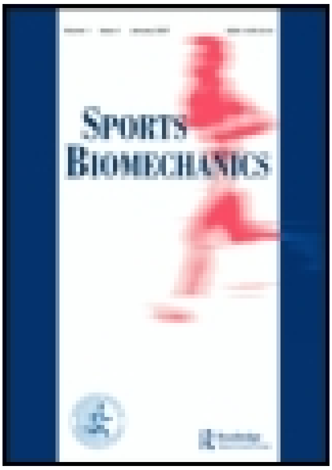

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Asymmetry in elite rowers: effect of ergometer design and stroke rate*

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Abstract
Between limb movement asymmetries and foot force production asymmetries are thought to be detrimental for both rower's performance and risk of injury, particularly when rowing frequently on ergometers. Several ergometers with different designs can be used by rowers as part of their indoor training. Hence, this study aimed to compare asymmetries in lower limb joint kinematics and foot force production with respect to ergometer design and rowing intensity. A new symmetry index was proposed to assess these asymmetries in elite rowers during a test on three ergometers. Additionally, the asymmetry in lower limb length was assessed to investigate its relationship with kinematic and kinetic asymmetries. Parameters describing medium (5–10%) or high (>10%) asymmetries were compared between rowing ergometers and intensities. Results indicated medium asymmetries for the ankle joint angle and hip–knee joint accelerations and high asymmetries for the resultant force and the ankle joint acceleration associated with a low inter-stroke variability. Kinetic asymmetry was neither correlated to kinematic asymmetry nor with lower limb length asymmetry. The use of a mobile ergometer led to higher joint acceleration asymmetries. Further studies are necessary to investigate the relation between these findings and muscular adaptations that may increase the risk of lower-back injury.

Keywords: *biomechanics, kinematics, kinetics, anthropometry, symmetry index*

Introduction

A high level of performance in rowing is commonly thought to be associated with high consistency between consecutive strokes and symmetry (Nolte, 2011). However, in contrast with sculling (i.e. almost symmetric task with two oars), sweep rowing consists of using only one oar, presenting an asymmetric task for the upper limbs, the lower limbs, and the trunk. Thus, Janshen, Mattes, and Tidow (2009) and Parkin, Nowicky, Rutherford, and McGregor (2001) reported asymmetries in sweep rowers. More precisely, Janshen et al. (2009) showed

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asymmetrical force production at the foot stretcher when rowing on ergometer. It means that even for a symmetrical task, elite sweep rowers produce asymmetrical forces, and it was associated with the daily practice that could result in chronic adaptations of asymmetry. These adaptations are thought to be detrimental for the performance and health of the rower. For instance, it is hypothesised that these asymmetries can induce lower back imbalance and thereby increase the risk of lumbar pain and injuries (Buckeridge, Bull, & McGregor, 2014a; Buckeridge, Bull, & McGregor, 2014b; Buckeridge, Hislop, Bull, & McGregor, 2012; McGregor, Anderton, & Gedroyc, 2002a; McGregor, Anderton, & Gedroyc, 2002b; Parkin et al., 2001; Pudlo, Pinti, & Lepoutre, 2005).

Recent studies examined the asymmetries of the lower limbs in both scullers and sweep rowers during ergometer rowing (Buckeridge et al., 2012, 2014a, 2014b). The work of Buckeridge et al. (2012, 2014b) separately showed asymmetry in both lower limb kinematics (Buckeridge et al., 2012) and foot stretcher forces (Buckeridge et al., 2014a). Surprisingly, the level of asymmetry was not significantly different either between sweep rowers and scullers, rowing intensities, or between elite, club and novice rowers (Buckeridge et al., 2014a). Therefore, these studies revisited the understanding of symmetry in rowing and it is of great interest to note that asymmetry in rowing is not only a feature of sweep or novice rowers and an elite sculler can also display high levels of kinematic and kinetic asymmetries for the lower limbs. Nevertheless, these results require further investigation to better understand and characterise asymmetry among elite rowers. Three points are of particular interest.

First, Buckeridge et al. (2012, 2014a, 2014b) reported the level of asymmetry using the absolute symmetry index (SI) originally proposed by Robinson, Herzog, and Nigg (1987). However, this index may limit the interpretation of the results because this formula uses discrete parameters (e.g. range of motion, peak force, and impulsion) and does not compare the patterns of kinematic and kinetic measurements. For instance, two impulses (areas under the force–time curves) can be similar whereas the patterns are different and the use of the peak-to-peak difference for the kinematic variables can be misleading to represent asymmetries in terms of pattern. In addition, Buckeridge et al. (2014a) reported the inter-stroke variability of the force values instead of the asymmetry values. Indeed, it could be hypothesised that an inter-stroke inconsistency of the asymmetry is important and it could influence the actual effect of the tested factor (e.g. rowing intensity or type of ergometer).

Second, the amount of asymmetry reported for the lower limb kinematics (see Table III of Buckeridge et al., 2012, for more details) seems to be much lower compared with foot stretcher forces (see Table II of Buckeridge et al., 2014a, for more details). Considering the principles of multibody system dynamics (i.e. Newton–Euler laws of motion), the asymmetry of force production should be explained by asymmetry of kinematics and/or anthropometry. Therefore, it seems valuable to report asymmetries in anthropometric, kinematic and kinetic variables for the same participants. Lower limb length is a simple parameter that can account for anthropometric asymmetries. Moreover, it seems relevant to include the analysis of joint accelerations, which are more related to the force production at the foot stretcher than the joint angles. In this case, the use of a new SI based on a pattern comparison is essential because the peak-to-peak difference proposed by Robinson et al. (1987) would be inappropriate to assess asymmetry in joint accelerations (Figure 2).

Third, these previous studies were performed on a stationary ergometer (Buckeridge et al., 2012, 2014a, 2014b; Janshen et al., 2009), while different ergometer designs, commonly separated as stationary and mobile ergometers, are widely used by rowers as part of their indoor training sessions and evaluations. Mobile ergometers differ from the stationary ergometers by the sliding motion of the foot stretcher-flywheel complex or the ergometer frame. Studies demonstrated that rowing on a stationary ergometer increases lower limb joint loads, and therefore the risk of injury, because of the higher inertial masses that the rower needs to overcome at the catch (Colloud, Bahuaud, Doriot, Champely, & Chèze, 2006; Greene, Sinclair, Dickson, Colloud, & Smith, 2013; Smith, Dickson, & Colloud, 2013). This difference in lower limb load could result in differences in the level of asymmetry, i.e. lower asymmetries expected during the mobile ergometer condition. Thus, it would be interesting to investigate the influence of the stationary and mobile rowing conditions on the level of kinetic and kinematic asymmetries to complete the findings of these previous studies.

In summary, several elements require further investigations, and the present study was designed to better characterise and understand the asymmetry of elite rowers on ergometers. For that purpose, this study proposed a new way to assess the asymmetry of patterns that could be useful to compare kinematic (joint angles and joint accelerations) and kinetic variables from the theory of multibody system dynamics. This SI was used in order to (i) assess asymmetry of kinematic and kinetic variables; (ii) analyse the consistency of the asymmetry; (iii) compare asymmetry across ergometers (i.e. fixed vs. mobile), and (iv) examine the relationships between kinetic and kinematic asymmetries and between lower limb length and kinematic–kinetic asymmetries. We hypothesised that (i) the amount of asymmetry is similar for kinetic and joint acceleration variables, but lower for joint angles, (ii) the asymmetry is consistent across strokes for elite rowers, (iii) the use of a mobile ergometer leads to lower asymmetry, and (iv) kinetic asymmetry is related to kinematic and lower limb length asymmetries.

Methods

Participants

Data from this study have been partially used in previous published articles (Greene, Sinclair, Dickson, Colloud, & Smith, 2009, 2013; Smith et al., 2013). Ten male rowers competing at an international level gave their informed consent to participate in this study. Their training frequencies ranged from 7 to 11 sessions per week. A specific 2000 m time-trial was performed prior to the experiments as part of the national training programme on a Concept2® Model C Indoor Rower (Concept2, Inc., Morrisville, VT, USA). Their main characteristics are summarised in Table I. All of them were free from pain or injury at the time of the experiment. The University of Sydney Human Ethics Review Committee approved this study. Rowers who stopped their rowing activity due to lower back pain in the 12 months prior to the experiments did not participate in the study.

Protocol

The experiment was conducted on three different rowing ergometers: the stationary Concept2® Model C Indoor Rower (Concept2, Inc., Vermont, USA) (C2F), the Concept2® Model C with slides fitted to the front and rear stands (C2S), and the RowPerfect® (RP) with a free-floating stretcher mechanism (Care RowPerfect BV, 7772 JV Hardenberg, The Netherlands). The C2F, C2S, and RP ergometer conditions were presented on the same day for each participant. Three rowing intensities were tested by means of an incremental test performed during each ergometer session: two imposed paces

Table I. Characteristics of the ten male rowers.

Participants	Age (y)	Height (m)	Mass (kg)	2000 m time (s)	Speciality
P1	29	1.93	90.0	380	Scull
P2	27	1.99	103.5	346	Scull-sweep
P3	29	2.00	95.0	361	Sweep
P4	24	1.94	95.0	364	Scull
P5	19	1.92	96.0	358	Sweep
P6	29	1.99	98.0	350	Scull-sweep
P7	23	1.96	95.0	361	Sweep
P8	29	1.93	99.0	380	Sweep
P9	19	1.88	87.0	374	Scull-sweep
P10	29	2.00	91.5	372	Scull-sweep
M ± *SD*	25.7 ± 4.2	1.95 ± 0.04	95.0 ± 4.7	364.6 ± 11.8	

(20 and 32 strokes per minute (spm)) and a self-selected or 'race' pace corresponding to a stroke rate used during a 2000 m competitive race. The average stroke rate of the race intensity condition was 35.9 ± 2.0 spm. The ergometer condition order was randomly assigned to each rower. Each trial lasted 60 seconds and was followed by a period of five-minute active rest on the ergometer at a self-selected, easy, and comfortable pace.

The stroke rate was controlled by the rowers using a visual display (Speed Coach®, Nielsen-Kellerman, Marcus Hook, PA, USA) placed on each ergometer. The flywheel resistance was set at levels commonly used by the Australian National Rowers: level 4 (drag factor set at 120) for the C2F and C2S ergometers and using a 400 mm diameter wind disc for the RP ergometer.

Data collection

Kinematic Data. A 9-cameras motion analysis system (Motion Analysis Corporation, Santa Rosa, CA, USA) was used to record the 3D kinematic data at 60 Hz. Ahead of the nine rowing sessions per athlete, a static acquisition followed by two hip joint motion trials (Begon, Monnet, & Lacouture, 2007) was performed by each rower to design its biomechanical model of the lower limbs. The lower limbs of the rower were equipped with 28 retroreflective skin markers (15 mm diameter) for these three trials (Greene et al., 2009). Afterwards, six markers were removed because of their inconvenient location for rowing on an ergometer. Seven additional markers were placed on the handle and the stretcher.

The hip joint motion trials were used to functionally estimate the hip joint centre locations using the symmetrical centre of rotation estimation method (Ehrig, Taylor, Duda, & Heller, 2006). The static trial was then used to design the biomechanical model comprising seven rigid bodies: pelvis, two thighs, two shanks, and two feet. The pelvis, considered as the root segment of the biomechanical model, had six degrees of freedom. Two consecutive rigid bodies were connected by a hinge joint (i.e. one degree of freedom) allowing the flexion–extension of the child segment. The recommendations of the International Society of Biomechanics were followed to attach a local frame to each rigid body and determine the joint kinematics using the appropriate Cardan sequence (Wu et al., 2002). Finally, the biomechanical model incorporated the marker coordinates expressed in their corresponding local frame.

A forward kinematic function $f(q)$ was designed to estimate the unknown variables of the biomechanical model, i.e. the joint kinematics and the position and orientation of the pelvis.

From these unknown variables, $f(q)$ gives the marker coordinates T of the biomechanical model in a global frame associated with the ergometer. The unknown variables are included in a vector q determined using a global optimisation algorithm that minimises the quadratic distance between the model-determined markers T and the markers recorded by the motion analysis system M (Lu & O'Connor, 1999; Fohanno, Begon, Lacouture, & Colloud, 2014):

$$\begin{cases} \min\limits_{q} \ 1/2\,[f(q){-}M]^{\mathrm{T}}\ [f(q){-}M] \\ \text{subject to } q_{\min} \le q \le q_{\max} \end{cases}, \tag{1}$$

where q_{min} and q_{max} are the lower and upper boundaries of the unknown variables included in q, respectively.

This non-linear least-squares equation was solved iteratively at each time step using the trust-region-reflective algorithm of the Matlab®'s *lsqnonlin* function (The MathWorks, Natick, MA, USA). Moreover, this minimisation procedure was performed in the sagittal plane of the ergometer to determine the planar joint kinematics of each lower limb. From the participant's rigid biomechanical model, each lower limb length was determined as the distance between the hip joint centre, determined using a functional approach recommended by the International Society of Biomechanics (Wu et al., 2002), and the ankle joint centre passing through the knee joint centre.

Kinetic Data. A specific instrumentation was designed to measure the forces exerted by the rower at the foot stretcher (Greene et al., 2009, 2013; Smith et al., 2013). This instrumentation was similar on the three ergometers. The foot stretcher measured separately the left and right 3D external forces. Each side of the foot stretcher was instrumented with two 3D force transducers (Model 9067, Kistler Instrument Corp., AG Winterthur, Switzerland, linearity ≤0.5%, hysteresis ≤0.5%). The force at the handle was measured using a one-dimensional force transducer (Model TLL-500, Transducer Techniques, Inc., Rio Nedo Temecula, CA, USA, linearity 0.24%, hysteresis 0.08%) attached between the handle and the chain. All the force transducers were calibrated against a force platform (Model 9281A, Kistler Instrument Corp., AG Winterthur, Switzerland). The calibration errors were lower than 1.5% for all the transducers.

Concerning the foot stretcher, only the force components lying in the plane collinear to the sagittal plane of the ergometer were used for the purpose of this study. As each side of the foot stretcher was instrumented with two force transducers, both force signals were summed in order to obtain global right and left forces. These forces were used to calculate the resultant force (*Fr*). The force signals were sampled at 120 Hz and synchronised with the motion analysis system.

Data analysis

The raw marker coordinates and force signals were filtered using a second-order low-pass filter with an optimal cut-off frequency of 5 Hz and 10 Hz, respectively (Giakas & Baltzopoulos, 1997). Ten consecutive strokes were selected in the middle of each trial so that the desired stable stroke rate is reached during this period. The catch and finish events of the ten strokes were automatically detected to time-normalise the joint angles and the forces between 0% and 100% of the drive phase. The catch and finish events are defined as the most anterior and posterior point of handle with respect of the stretcher, respectively. These points were calculated using the longitudinal component of the middle of the markers placed on both extremities of the handle. A total of 900 strokes were obtained from 10 participants, 3 rowing intensities, and 3 ergometer conditions. All the calculations were derived from the 10 time-normalised curves of each trial.

A SI was calculated for each stroke from the time-normalised kinematic and kinetic curves (Figure 1). Kinematic and kinetic patterns were normalised with the two extreme values reached during each stroke. Then, the SI was defined as the root-mean-square difference between the values of the two curves for each stroke. This normalisation procedure ensured that SI values could be compared across the different variables. In this study, the average SI over the ten consecutives strokes of each trial was reported and used for the statistical analysis.

To evaluate the variability of the asymmetry across strokes, the SI was calculated for the foot stretcher resultant force (*Fr*) and the hip, knee, and ankle joint angles (θ_{Hip}, θ_{Knee}, and θ_{Ankle}) and accelerations (α_{Hip}, α_{Knee}, and α_{Ankle}). Then, the inter-stroke variability was computed as the SI's 95% confidence interval for the 10 consecutive strokes of each trial.

Statistical analysis

The comparison of the asymmetries (dependant variable) between the three ergometer conditions and the three rowing intensities (independent variables) was performed using two-way ANOVAs for the parameters with SI values above 5%. This threshold was selected arbitrarily to take into account only the variables of interest, i.e. those for whom the level of asymmetry was considered as relevant. Partial η-squared ($p\eta^2$) values were reported as measures of effect size, with moderate and large effects considered for $p\eta^2 = 0.07-0.14$ and $p\eta^2 > 0.14$, respectively (Cohen, 1988). A Bonferroni post hoc procedure was followed when appropriate. Pearson correlation coefficients (*r*) were calculated to examine the correlations (i) between kinetic (*Fr*) and kinematic (θ_{Hip}, θ_{Knee}, θ_{Ankle}, α_{Hip}, α_{Knee} and α_{Ankle}) asymmetries and (ii) between lower limb length asymmetry and kinematic and kinetic asymmetries. For all statistical procedures, a statistical difference was established when the p value was less than 0.05.

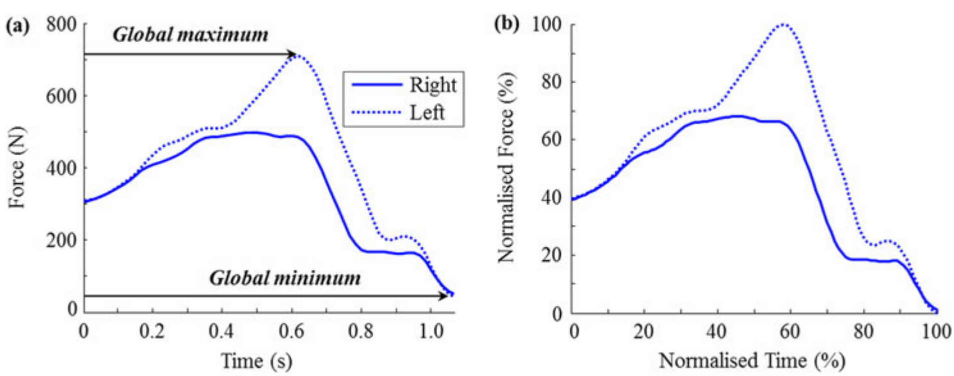

Figure 1. Data processing for the calculation of the SI: example for the resultant foot force (participant 2, C2F, 20 spm). Solid line and dashed line represent the right and left patterns, respectively. (a). Raw data and determination of global maximum and minimum among the left and right data. (b). Time and force normalisation using the global maximum and minimum. Then, the SI is calculated as the root-mean-square difference between the right and left normalised signals. In this example, the SI is 12.5%. Using the formula of Robinson et al. (1987) and the impulse as in Buckeridge et al. (2014a), the SI is 15.4%.

Results

Level of asymmetry

Examples of the measured parameters are given in Figure 2. The average values of asymmetry were 10.9 ± 3.7%, 3.3 ± 1.6%, 3.7 ± 2.0%, 6.4 ± 2.8%, 6.4 ± 1.8%, 5.9 ± 1.4%, and 12.5 ± 3.1% for *Fr*, θ_{Hip}, θ_{Knee}, θ_{Ankle}, α_{Hip}, α_{Knee} and α_{Ankle}, respectively (Table II). For each variable, a low standard deviation was observed. Half of these variables showed mean values above 5%: for *Fr*, θ_{Ankle}, α_{Hip}, α_{Knee} and α_{Ankle}.

Inter-stroke variability of the asymmetry

The average consistency of the asymmetry was high for both kinetic and kinematic variables. The 95% confidence intervals reached 4.2 ± 2.3%, 1.0 ± 1.3%, 1.6 ± 2.8%, 3.0 ± 3.2%, 3.5 ± 2.6%, 3.7 ± 2.6%, and 5.9 ± 3.9% for *Fr*, θ_{Hip}, θ_{Knee}, θ_{Ankle}, α_{Hip}, α_{Knee} and α_{Ankle}, respectively.

Comparison between ergometers and rowing intensities

For *Fr*, the results of the two-way ANOVA showed neither significant effect of the rowing intensity ($p = 0.70$, $p\eta^2 = 0.04$) nor the ergometer ($p = 0.49$, $p\eta^2 = 0.08$).

For θ_{Ankle}, the two-way ANOVA indicated significant main effects of the ergometer ($p = 0.008$, $p\eta^2 = 0.41$) and rowing intensity ($p = 0.01$, $p\eta^2 = 0.40$) without interaction ($p = 0.21$, $p\eta^2 = 0.15$). Asymmetries were lower when using the RP ergometer in comparison with the C2F ergometer. No difference was observed between the C2S and the two other ergometer conditions. Moreover, higher asymmetries were reported when rowing at 20 spm.

For α_{Hip} and α_{Knee}, statistical results highlighted significant main effects of the ergometer design ($p < 0.001$, $p\eta^2 = 0.87$ and $p = 0.02$, $p\eta^2 = 0.35$, respectively) and rowing intensity ($p = 0.01$, $p\eta^2 = 0.39$ and $p = 0.01$, $p\eta^2 = 0.41$, respectively) associated with a positive interaction between ergometer and rowing intensity ($p < 0.001$, $p\eta^2 = 0.51$ and $p < 0.001$ and $p\eta^2 = 0.46$). More precisely, asymmetries of both variables were lower for the stationary condition in comparison to the two mobile conditions. In addition, these asymmetries were higher at 20 spm for both mobile conditions but were similar for the stationary condition.

For α_{Ankle}, the results of the two-way ANOVA showed a significant effect of the ergometer ($p < 0.001$, $p\eta^2 = 0.60$) associated with a positive interaction with the rowing intensity ($p < 0.001$, $p\eta^2 = 0.55$). The Bonferroni procedure indicated higher asymmetries for the mobile ergometers (C2S and RP) in comparison with the stationary ergometer (C2F) at 20 and 32 spm. No significant main effect of the rowing intensity was reported ($p = 0.18$, $p\eta^2 = 0.17$). The statistical results indicated a large effect size with 13 of the 15 analysed factors reporting a large effect size, i.e. $p\eta 2 > 0.14$.

Relationships: lower limb length asymmetry, and kinetic and kinematic asymmetries

The results of the correlation between the lower limb length asymmetry and the kinetic and kinematic asymmetries are low and not significant except for the correlation with the knee joint angle asymmetry ($r = 0.74$, $p = 0.013$, Table III). In addition, no significant correlation between kinetic and kinematic asymmetries was reported (Table III).

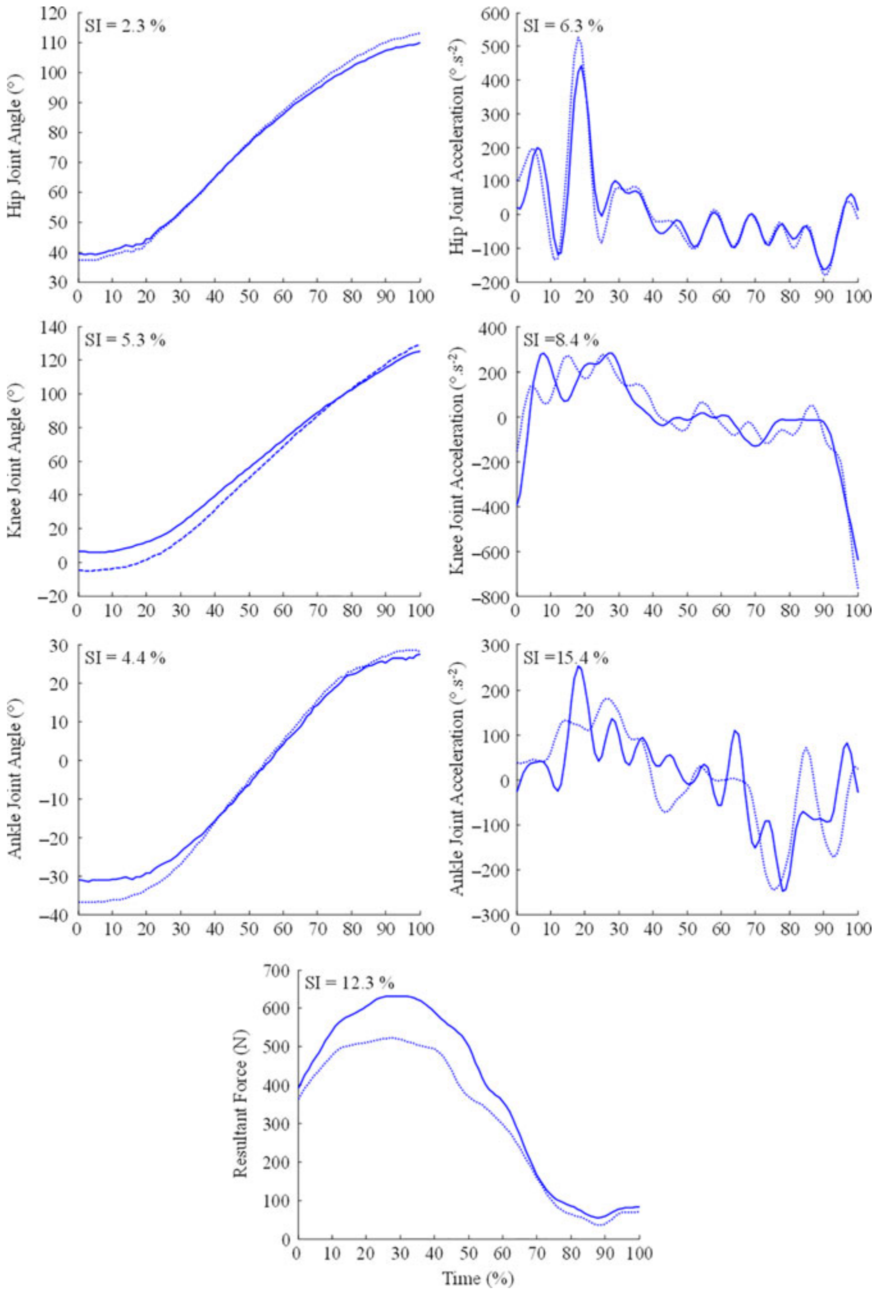

Figure 2. Examples of the measured parameters for one stroke (participant 9, RP, 20 spm). The curves were only time normalised. Solid line and dashed line represent the right and left patterns, respectively. The SI is provided for each parameter.

Discussion and implications

This study focused on the analysis of asymmetry in elite rowers during on-ergometer sessions. The results indicated that low-pattern asymmetries (3–4%) were reported for hip–knee joint

Table II. SIs in percentage ($M \pm SD$) for the kinetic and kinematic parameters for each ergometer (C2F, C2S, and RP) and intensity (20 spm, 32 spm, and race pace) combination.

	C2F				C2S				RP				
Measure	20	32	Race	Average	20	32	Race	Average	20	32	Race	Average	Average
Fr	9.1 ± 3.9	10.5 ± 3.9	11.4 ± 4.7	10.5 ± 4.0	10.9 ± 5.0	11.2 ± 3.7	10.9 ± 3.5	11.0 ± 4.0	11.7 ± 2.7	10.8 ± 3.0	11.7 ± 2.9	11.4 ± 2.8	10.9 ± 3.7
θ_{Hip}	2.8 ± 1.7	3.0 ± 1.6	3.2 ± 1.6	3.0 ± 1.6	3.5 ± 2.0	3.2 ± 1.6	3.2 ± 1.5	3.3 ± 1.7	3.8 ± 2.5	3.3 ± 1.5	3.3 ± 1.4	3.5 ± 1.8	3.3 ± 1.6
θ_{Knee}	2.8 ± 1.4	3.5 ± 2.1	3.6 ± 2.1	3.3 ± 1.8	4.7 ± 2.4	3.5 ± 1.9	3.5 ± 1.9	3.9 ± 2.1	4.5 ± 3.1	3.5 ± 1.9	3.4 ± 2.0	3.8 ± 2.4	3.7 ± 2.0
θ_{Ankle}	8.6 ± 3.7	5.9 ± 3.0	7.7 ± 4.2	7.4 ± 3.7	7.1 ± 2.5	6.0 ± 2.2	5.5 ± 2.2	6.2 ± 2.3	6.4 ± 2.4	5.2 ± 2.2	5.1 ± 2.0	5.6 ± 2.2	6.4 ± 2.8
α_{Hip}	4.3 ± 0.9	5.3 ± 1.4	5.3 ± 1.5	4.9 ± 1.3	8.2 ± 2.0	6.8 ± 1.2	6.3 ± 1.2	7.1 ± 1.7	8.3 ± 1.6	6.8 ± 1.8	6.2 ± 1.1	7.1 ± 1.7	6.4 ± 1.8
α_{Knee}	5.0 ± 1.2	5.7 ± 1.0	5.6 ± 1.6	5.4 ± 1.3	7.4 ± 1.9	5.9 ± 1.2	5.7 ± 1.3	6.3 ± 1.6	6.8 ± 1.3	5.6 ± 1.5	5.1 ± 1.2	5.8 ± 1.5	5.9 ± 1.4
α_{Ankle}	9.1 ± 1.4	10.0 ± 2.0	11.8 ± 2.9	10.3 ± 2.4	15.8 ± 3.6	14.0 ± 2.7	11.9 ± 1.8	13.9 ± 3.2	14.9 ± 2.3	12.6 ± 2.0	12.4 ± 3.5	13.3 ± 2.8	12.5 ± 3.1

Table III. Correlation coefficients for the examination of (i) the relationship between the level of lower limb length difference and the eight parameters reflecting kinetic and kinematic asymmetries and (ii) the relationship between *Fr* and the kinematic asymmetries.

Parameter	*Fr*	θ_{Hip}	θ_{Knee}	θ_{Ankle}	α_{Hip}	α_{Knee}	α_{Ankle}
(i) Lower limb difference	0.03	0.49	0.73*	0.34	-0.44	-0.11	-0.43
(ii) *Fr*	–	0.47	−0.03	0.09	0.23	−0.04	−0.05

*$p < 0.05$.

angles, medium pattern asymmetries (5–7%) were found for ankle joint angle and hip–knee joint accelerations, and high-pattern asymmetries (> 10%) were noted for the resultant force and ankle joint acceleration. Additionally, the asymmetry was consistent across strokes for elite rowers. More importantly, the use of a mobile ergometer significantly increased the asymmetry for joint accelerations. Finally, kinetic asymmetry is correlated neither with kinematic asymmetry nor with lower limb length asymmetry.

The level of asymmetry reported for the forces at the foot stretcher in the present study (10.9%) is slightly higher than what was reported (8.0% for the averaged force) by Buckeridge et al. (2014a). As this last study did not show any effect of the group of rowers, it can be assumed that this discrepancy should be due to the use of a different SI (see Figure 1 for an example). In results published by Buckeridge et al. (2012, 2014a, 2014b), the SIs are based on the formula defined by Robinson et al. (1987), which used the impulse and range of motion to evaluate the kinetic and kinematic asymmetries, respectively. Nevertheless, to provide a more representative analysis, it could be interesting to analyse the kinetic and kinematic asymmetries of the entire patterns. Indeed, the main originality of this study was the simultaneous examination of kinetic (foot force production) and kinematic (lower limb joint kinematics) asymmetries in elite rowers. Regarding the aims of this study, the use of the new SI, which is a simple normalised root-mean-square difference between right and left patterns, was relevant to compare the kinematic and kinetic asymmetries based on the principles of multibody system dynamics.

Taken together with what was reported by Buckeridge et al. (2012, 2014a), findings of the present study contradict the assumption of high symmetry during simulated rowing on ergometers in elite rowers. Most of the rowers who participated in this study were involved in international competitions, such as Olympic Games or World Championships. Thus, kinetic and kinematics asymmetries cannot be considered alone as an indicator of rowing performance. In this study, the high levels of kinetic and ankle joint acceleration asymmetries were associated with a low inter-stroke variability. In other words, elite rowers were able to reproduce a constant level of asymmetry during the ten consecutive strokes. This finding is valid for non-fatiguing rowing sessions because this study prevented the appearance of fatigue. As common rowing tests on ergometer (e.g. all-out 2000 m) and training sessions induce fatigue, it could be interesting to analyse the changes in the symmetry during prolonged rowing sessions. However, Janshen et al. (2009) did not find any changes in kinetic, kinematic, and electromyographic patterns between the beginning and the finish of an all-out 2000-m trial for elite sweep rowers. Therefore, it could be hypothesised that elite rowers can maintain the same level of asymmetry during a race, but this assumption remains yet to be validated. In addition, it could be interesting to perform a follow-up to determine the asymmetry evolution during one or more rowing seasons. It is also important to design and study the effects of chronic strength training programmes that could influence this asymmetry.

According to the principles of multibody dynamics, the high difference of foot force production between left and right feet may have two origins: kinematics and anthropometrics. Therefore, the analysis of joint accelerations has also been performed in this study. The asymmetry at the ankle joint (12.5%) was in the same range than the asymmetry of the resultant force at the foot stretcher (10.9%). Interestingly, joint acceleration asymmetries of knee and hip joints were lower (6.4% and 5.9%, respectively), indicating that asymmetry on the kinematics was focused on the most distal joint. Although, the results of this study indicated that the level of joint acceleration asymmetries is close to the level of the kinetic asymmetry, no significant correlation was found between these two variables. However, the results related to joint accelerations must be interpreted carefully because of the calculation process. Indeed, Figure 2 showed some typical oscillations in the acceleration patterns that can be accounted for the finite difference derivation rather than the rowing movement itself.

In general, the results of this study suggested that bilateral anthropometric difference and kinematic asymmetries of the lower limbs were not related to kinetic asymmetries. Results only indicated that the lower limb length difference was positively correlated with asymmetry in knee joint angle. Although the level of asymmetry of the knee joint angle was low, this finding is important since the knee extension is largely involved in the transfer of the power to the oars during the drive phase (Greene et al., 2009; Nolte, 2011). However, more anthropometric parameters (i.e. mass and inertia of body segments) should be investigated in the future with accurate methods (e.g. magnetic resonance imaging as in McGregor et al. (2002a, 2002b).

The comparison of the asymmetry level between ergometer conditions represents another original investigation in this study. Training programmes of elite rowers include hours of training on ergometers. However, lower back injuries in rowers represent the most frequent case of injury in elite rowers and are commonly associated with an extensive use of the ergometer (Hickey, Fricker, & McDonald, 1997; Shephard, 1998). For instance, Wilson, Gissane, Gormley, and Simms (2013) have recently demonstrated the overuse of lumbar spine flexion during a step test when comparing rowing on a stationary ergometer with on-water rowing. For this purpose, biomechanical comparisons between stationary and mobile ergometers were focused on mechanical energy production, lower-back loading, and muscle activities to prevent or explain the risk of lower back injury. Although Nowicky, Burdett, and Horne (2005) noted no difference in muscle activity between the mobile and stationary conditions, Colloud et al. (2006) and Greene et al. (2013) found greater mechanical energy production at the lower limbs for the stationary condition. More recently, Smith et al. (2013) have demonstrated that rowing on the C2F ergometer places greater compressive stress on the lumbar spine compared with the C2S and RP ergometers. The study of kinematic and kinetic asymmetries can also indicate a risk of injury as repeated lower limb asymmetries can lead to both fatigue and lower back injury. This study did not reveal higher asymmetries for the stationary condition. On the contrary, results indicated higher asymmetries for joint accelerations at a low intensity when the rower is using a mobile ergometer (i.e. C2S and RP ergometers). Therefore, this study clearly showed that the use of mobile ergometers did not decrease asymmetry. However, the results do not show a general influence of the ergometer design on asymmetries, and the cause of the foot force asymmetries remains unclear. Hence, further studies should combine the assessment of muscle activity and the estimation of joint loads to better understand the relationship between the ergometer design and the asymmetries and provide clinical implications for the practitioners.

Finally, the drag factor was not strictly controlled during the experiments and could represent a limitation in this study. Indeed, the possible differences in mechanical resistance between ergometer conditions could have influenced the outcomes of this study. For instance, Kane, Jensen, Williams, and Watts (2008) and Kane, MacKenzie, Jensen, and Watts (2013) showed that a drag factor of 100 and 150 caused different physiological and mechanical responses. Although the drag factor was not controlled in this study, the three ergometers were strictly reserved for experiments and controlled regularly before each test. Moreover, the drag factors on the C2S and C2F were identical and the resistance on the RP was set using the recommendations of the Australian Federation to match the resistance set on both C2F and C2S ergometers.

The mobile ergometers were introduced to better simulate the ecological condition (Elliott, Lyttle, & Birkett, 2002) by mounting the ergometer frame (for the C2S ergometer) or the flywheel (for the RP ergometer) on slides. However, it has not been clearly reported that the biomechanical responses between on-water and on-ergometer rowing are similar (Soper & Hume, 2004). To our knowledge, no previous study analysed asymmetry on water. Hence, it seems important to perform this analysis in elite athletes during sculling. More importantly, investigating the asymmetry of the forces exerted at the oarlocks would help to better understand the relationship with asymmetry in foot force production.

To conclude, this study provides a better understanding of the asymmetry in ergometer rowing by designing a new SI in order to assess and compare simultaneously the level of kinematic and kinetic asymmetries of elite rowers. Elite rowers were able to reproduce a constant level of asymmetry across strokes. More than 10% asymmetries were reported in the foot force production and ankle joint acceleration. Moreover, the use of a mobile ergometer increased asymmetries in joint accelerations. Further researches should be focused on the simultaneous assessment of muscle activity, joint loads and lower limb asymmetries to better understand the relationship between the ergometer design and asymmetries from the viewpoints of both performance enhancement and injury prevention.

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