Force coordination strategies in on-water single sculling: Are asymmetries related to better rowing performance?

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Abstract

Asymmetries of the rowing stroke cycle have been assessed with reference to kinematics and foot-force measures in laboratory testing environments. It remains unclear how asymmetries in propulsive kinetic measures are related to on-water rowing performance. A new approach for the evaluation of both global and local asymmetries across the entire movement was used to assess the continuous role of asymmetries and whether these change according to level of competitive representation. Twenty seven highly skilled female rowers (national and international competition level), rowing at 32 strokes per minute in a single scull boat were evaluated. A symmetry index (SI) and functional data analysis (FDA) techniques were applied to a continuous *difference* time-series, which described fluctuating asymmetry in propulsive pin forces for each rower. Univariate ANOVAs revealed that differences in asymmetries were present as a factor of competition level for the SI and results of FDA. International athletes were more likely to utilize an asymmetry strategy with increased stroke-side (port-side) force early in the drive phase, and increased bow-side (starboard) force through the second half of the drive. This was likely the result of international performers customizing their movement strategies relative to known boat mechanical offsets. The first half of the drive phase was also found to be an adaptive part of the rowing stroke cycle, suggesting asymmetries may have a functional role in successful execution of movements during the rowing stroke.

Key Words : Symmetry; Biomechanics, Sport Expertise, Rowing.

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Introduction

Coordination patterns have been analysed in various sporting and human movement contexts including rowing[1, 2], swimming[3], golf[4], karate[5], gymnastics[6, 7], athletics in disciplines such as triple jump[8] and dancing[9]. In each of these instances coordination was explored by examining relationships between kinematic variables such as body joint or segmental kinematics. In practice it is possible that variables describing structures of coordination in sporting contexts can be more complex than simple kinematic measures. One such example is on-water rowing, where bilateral forces are collected during sculling. Interestingly, in this context the relationship between bilateral forces is often viewed from the perspective of asymmetries, rather than structures of coordination between continuous variables.

It has been conventionally assumed that a high boat velocity is achieved through the production of large, *symmetrical* forces, which are efficiently delivered through the feet, up the human kinetic chain to the handle and oars[10, 11]. Despite this, recent advances in laboratory research have demonstrated evidence of lower limb asymmetries in biomechanical variables. For kinematic measures, asymmetries have been identified at the hip and knee in ergometer rowing[10] and a growing evidence base supports the presence of kinetic asymmetries, where discrepancies in foot-stretcher forces have been identified during ergometer rowing[12-15]. The level of kinetic foot-stretcher asymmetry noted by Buckeridge, Bull and McGregor[13] was not significantly different between sweep rowers and scullers. These findings are of interest, given that scullers are generally considered to have symmetrical force outputs as a consequence of the assumed symmetrical rowing action achieved on-water, compared to sweep rowers. Additionally, Fohanno, Nordez, Smith and Colloud[15] demonstrated foot-stretcher asymmetries with low intra-stroke variability for elite scullers. The findings of Buckeridge et al.[13] and Fohanno et al.[15] suggest that asymmetries in skilled rowers may be deliberate parts of an underlying kinetic coordination structure across the stroke cycle.

As the majority of rowing training and rowing competition takes place on-water, it is possible that any intentional asymmetries, or coordination of forces, may be associated with movement patterns that are learned and practiced in an on-water environment. Evidence of asymmetries in on-water rowing is more limited however, with some differences in propulsive forces (measured at the pin) reported across both sides of the boat in sculling. Greater peak propulsive forces have been noted on the bow side pin compared with the stroke side pin[16]. Similarly, Elliott, Lyttle, and Birkett[17] reported greater bow oar peak force of eight sculling rowers across three different stroke rates. Due to the inboard length of the oars used during on-water sculling, the oar handles must overlap when the blades are perpendicular to the boat, resulting in upper body postural asymmetry throughout the stroke cycle. This fixed mechanical asymmetry may lead to asymmetries in peak force production[16, 17]. It is also possible that kinetic asymmetries may act to mediate the effects of the mechanical offset present in boat rigging. Despite the presence of established mechanical asymmetries during sculling and the growing evidence of kinetic asymmetries in laboratory based research, there is limited evidence to suggest whether the nature of these asymmetries on-water is erroneous or functional, and if these asymmetries are consistent across the entire stroke cycle, or change according to specific phases of the movement.

Difficulties in building such an evidence base are partly due to the measures used to quantify force asymmetries in ergometer rowing. These have often involved indices that describe the magnitude of asymmetry for each rower[13, 15]. Similarly differences in discrete point measures such as peak force have been reported in on-water research[16, 17]. Therefore, understanding the potentially functional role of asymmetries across the stroke cycle would be useful from a technical perspective[18]. Various methods for analysing complex time-series data such as functional data analysis (FDA) techniques have been used in conjunction with biomechanical data in on-water rowing to explore patterns of variability in force-angle profiles across the rowing stroke cycle[19, 20]. In the present study the FDA techniques functional principal components analysis (*f*PCA) and analysis of characterizing phases (ACP), were applied in conjunction with established approaches for measuring asymmetries (i.e. the symmetry index used by Fohanno, Nordez, Smith and Colloud[15]), for a more holistic evaluation of asymmetries during on-water sculling. This mixed analytical approach was used to capture information related to changes in asymmetry across the entire movement cycle. The symmetry index applied by Fohanno, Nordez, Smith and Colloud[15] provides a total amount of asymmetry across the whole movement, and in this study represents a measure of '*global*' asymmetry across the rowing stroke cycle. The FDA techniques (*f*PCA and ACP) provide amounts of asymmetry that are present at specific parts of the movement, and in this study represent measures of '*local*' asymmetry at particular parts of the rowing stroke cycle. Consequently, the purpose of this study was to use this mixed analytical approach in the exploration of asymmetries in on-water single sculling. More specifically, differences in propulsive force asymmetries were assessed relative to the performance metric of competition level for a group of highly trained single sculling rowers. By doing this, this study aimed to understand whether asymmetries are deliberate parts of an underlying kinetic coordination structure in on-water rowing (following from the findings of Buckeridge, Bull and McGregor[13] and Fohanno, Nordez, Smith and Colloud[15] in ergometer research).

Methods

Participants

Following institutional ethical approval, 27 female rowers voluntarily consented to participate in this study (*M* age = 25.60 ± 4.88 years; *M* height = 1.74 ± 0.04 cm; *M* mass = 75.62 ± 4.61 kg). Participants were highly trained heavyweight and lightweight scullers. At the time of testing, competitive performance was used to categorize participants as either 'national' (n = 14) or 'international' level (n = 13) rowers. National rowers had competed in an Australian national age group championship or an Australian national open championship. International rowers had competed as an Australian representative at an Under 18, 23, an open level event or above.

Procedures

Participants were instructed to row for 1000m, composed of 250m at four ascending, pre-selected stroke rates (i.e., 20, 24, 28 and 32 stokes per minute). A short period of active rest (250m of light rowing) followed each stroke rate condition to control for fatigue effects. Rowers used *Nielsen-Kellerman © Strokecoaches* to control stroke rate outputs. For this study, only the 32 strokes/min data was analyzed. Data was obtained using ROWSYS instrumentation[21]. Propulsive pin force was measured using three-dimensional piezoelectric transducers (Kistler, Switzerland) and the pin was mounted on the rigger and was the axis of rotation for the gate. Horizontal oar angles were measured by low-friction potentiometers and a fiberglass arm attached to the inboard end of the oar, enabling free rotation of the oar around its longitudinal axis.

Data Processing

Data from ten strokes at 32 stokes per minute were selected for each rower on both sides of the boat. The same ten strokes were selected for the bow and stroke side for each rower (these sides of the boat are also referred to as starboard and port-side respectively). For each rower, the drive and recovery phases of the stroke were identified using oar angle relative to the horizontal[21], and the drive phase was examined further. A linear length normalization strategy using an interpolating cubic spline was applied, normalizing each curve to 100% of the drive phase. In addition to the ten individual curves, an ensemble average profile was created for each rower and for each boat-side.

Difference Time-Series

A difference-based time-series was created for each individual stroke and ensemble average profile, for each participant. The difference-based time-series was created by subtracting stroke-side force from bow-side force across the entire drive phase. This resulted in a continuous waveform describing fluctuating force asymmetry across the entire movement with zero, on the time-series, indicating perfect symmetry between boat-side forces; a positive value indicating higher force on the bow side; and a negative value indicating a higher force on the stroke side (see Figure 1). Once all difference-based time-series were defined, the symmetry index (SI), *f*PCA and subsequent ACP were conducted[22].

Symmetry Index

The SI was defined as the root-mean-square difference between values of the bow and stroke side propulsive pin-force curves across the entire drive phase[15]. Previously, Fohanno et al[15] normalized each curve relative to the maxima of the two parameters for each SI. This normalization process ensured that SI values could be compared between different variables as a percentage. In this study, only a single variable and measure (i.e., force and Newtons) was used, thus no normalization was necessary. An SI was calculated for each of the individual strokes and the average profile for each participant. Intra-athlete variability of SI was determined by calculating SI standard deviations ($SI\text{-}SD_{Intra}$) across ten strokes for each participant.

fPCA and ACP

As preliminary step in applying *f*PCA, each of the difference-based time-series were represented as functions using B-splines. The derived functions were smoothed by adding a roughness penalty to the fitting procedure. The roughness penalty term was controlled by a smoothing parameter (λ), which was selected using a combination of generalized cross-validation and visual inspection. An outline of the data fitting and smoothing processes for *f*PCA can be found in Ramsay and Silverman[23]. *f*PCA was conducted using all participant (ten per person) functions and each participant's ensemble average function. A comprehensive theoretical description of *f*PCA can be found in Ramsay and Silverman[23] and customized Matlab software for the implementation of this process can be found at the website *www.functionaldata.org*. In summary, *f*PCA is an extension of the classical multivariate technique PCA, but has been adapted to be appropriate for data in the functional domain. In *f*PCA, eigenfunctions rather than eigenvectors are used to represent principal components (also referred to functional principal components or *f*PCs). *f*PCs are defined in the same domain as the original functional observations and consequently have a definite biomechanical interpretation. Each *f*PC can be added and subtracted from the average function from the original data to demonstrate '*where*' variation in patterns are present in a data set across an entire movement cycle (see Figure 2A, where the '+' line is an *f*PC added to the average function, and the '–' is an *f*PC subtracted from the average function). The total number of *f*PCs required to retain 95% of variance in the data set were used. Retained *f*PCs were used to undertake ACP.

A requirement of ACP is that a VARIMAX rotation is performed on the data to optimize the interpretability of each *f*PC, and reveal a single *main phase* for analysis[22]. Once each of the main phases were identified (see Figure 2), these portions of the rowing drive phase were isolated to calculate an ACP score for each retained *f*PC. To achieve this, each *f*PC was re-sampled from a function into a vector of data points using the same frequency as the original data (100Hz). The position and sign of each *f*PC's absolute maximum were used to establish the start and end point of each main phase. The last value differing in sign before and after the absolute maximum defined the start and end of the main phase for each *f*PC. The benefit of using an *f*PCA decomposition is that each *f*PC (and associated main phases) are directly reflective of structural variability in the original time-series data. The conventional equation for the ACP score calculation is[24]:

$$ACP_{Score} = \sum_{i=1}^{n}(q_i - p_i)$$

These scores are calculated using the point-by-point Euclidean distance defined *area* between a participant's curve (p) and the mean curve across the data set (q) for every point (i) within the main phase (identified using the VARIMAX rotation for each *f*PC). In the present study a modified ACP_{Score} equation was used, where each ACP_{Score} was reflective of the point-by-point Euclidean distance based *average* between a participant's curve and the mean curve using the equation below:

$$ACP_{Score} = \frac{\sum_{i=1}^{n}(q_i - p_i)}{n}$$

where (*p*), (*q*) and (*i*) referenced identically to the original equation and (*n*) is the number of data points in the main phase. Using this approach for score calculation allowed an intuitive comparison between the overall SI for each participant and the ACP_{Scores}. The SI provided a measure of *average difference* between two curves across the entire waveform (measuring global asymmetry across the entire movement), and the ACP_{Score} for each *f*PC provided a measure of *average difference* between two curves, but was targeted at selected phases within the waveform (measuring local or '*movement phase*' asymmetry). For the SI and ACP_{Scores}, both measures of asymmetry were observed using the same scale and units of measure (Force and Newtons). In this study, the direction of each ACP_{Score} was also referenced relative to the direction of differences found in the original difference-based time-series. Therefore, a positive ACP scorer – for any given *f*PC - had an average increase in bow force relative to stroke force across a key phase; while a negative scorer had an average increased stroke force relative to bow force. ACP_{Scores} were also used to also calculate intra-rower asymmetry variability, defined as the ACP_{Score} standard deviation ($ACP\text{-}SD_{Intra}$) of the ten strokes for each participant.

Statistical Analysis

Differences in asymmetry relative to competition level were examined using the SI, $SI\text{-}SD_{Intra}$, ACP_{Scores} and $ACP\text{-}SD_{Intra}$. To assess differences relative to competition level, separate univariate ANOVAs were applied to measures of SI, $SI\text{-}SD_{Intra}$, ACP_{Score} and $ACP\text{-}SD_{Intra}$ ($\alpha = 0.05$). Only the scores for the average difference curves were included in each ANOVA for SI and ACP_{Scores}. As previously mentioned, for ease of interpretation with the results of these different analytical techniques the terms *global* and *local* asymmetry will be used. The SI represents global asymmetry across the stroke cycle, the $SI\text{-}SD_{Intra}$ represents global asymmetry variability (within a participant), the ACP_{Scores} represent local asymmetry at selected parts of the stroke cycle and $ACP\text{-}SD_{Intra}$ represents local asymmetry variability (within a participant).

Results

fPCA decomposition

The first five *f*PCs accounted for 95.2% of all variance in all curves. The content of these *f*PCs is demonstrated in Figure 3. The main phase from *f*PC1 described the presence of asymmetry starting from the catch position and continuing until approximately 35% of the drive phase. The main phase for *f*PC2 highlighted asymmetry in the middle of the drive phase. The main phase for *f*PC3 highlighted asymmetry beginning in the middle of the drive phase and continuing through the second half of force application. The fourth *f*PC's showed an asymmetry main phase at the end of the drive phase until the finish position. The fifth *f*PC's main phase showed asymmetry beginning early in the drive phase and continuing through until half way through force application.

Competition Level

All descriptive statistics and univariate ANOVA results for global and local symmetry measures are shown in Table 1. SI differences were statistically significant between international and national level rowers ($p < 0.05$), indicating that international level rowers possessed a higher SI. No statistical differences according to competition level were found for $SI\text{-}SD_{Intra}$. ACP_{Scores} demonstrated competition level differences, with scores for *f*PC1, *f*PC3, *f*PC4 and *f*PC5 demonstrating significance ($p < 0.05$) for competition level. For *f*PC1 and *f*PC5, international rowers were indicative of negative scorers, while for *f*PC2 and *f*PC3 international rowers were indicative of positive scorers. $ACP\text{-}SD_{Intra}$ measures also identified a difference for competition level for *f*PC2. International rowers reported a lower $ACP\text{-}SD_{Intra}$ variability during the middle phase of the drive phase.

Discussion

Symmetry, Asymmetry and Performance

The purpose of this study was to explore the role of asymmetries in on-water single sculling and assess whether these asymmetries can differentiate between rowers according to performance characteristics such as level of competitive representation. The symmetry index (SI) used in this study revealed differences for competition level, where international athletes significantly differed from their national counterparts in the amount of global asymmetry across the entire movement cycle. International athletes were more likely to have an increased SI indicating that the total global asymmetry present for these athletes tended to be higher than that in national level athletes. The inclusion of the ACP_{Scores} as a measure of local asymmetry also revealed that the structure of these asymmetries may have also differed as a factor of competition level, at particular sections of the drive phase. Four of the five retained *f*PCs (and their associated ACP_{Scores}) revealed statistical significance between international and national athletes. International athletes scored negatively on *f*PC1 and *f*PC5 indicating a trend for stroke-side pin force to lead bow-side pin force from the start of the drive phase until half way through the movement cycle. *f*PC3 and *f*PC4 were also more likely to be positive for international athletes indicating a trend for this early asymmetry to reverse through the second half of the drive phase, with the bow-side leading the stroke-side towards the finish. The reverse of these characteristics (described by the four *f*PCs) was found for national level athletes. One explanation for these differences in asymmetry patterns may be related to the fixed mechanical offset present in boat rigging during sculling[18, 21].

Smith and Loschner[21] illustrated (descriptively through graphical depictions of the rowing '*hand curve*') that a vertical oar angle offset was present in a single scull, for an exemplar highly skilled rower. This offset was relatively consistent across the whole movement, but more prominent early in the drive phase. Burnett, Doyle and Elliot[25] supported this finding and demonstrated increased vertical oar angles (and a subsequently higher handle position) for the bow side oar when compared to the stroke side oar for single scullers, at both the catch and finish positions of the drive phase. Burnett, Elliot and Doyle also found that sculling rowers possessed a tendency to drop their left hand downwards as they approach the catch to a larger extent than their right. It was suggested that this was likely a consequence of the same mechanical offset and as a sculling rowers approached the catch position, the left hand was dropped down towards the water to minimize the height difference between the hands and keep the boat balanced. This indicates, that for the present study, stroke-side force application may have begun at the catch in a well '*anchored*' position and possibly allows for controlled, and increased force application early in the drive, relative to the bow side. It is possible that international athletes are more efficient at modifying their movement strategies relative to this mechanical constraint and are consequently anchoring strongly with the stroke-side oar early in the drive, with the bow-side then applying more force halfway through the stroke cycle to counterbalance for this early kinetic offset.

When assessing changes in global asymmetry variability relative to level of competitive representation, the SI-SD_{Intra} did not show any significant differences. Additionally, only a reduction in local asymmetry variability for *f*PC2 (demonstrated through ACP_{Scores}) was shown to be significant for international athletes. This indicates that minimal asymmetric fluctuations halfway through the drive phase may be relevant descriptor of better rowing skill. This is logical since effective force application (oars being perpendicular to the longitudinal axis of the boat) occurs throughout the middle part of the drive phase[18] and stability in force application through this part of the stroke would likely be of benefit to rowers and increase rowing efficiency. It is important to note that this difference between competition levels for local asymmetry variability would not have been detected if the SI was used alone, demonstrating the benefit of including novel analytical approaches such as *f*PCA and ACP for reducing the stroke cycle into specific phases of asymmetry patterns.

Functional asymmetries and coordination

One further co-incidental finding is related to the amount of variability within the international and national cohorts for local asymmetry measures. It can be seen in Table 1 that the group standard deviations for ACP_{Scores} in international athletes for *f*PC1, *f*PC2 and *f*PC5 were considerably higher than group standard deviations for the national level rowers. The main phases for these *f*PCs describe different sections of asymmetry starting at the catch and continuing through until 50% of the way through the drive phase. This indicated that international rowers explored a broader range of asymmetry patterns in the first half of the drive phase. Furthermore, once athletes have adopted a suitable asymmetry strategy, irrespective of competitive level, *f*PC1, *f*PC2 and *f*PC5 again revealed higher $ACP\text{-}SD_{Intra}$ scores, indicating an increased amount of local asymmetry variability at each of these phases on the stroke cycle (when compared to *f*PC3 and *f*PC4). This indicated that the first half of the drive phase may be a more functionally adaptive part of the stroke cycle, with larger amounts of between-athlete variation for asymmetry patterns (particularly for international athletes) and also large amounts of within-athlete variation. These higher levels of variability (both between and within rowers) may account for potentially large changes in boat acceleration during the early stages of the drive phase. Studies on a stationary ergometer have demonstrated increased lower limb joint loads as a consequence of higher inertial masses that the rower needs to overcome at the catch[26, 27]. It is possible that these loads will affect the dynamic stability of the boat and rower position in an on-water environment.

Findings from this study also imply that features of kinetic asymmetries in on-water rowing should not necessarily be viewed as a negative feature of rowing performance. Rather, asymmetries should be interpreted as possible structures of coordination in the output of force across the stroke cycle. Asymmetries in on-water rowing may act as flexible parts of a dynamic system operating relative to unique constraints imposed upon each individual athlete and the task context of the skill[28], particularly in light of the mechanical constraint of boat rigging in the present study. Finally, the concept of asymmetry variability presented in this study, illustrates the importance of exploring movement patterns across multiple movement cycles. Force profiles, evaluated in isolation are generally assumed to be quite stable within each rower, and historically individuals have generally maintained the same harmonic structure of their own unique force signature with every repetition of the skill[29, 30] (Figure 1). It is clear from present results, however that the nature of within-rower asymmetry variability, when explored from a bilateral perspective, reveals a complex relationship in the structure of waveform changes in on-water rowing. This was observed in Figure 4 where ACP_{Scores} for the ensemble average difference curves of two exemplar rowers were plotted in conjunction with ACP_{Scores} of each individual stroke for these two exemplar rowers. For both athletes, there was a substantial amount of intra-athlete variation in ACP_{Scores} of the individual strokes when compared to the ACP_{Scores} of each rower's average.

The benefit of using a mixed analytical approach in the identification of symmetry differences has proven useful for understanding asymmetries as a complex but potentially necessary part of on-water sculling. The use of *f*PCA and ACP has built on previous work exploring the use of symmetry indexes. More specifically, the symmetry index of Fohanno, Nordez, Smith and Colloud[15] used in conjunction with *f*PCA and ACP has facilitated an intuitive comparison of global and local asymmetry differences, with all measures presented using the same scale and units of measure (in this instance: Newtons).

Further to this, a number of new questions have emerged that can be explored using the analytical approach from the present study. Firstly, given that a mechanical offset is present in boat rigging and may have influenced results in the present study, this should be explored further in future research (for example, do patterns of asymmetries in the present study become more pronounced as rigging offsets become larger). Another future question relates to whether factors such as fatigue or stroke rate influence the patterns of asymmetry, particularly given that only a single stroke rate and short rowing period was investigated in the present study. Developing a better understanding of whether these asymmetries are intentional is also desirable. It is possible that elite rowers learn to introduce asymmetries relative to boat rigging constraints, and longitudinal experimental designs considering boat speed changes relative to asymmetry changes may provide some insight into whether these patterns of asymmetry are deliberately introduced by more highly skilled rowers.

The concept of synchronicity is also of contemporary interest in on-water rowing[31], and symmetry can be viewed as a form of intra-rower synchronicity. Given that asymmetrical offsets in force application from the present study may be intentional, this finding can also be viewed from the perspective of intrapersonal coordination dynamics. Differences between hands and limb movements have been demonstrated for bimanual motor activities, relative to hand dominance (such as that the preferred hand generally leads)[32]. As such, the higher force applied at the stroke stroke-side from the beginning of the stroke, might also be related to right-handedness (or sidedness). It is plausible that rowers might be able to catch 'sharper' with their preferred hand, with hand dominance often more likely to be right than left. Despite this not assisting in the understanding of why international rowers show different structures of asymmetries to national rowers, this should also be a point for future exploration of asymmetries in on-water rowing.

Perspectives

The purpose of this study was to use a novel analytical approach to explore the role of asymmetries in on-water single sculling and to assess whether they have functional consequences in terms of performance characteristics. Global and local measures of asymmetry were assessed across the entire movement cycle and differences were revealed according to levels of competitive representation. International athletes were more likely to demonstrate an asymmetry strategy with increased stroke-side force early in the drive phase, and increased bow side force through the second half of the drive. This was most likely the result of international athletes, better modifying their movement strategies relative to known mechanical offsets that are present in sculling as a consequence of boat rigging. The first half of the drive phase was also found to be a functionally adaptive part of the rowing stroke cycle. This part of the movement demonstrated higher levels of between athlete (particularly for international rowers) and within athlete (for all rowers) asymmetry variation. Overall, results suggest asymmetries may have a functional role in successful execution of the rowing stroke. Rather than asymmetries being dismissed as a potential problem and negative influence on performance, they might actually need to be carefully evaluated as they could be positive to performance.

References

1. Découfour N, Pudlo P. The continuous relative phase: an interesting data to appraise rowing coordination. *Arch Physiol Biochem, Supplement.* 2004:75-75.
2. Decoufour N, Pudlo P, Barbier F, Gorce P. Variations in expert rower coordination when rate increases on ergometer concept2®. *Comput Methods Biomech Biomed Eng.* 2008; 11(S1):79-80.
3. Seifert L, Leblanc H, Herault R, Komar J, Button C, Chollet D. Inter-individual variability in the upper–lower limb breaststroke coordination. *Hum Mov Sci.* 2011; 30(3):550-565.
4. Horan SA, Evans K, Morris NR, Kavanagh JJ. Thorax and pelvis kinematics during the downswing of male and female skilled golfers. *J Biomech.* 2010; 43(8):1456-1462.
5. Quinzi F, Sbriccoli P, Alderson J, Di Mario A, Camomilla V. Intra-limb coordination in karate kicking: Effect of impacting or not impacting a target. *Hum Mov Sci.* 2014; 33:108-119.
6. Irwin G, Kerwin DG. Inter-segmental coordination in progressions for the longswing on high bar. *Sports Biomech.* 2007; 6(2):131-144.
7. Williams GK, Irwin G, Kerwin DG, Hamill J, Van Emmerik RE, Newell KM. Coordination as a function of skill level in the gymnastics longswing. *J Sport Sci.* 2016; 34(5):429-439.
8. Wilson C, Simpson S, Hamill J. Movement coordination patterns in triple jump training drills. *J Sport Sci.* 2009; 27(3):277-282.
9. Armour Smith J, Siemienski A, Popovich Jr JM, Kulig K. Intra-task variability of trunk coordination during a rate-controlled bipedal dance jump. *J Sport Sci.* 2012; 30(2):139-147.

10. Buckeridge E, Hislop S, Bull A, McGregor A. Kinematic asymmetries of the lower limbs during ergometer rowing. *Med Sci Sports Exerc.* 2012; 44(11):2147-2153.

11. Hofmijster MJ, Van Soest A, De Koning JJ. Rowing skill affects power loss on a modified rowing ergometer. *Med Sci Sports Exerc.* 2008; 40(6):1101.

12. Baca A, Kornfeind P, Heller M. Comparison of foot-stretcher force profiles between on-water and ergometer rowing. In: Schwameder H, Strutzenberger G, Fastenbauer V, Lindinger S, Müller E, eds. *XXVth Conference of the International Society of Biomechanics in Sports.* Vol 1. Salzburg, Austria2006:1-4.

13. Buckeridge EM, Bull AM, McGregor AH. Foot force production and asymmetries in elite rowers. *Sports Biomech.* 2014; 13(1):47-61.

14. Colloud F, Bahuaud P, Doriot N, Champely S, Monteil K, Chèze L. Is force symmetry influenced by using a fixed versus a free-floating rowing ergometer mechanism? *XXVIe Congrès de la Société de Biomécanique.* Vol 1092001:65.

15. Fohanno V, Nordez A, Smith R, Colloud F. Asymmetry in elite rowers: effect of ergometer design and stroke rate. *Sports Biomech.* 2015; 14(3):1-13.

16. Loschner C, Smith R, Barrett R, Simeoni R, D'Helon C. The relationship between pin forces and individual feet forces applied during sculling. In: Barrett R, Simeoni RJ, D'Helon C, eds. *Third Australasian Biomechanics Conference (ABC3)*. Queensland, Australia2000.

17. Elliott B, Lyttle A, Birkett O. Rowing: The RowPerfect Ergometer: a training aid for on- water single scull rowing. *Sports Biomechanics.* 2002; 1(2):123-134.

18. Soper C, Hume PA. Towards an ideal rowing technique for performance. *Sports Med.* 2004; 34(12):825-848.

19. Warmenhoven J, Cobley S, Draper C, Harrison AJ, Bargary N, Smith R. Assessment of propulsive pin force and oar angle time-series using functional data analysis in on-water rowing. *Scand J Med Sci Sports.* 2017; In Press.

20. Warmenhoven J, Cobley S, Draper C, Harrison AJ, Bargary N, Smith RS. How gender and boat-side affect shape characteristics of force-angle profiles in single sculling: Insights from functional data analysis. *J Sci Med Sport.* 2017; In Press.

21. Smith RM, Loschner C. Biomechanics feedback for rowing. *J Sport Sci.* 2002; 20(10):783-791.

22. Richter C, O'Connor NE, Moran K. Analysis of characterizing phases on waveforms–an application to vertical jumps. *J Appl Biomech.* 2014; 30(2):316-321.

23. Ramsay JO, Silverman BW. *Functional data analysis*, Wiley Online Library; 2005.

24. Richter C, Marshall B, Moran K. Comparison of discrete-point vs. dimensionality-reduction techniques for describing performance-related aspects of maximal vertical jumping. *J Biomech.* 2014; 47(12):3012-3017.

25. Burnett A, Doyle M, Elliott B. Continuous registration of the hand-curve in rowing: Differences between scull and sweep rowers. *XXIIth Conference of the International Society of Biomechanics in Sports.* Vol 1. Ottawa: Canada2004.

26. Colloud F, Bahuaud P, Doriot N, Champely S, Chèze L. Fixed versus free-floating stretcher mechanism in rowing ergometers: mechanical aspects. *J Sport Sci.* 2006; 24(05):479-493.

27. Greene A, Sinclair P, Dickson M, Colloud F, Smith R. The effect of ergometer design on rowing stroke mechanics. *Scand J Med Sci Sports.* 2013; 23(4):468-477.

28. Newell KM. Constraints on the development of coordination. *Motor development in children: Aspects of coordination and control.* 1986; 34:341-360.

29. Hill H. Dynamics of coordination within elite rowing crews: evidence from force pattern analysis. *J Sport Sci.* 2002; 20(2):101-117.

30. Wing AM, Woodburn C. The coordination and consistency of rowers in a racing eight. *J Sport Sci.* 1995; 13(3):187-197.

31. Cuijpers LS, Passos PJM, Murgia A, Hoogerheide A, Lemmink KAPM, Poel HJ. Rocking the boat: does perfect rowing crew synchronization reduce detrimental boat movements? *Scand J Med Sci Sports*. 2016; *In Press*.

32. De Poel HJ, Peper CLE, Beek PJ. Handedness-related asymmetry in coupling strength in bimanual coordination: furthering theory and evidence. *Acta Psychol*. 2007; 124(2): 209-237.

Table I: Descriptive statistics (mean and standard deviation) and univariate ANOVA results for SI, SI-SD_{Intra}, ACP_{Scores} and ACP-SD_{Intra}.

	International	**National**	***F* Statistic**	**Sig.**
SI	16.36 (9.54)	7.55 (5.66)	8.67	0.01*
SI-SD_{Intra}	8.41 (2.68)	9.40 (3.75)	0.62	0.44
ACP_{Scores} (*f*PC1)	-9.45 (27.46)	8.78 (15.48)	4.60	0.04*
ACP_{Scores} (*f*PC2)	-4.10 (32.81)	3.81 (13.62)	0.69	0.41
ACP_{Scores} (*f*PC3)	7.41 (19.09)	-6.88 (14.38)	4.88	0.04*
ACP_{Scores} (*f*PC4)	4.37 (8.10)	-4.06 (11.52)	4.77	0.04*
ACP_{Scores} (*f*PC5)	-13.70 (38.61)	12.72 (14.67)	5.69	0.02*
ACP-SD_{Intra} (*f*PC1)	21.82 (7.80)	23.31 (8.73)	0.22	0.64
ACP-SD_{Intra} (*f*PC2)	16.55 (5.45)	23.35 (9.97)	4.72	0.04*
ACP-SD_{Intra} (*f*PC3)	11.40 (4.89)	15.42 (5.81)	3.76	0.06
ACP-SD_{Intra} (*f*PC4)	8.61 (3.74)	9.98 (3.17)	1.07	0.31
ACP-SD_{Intra} (*f*PC5)	20.35 (8.21)	26.56 (12.52)	2.29	0.14

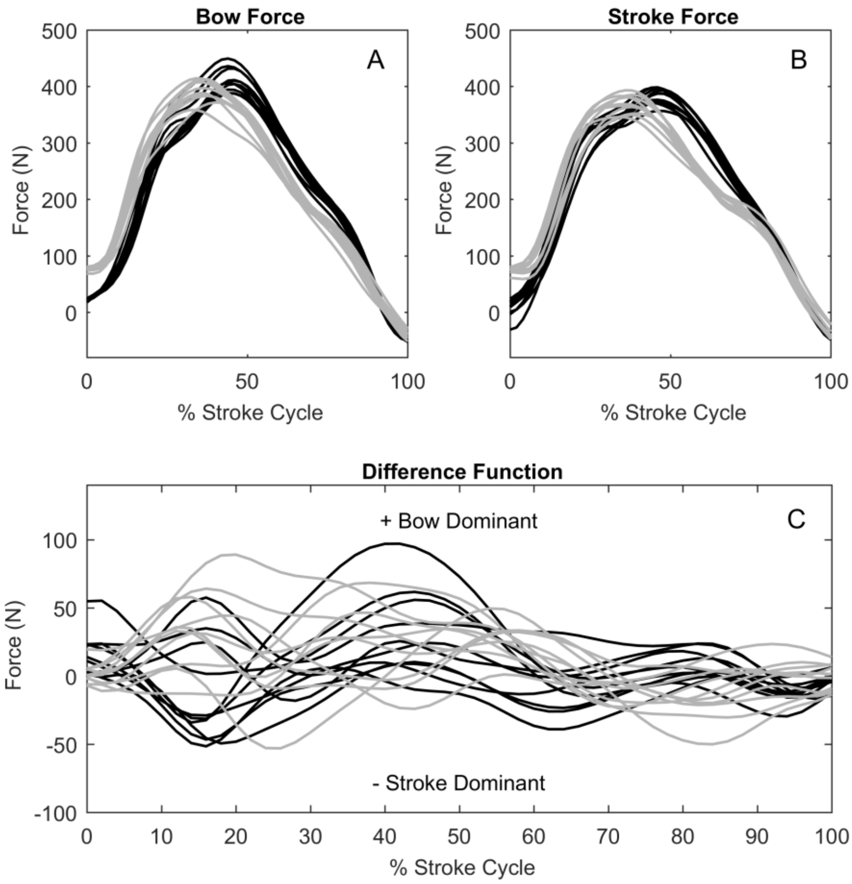
Table Notes: * = $p<.05$.

Figure I: A: Bow side force. B: Stroke side force. C: Difference-based time series created by subtracting stroke-side force from bow-side force. For all subplots ten strokes have been plotted for two athletes. International level rower in dotted grey. National level rower in black.

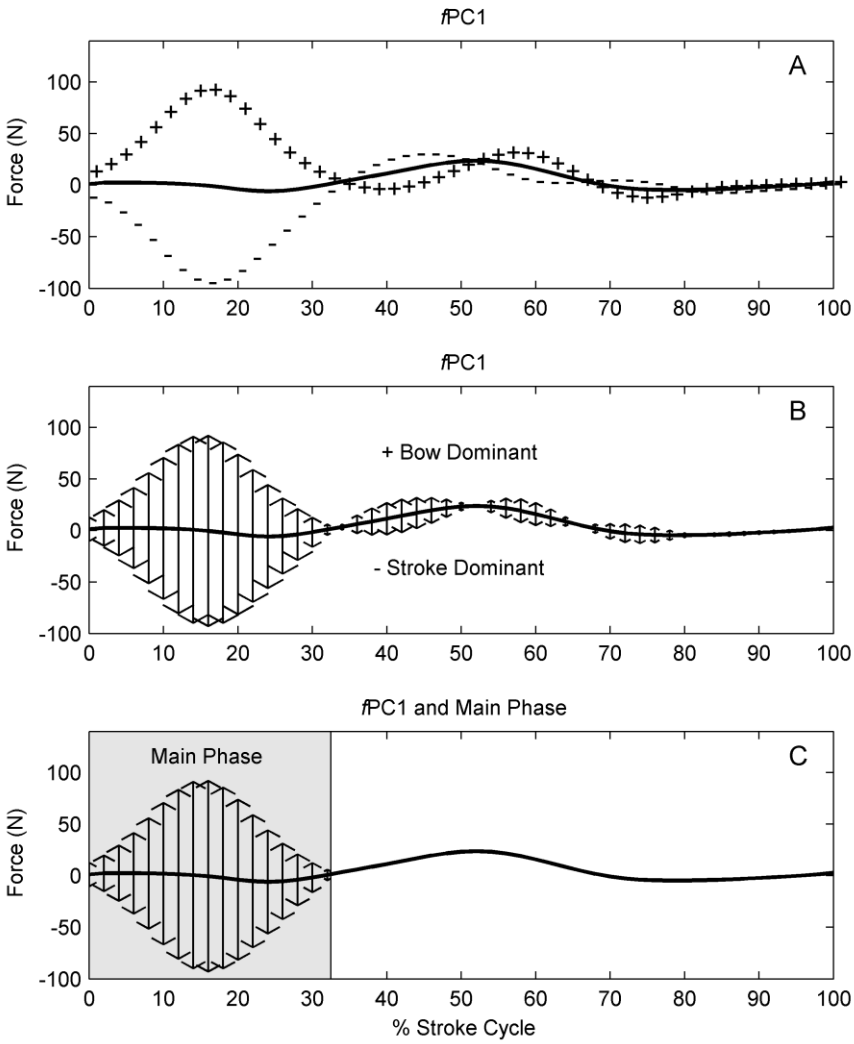
Figure II: A: *f*PC1 plotted using conventional illustration of positive and negative scorers (Dona et al. 2009). B: *f*PC1 plotted with positive scorers likely to bare characteristics of increased bow-side force and negative scorers increased stroke-side force. C: *f*PC1 with *main phase* identified.

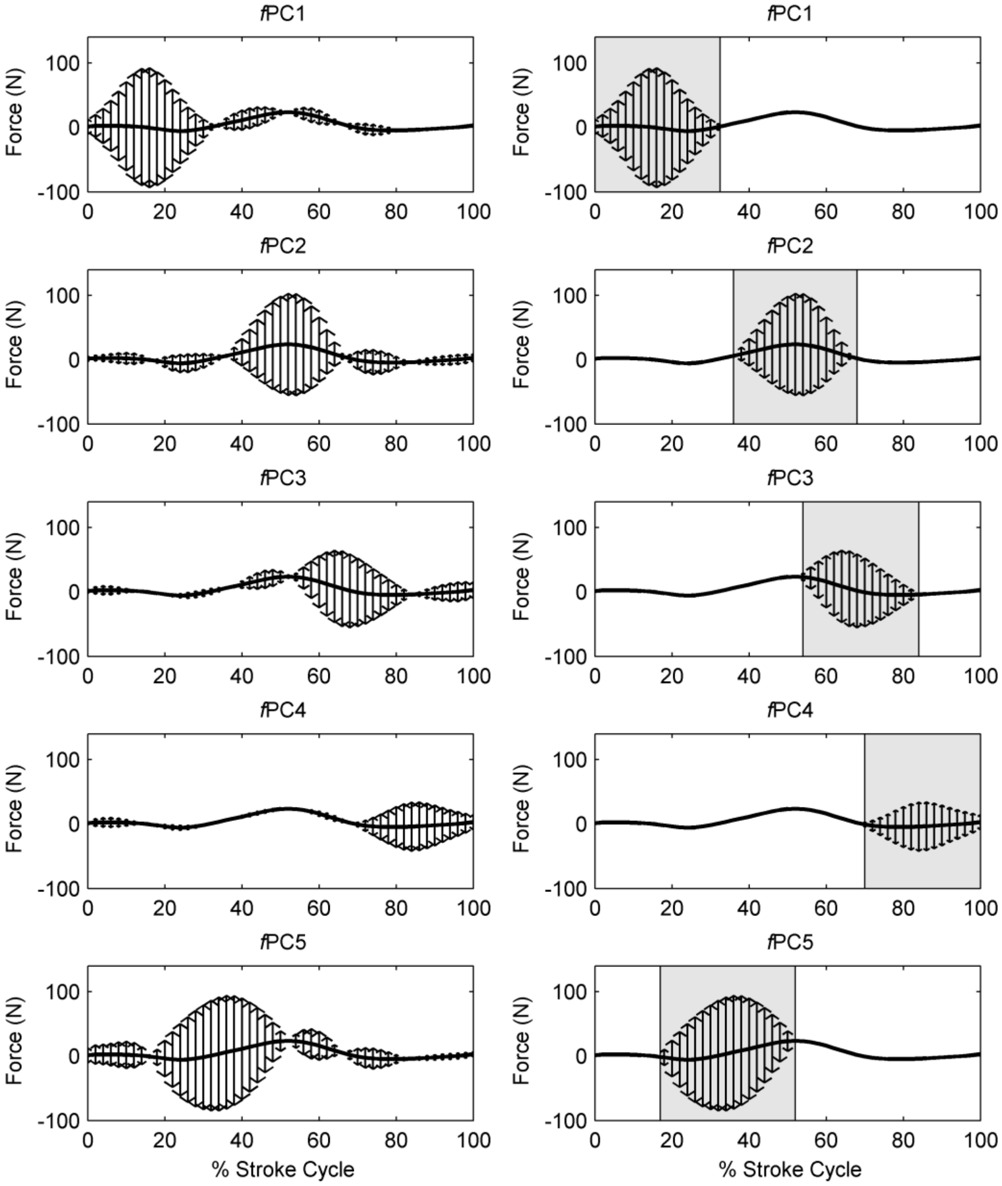
Figure III: Left: *f*PC1, *f*PC2, *f*PC3, *f*PC4 and *f*PC5 plotted across the whole drive phase movement cycle with each *f*PC varimax rotated. Right: *f*PC1, *f*PC2, *f*PC3, *f*PC4 and *f*PC5 plotted with only the main phase for each *f*PC remaining.

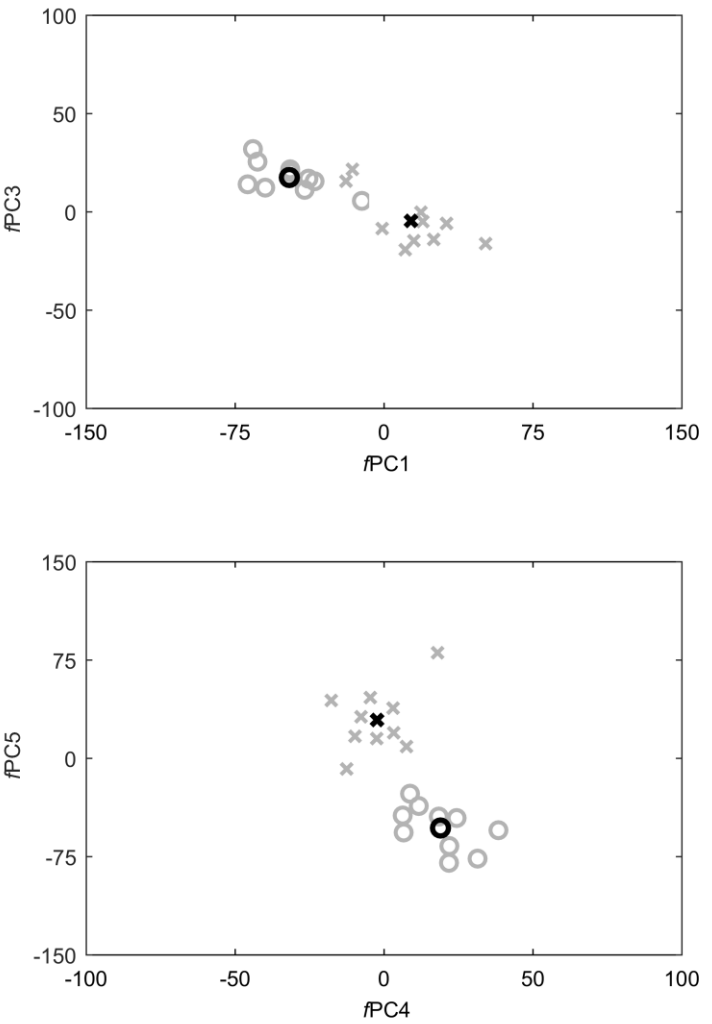
Figure IV: Top: Scatter plot of ACP_{Scores} for *f*PC1 and *f*PC3. Bottom: Scatter plot of ACP_{Scores} for *f*PC4 and *f*PC5. In both plots, ACP_{Scores} for mean asymmetry profiles are illustrated for two exemplar athletes (1 *national* as '×', and 1 *international* as 'o') in bold. The ACP_{Scores} of each athletes' individual ten strokes are also plotted as '×' for the national athlete and 'o' for the international athlete.



Bow Force
A
Force (N)
% Stroke Cycle
Stroke Force
B
Force (N)
% Stroke Cycle
Difference Function
C
+ Bow Dominant
- Stroke Dominant
Force (N)
% Stroke Cycle


fPC1
A
Force (N)
fPC1
B
+ Bow Dominant
- Stroke Dominant
Force (N)
fPC1 and Main Phase
Main Phase
C
Force (N)
% Stroke Cycle


fPC1
fPC1
fPC2
fPC2
fPC3
fPC3
fPC4
fPC4
fPC5
fPC5
Force (N)
100
0
-100
0
20
40
60
80
100
% Stroke Cycle
% Stroke Cycle


100
50
0
-50
-100
fPC3
-150
-75
0
75
150
fPC1
150
75
0
-75
-150
fPC5
-100
-50
0
50
100
fPC4