualize' these shapes to fit other key performance characteristics. Both *f*PC and *bf*PC scores also provided high correct classification percentages for gender, particularly for female rowers. Female rowers demonstrated a better ability to develop force early in the stroke and maintain force leading into the release, but males demonstrated a greater ability to maintain a higher force production closer to the oar angle equaling zero degrees. As a result of these differences it is advisable to assess shape characteristic differences independent of gender, given that gender effects in the present study may have masked the discriminating ability of FDA at higher competition levels. Importantly, this preliminary investigation into shape differences has also been able to show the use of *bf*PCA in particular as a novel method for assessment of the force-angle profile, something which has traditionally been assessed qualitatively. It is known that the shape of the force/angle profile has reflected the seat that the rower occupies in a crewed boat (Smith and Loschner, 2002; Roth, Schwanitz, Pas & Bauer, 1998). The FDA method described here provides a quantitative analysis of curve shape that can clearly isolate and define time segments where changes can be made to better approximate an elite performance. The importance of segments of the force curves suggested by the *f/bf*PCA analysis provides a strong evidence base for discussions with coaches and athletes about how to increase performance in on-water rowing.

REFERENCES:

Harrison, A. J., Ryan, W., & Hayes, K. (2007). Functional data analysis of joint coordination in the development of vertical jump performance. *Sports Biomechanics*, *6*(2), 199-214.

Ishiko, T. (1971). Biomechanics of rowing. In J. a. W. Vredenbregt, J. (Ed.), *Biomechanics II, International Series on Biomechancis* (Vol. 2, pp. 249-252). Eindhoven, Netherland. Baltimore, MD: University Park Press.

Körner, T., & Schwanitz, P. (1987). *Rudern*. Sportverlag.

Ramsay, J. O. (2006). *Functional data analysis*. John Wiley & Sons, Inc.

Roth, W., Schwanitz, P., Pas, P., & Bauer, P. (1993). Force-time characteristics of the rowing stroke and corresponding physiological muscle adaptations. *International Journal of Sports Medicine*. *14*, S32-S34.

Ryan, W., Harrison, A., & Hayes, K. (2006). Functional data analysis of knee joint kinematics in the vertical jump. *Sports Biomechanics, 5*(1), 121-138.

Smith, R. M., & Loschner, C. (2002). Biomechanics feedback for rowing. *Journal of Sports Sciences*, *20*(10), 783-791.

Smith, R. M., & Spinks, W. L. (1995). Discriminant analysis of biomechanical differences between novice, good and elite rowers. *Journal of sports sciences, 13*(5), 377-385.

Spinks, W. (1996). Force-angle profile analysis in rowing. *Journal of Human Movement Studies, 31*(5), 211-233.

Acknowledgement

The authors would like to acknowledge the International Society of Biomechanics in Sport as this project was supported by an ISBS Student Mini Research Grant for 2014.