THE IMPACT OF LIMB SYMMETRY ON STROKE-TO-STROKE MOVEMENT VARIABILITY IN PARA-SWIMMERS DURING AN ADAPTED AEROBIC STEP TEST

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The study purpose was to measure effects of anthropometric limb characteristics on fatigue-related changes in stroke-to-stroke motor variability (MV) of trunk mediolateral (ML) acceleration. Six Paralympic swimmers performed an in-water, fatiguing, freestyle aerobic test consisting of 5 steps of 200m (n = 4); 150m (n = 1) or 100m (n = 1) with a sacrum worn inertial measurement unit. Upper-limb segment lengths were measured, and symmetry indices (LSI) were calculated. Sample entropy (SampEn) and fractal dimension (FD) were calculated on ML acceleration. Fatigue was confirmed with increased RPE ($p < 0.01$). ANOVA fatigue response models of SampEn and FD improved with LSI as a covariate ($p < 0.01$), showing that symmetry indices affected individual responses to fatigue. Coaches should consider anthropometric symmetry when designing para-swimming training plans.

KEYWORDS: swimming, anthropometry, fatigue, complexity, movement irregularity.

INTRODUCTION: Freestyle swimming is a bilateral, cyclical movement task that requires symmetry in propulsion between limbs to maximise forward propulsion while minimising the mediolateral movement. Performance in swimming is reliant on maximizing forward propulsion while minimizing drag. Drag is dependent on multiple hydrodynamic and morphologic variables, including the frontal surface area (FSA) (Kjendlie & Stallman, 2008). Increased irregularity of mediolateral movement during freestyle swimming may increase non-forward propulsive movement and thus FSA. Para-swimmers have physical and/or neurological impairments that may impact their ability to achieve an optimal propulsive symmetry. As a result, para-swimmers must develop strategies that account for physical symmetries to facilitate efficient forward propulsion. Motor variability is the natural variation that occurs across repetitions of a movement task (Stergiou et al., 2006), and has been considered to reflect a motor control strategy to mitigate the negative effects of fatigue, using task-specific movement adaptations to maintain performance of a task (Slopecki et al., 2022). Several analytical approaches have been developed to quantify the adaptive responses that use variability. Two such methods are Sample Entropy (Richman & Moorman, 2000), quantifying the inter-cycle irregularity of cyclical movement, and Fractal Dimension (Higuchi, 1988), quantifying the amount of complexity present in a signal. Previous studies of other cyclical tasks performed by able-bodied participants showed that fatigue induced through running led to increased mediolateral range of motion of the centre of mass (Möhler, Fadillioglu, & Stein, 2022) and increased motor variability that negatively impacted task performance, attributed to a decrease in control of the centre of mass (Möhler, Fadillioglu, Scheffler, et al., 2022). This loss of control of the centre of mass also correlated with the degree of fatigue. Additionally, sample entropy of resultant movement trajectory during a repeated kettlebell clean task was proposed as a useful tool to detect fatigue (Taylor et al., 2017). Taken together, these results suggest that increased movement outcome variability may reflect the onset of the negative effects of fatigue. However, no research to date has investigated how features of variability evolve with fatigue in paralympic swimmers, and whether individual features of anthropometric symmetry affect those patterns of movement outcome variability. Our objective was to investigate how limb symmetries affect mediolateral movement variability responses to fatigue. We hypothesized that a) movement outcome variability characteristics would increase with fatigue and b) accounting for individual limb symmetries would improve modelling of fatigue related responses in movement outcome variability.

METHODS: A cross sectional study was conducted with 6 elite Paralympic swimmers classified by the World Para Swimming Classification Panels and who compete at an international level. Impairment and swimming classification groups are detailed in Table 1. Informed consent was obtained from all participants. The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Boards of McGill University (protocol code 22-05-021) and École de Technologie Supérieure (protocol code H20221001). Participants performed an adapted freestyle aerobic step test (Anderson et al., 2008) made up of 5 incrementally faster steps of 200m (n = 4), 150m (n = 1) or 100m (n = 1), based on athlete impairment. Borg CR-10 ratings of perceived exertion (RPE) were recorded after each step (Borg, 1982). A single sacrum worn IMU (120 Hz, Movella Dot; Netherlands) recorded tri-axial linear accelerations and angular velocities. In the present study, lateral acceleration signals were analysed. Three manual measurements were taken of left and right 1) upper arms, 2) forearms and 3) hand lengths. In the case of undeveloped or amputated limbs, measurements were taken to the most distal part of the segment. Mean (± SD) of each manual measurement were calculated. Upper limb length was calculated by summing the mean values of each segment length. The Limb Symmetry Index (LSI) (Wojdala et al., 2022) of the left and right limb lengths (LSI_{LL}) were calculated (Equation 1) and are displayed in Table 1. While initially applied to electromyographic signals, this equation was chosen as it required no prior definition of limb dominance. Positive LSI_{LL} values represent a greater left limb length in proportion to right.

$$LSI_{LL} = 2 \times \frac{(Left\ Limb\ Length\ +\ Right\ Limb\ Length\ )}{(Left\ Limb\ Length\ \ -\ Right\ Limb\ Length)} \quad (1)$$

Table 1. Details of disabilities and para-swimming classifications.

Participant	Disabilities	Class	LSI_{LL}
1	Right femoral-fibula-ulnar syndrome; Dysmeliac right upper limb	S8	24.07
2	Intellectual Impairment	S14	-3.38
3	Dysmelia, congenital left hand amputee	S10	-20.09
4	Cerebral palsy	S9	-0.25
5	Pseudoachondroplasia	S5	2.21
6	Achondroplasia dwarfism	S6	2.57

Note: For freestyle swimming, World Para Swimming classifications for physical impairment range from S1 to S10. S14 refers to an intellectual impairment. A lower number indicates a more severe activity limitation than a higher number.

Sample Entropy (SampEn) (Richman & Moorman, 2000) and Fractal Dimension (FD) (Higuchi, 1988) were applied to the raw lateral acceleration signal. For sample entropy, *N* was defined as the length of the dataset, embedding dimension, *m*, was defined as 2 using false nearest neighbours method (Kennel & Abarbanel, 2002) and the tolerance limit, *r*, was set as 0.1 x SD. For statistical analyses, absolute values of LSI_{LL} were calculated ($AbsLSI_{LL}$), representing a non-directional magnitude of symmetry. An ANOVA compared *Step (1:5)* on RPE values, using base R’s “aov” function. ANOVAs also compared main effect of *Step (1:5)* with and without the covariate $AbsLSI_{LL}$ on SampEn and FD % changes. Additionally, comparisons were made between the ANOVA models that did and did not include the covariate $AbsLSI_{LL}$, using Base R’s “anova” function. This allows us to test the null hypothesis that the inclusion of the covariate does not significantly improves the ANOVA model’s fit, or the ability to explain variance in the response variable. After determining the usefulness of the covariate, post-hoc Tukey’s HSD were run on significant main effects from the respective ANOVA model, using base R’s “TukeyHSD” function.

RESULTS: RPE increased significantly by Step ($F(1,28) = 657$, $p < 0.001$), with significant differences between all steps ($p < 0.01$). Mean (±SD) RPE from Step 1 to 5 were 2.0 (0.6), 3.6 (0.7), 6.1 (0.7), 7.8 (0.6) and 9.8 (0.4), respectively, confirming that significant fatigue was reached. $AbsLSI_{LL}$ as a covariate, show a significant impact on the ANOVA models (see Table 2) for lateral acceleration sample entropy % change (F = 5.39, p < 0.01). Therefore, we may reject the null hypothesis and determine that the ANOVA model including $AbsLSI_{LL}$ as a covariate provides a better fit of the SampEn percentage change results. Post-hoc comparisons show that SampEn percentage change significantly increased from Steps 1, 2, 3 (p < 0.001); and 4 (p < 0.05) to Step 5; and from Step 1 (p < 0.01) and 2 (p < 0.05) to Step 4 (Figure 1A).

Table 2. ANOVA models for lateral acceleration MV outcomes

Variable		Step	$AbsLSI_{LL}$
Sample Entropy	With covariate	**F(4,20) = 17.77, *p < 0.001******	**F(5,20) = 5.39, *p < 0.01*****
	Without covariate	**F(4,25) = 9.46, *p < 0.001******	
Fractal Dimension	With covariate	**F(4,20) = 40.48, *p < 0.001******	**F(5,20) = 5.54, *p < 0.01*****
	Without covariate	**F(4,25) = 21.21, *p < 0.001******	

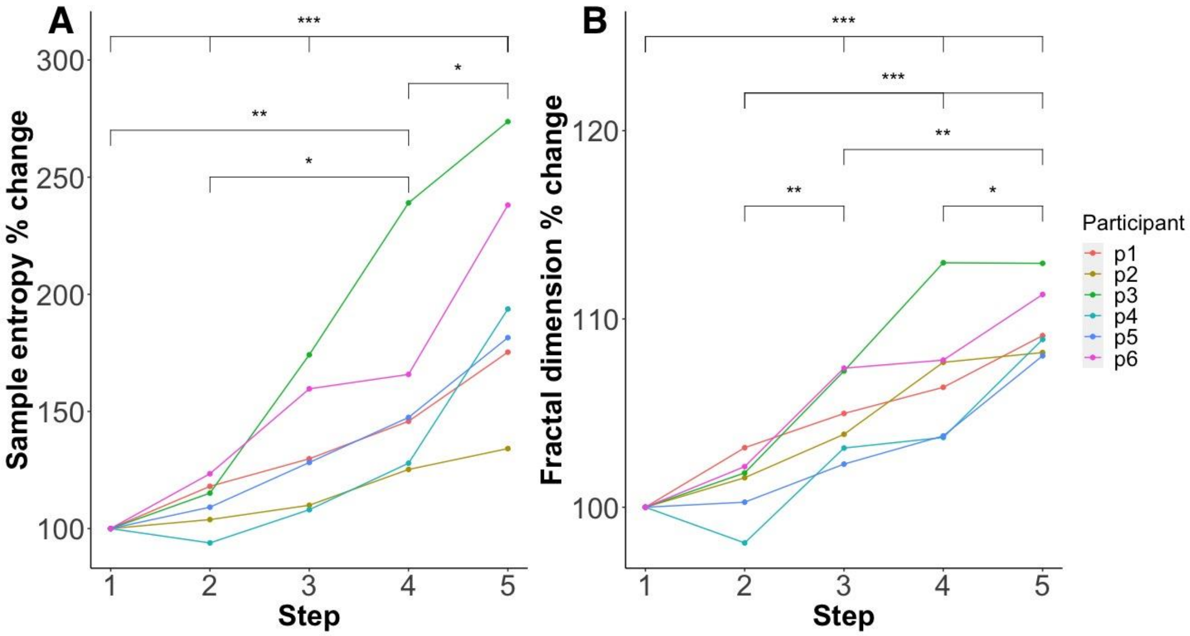

Figure 1. A) Sample entropy and B) Fractal Dimension percentage change by step with post-hoc differences. * denotes statistical significance at p < 0.001, ** denotes statistical significance at p < 0.01 and *** denotes statistical significance at p < 0.05.**

Similarly, $AbsLSI_{LL}$ as a covariate, shows a significant impact on the ANOVA models (see Table 2) for fractal dimension percentage change (F = 5.54, p < 0.01). Therefore, we may reject the null hypothesis and determine that the ANOVA model including $AbsLSI_{LL}$ as a covariate provides a better fit of the fractal dimension percentage change results. Post-hoc comparisons from the ANOVA model including the covariate (Figure 1B) show increased FD percentage change from Step 1 to 3, 4 and 5 (p < 0.001); Step 2 to 3 (p < 0.05), 4 and 5 (p < 0.001); Step 3 to 5 (p < 0.01); and Step 4 to 5 (p < 0.05).

DISCUSSION: In the present study, fatigue was confirmed as RPE values increased in all participants through each step of the test. Similarly, sample entropy and fractal dimension percentage change values also significantly increased through each step. This suggests that the changes in variability may be attributed to fatigue. In the present study, these outcome variability changes likely reflect some negative effects of fatigue manifesting to a level that cannot be sufficiently mitigated by motor control adaptations of the participants. Similarly, in running, increased motor variability and reduced control at the centre of mass (Möhler, Fadillioglu, Scheffler, et al., 2022), combined with increased mediolateral range of motion of the centre of mass (Möhler, Fadillioglu, & Stein, 2022) was induced by fatigue. In the current sample, it is possible that impairments and reductions in control of degrees of freedom, and limb symmetries additionally placed a stress on the motor control system. However, future work should confirm this by directly studying elemental variabilities in this context.

Limb symmetry was highlighted in the present study as a variable that contributes to fatigue-related changes in SampEn and FD. The inclusion of $AbsLSI_{LL}$ as a covariate in the ANOVA models helped to better explain the variance in response of SampEn and FD % changes. This suggests that limb symmetries of the participants were contributing to these changes in motor variability responses. As such, the motor control system had to account for both the bilateral limb symmetries and the negative effects of fatigue.

CONCLUSION: In conclusion, limb symmetries of the upper limb contribute to fatigue-related increases in lateral movement irregularity and the amount of complexity in the lateral movement patterns of Paralympic swimmers. This implies that subject-specific anthropometric symmetries will affect how para-swimmers experience the negative effects of fatigue. However, future studies with statistically robust single-subject designs should directly test if larger differences between limbs result in an earlier onset of the negative effects of fatigue. Coaches may want to consider the magnitude of limb symmetries when programming training plans for para-swimmers, to accommodate for individual differences in motor variability responses to delay fatigue-related performance reductions. However, future studies should determine if fatigued-related changes in motor variability characteristics in mediolateral acceleration relate and/or explain changes in forward velocity, as a proxy for swimming performance.

REFERENCES:

Anderson, M., Hopkins, W., Roberts, A., & Pyne, D. (2008). Ability of test measures to predict competitive performance in elite swimmers. *Journal of Sports Sciences*, *26*(2), 123-130. https://doi.org/10.1080/02640410701348669

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, *14*(5), 377-381.

Higuchi, T. (1988). Approach to an irregular time series on the basis of the fractal theory. *Physica D: Nonlinear Phenomena*, *31*(2), 277-283. https://doi.org/10.1016/0167-2789(88)90081-4

Kennel, M. B., & Abarbanel, H. D. I. (2002). False neighbors and false strands: A reliable minimum embedding dimension algorithm. *Physical Review E*, *66*(2). https://doi.org/10.1103/physreve.66.026209

Kjendlie, P.-L., & Stallman, R. K. (2008). Drag Characteristics of Competitive Swimming Children and Adults. *Journal of Applied Biomechanics*, *24*(1), 35-42. https://doi.org/10.1123/jab.24.1.35

Möhler, F., Fadillioglu, C., Scheffler, L., Müller, H., & Stein, T. (2022). Running-Induced Fatigue Changes the Structure of Motor Variability in Novice Runners. *Biology*, *11*(6), 942. https://doi.org/10.3390/biology11060942

Möhler, F., Fadillioglu, C., & Stein, T. (2022). Changes in spatiotemporal parameters, joint and CoM kinematics and leg stiffness in novice runners during a high-intensity fatigue protocol. *PLOS ONE*, *17*(4), e0265550. https://doi.org/10.1371/journal.pone.0265550

Richman, J. S., & Moorman, R. J. (2000). Physiological time-series analysis using approximate entropy and sample entropy. *American Journal of Physiology-Heart and Circulatory Physiology*, *278*(6), H2039-H2049. https://doi.org/10.1152/ajpheart.2000.278.6.H2039

Slopecki, M., Hasanbarani, F., Yang, C., Bailey, C. A., & Côté, J. N. (2022). Uncontrolled Manifold Analysis of the Effects of Different Fatigue Locations on Kinematic Coordination During a Repetitive Upper-Limb Task. *Motor Control*, *26*(4), 713-728. https://doi.org/10.1123/mc.2021-0114

Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal Movement Variability. *Journal of Neurologic Physical Therapy*, *30*(3), 120-129. https://doi.org/10.1097/01.npt.0000281949.48193.d9

Taylor, P. G., Ross, J. A., & Keogh, J. W. (2017). Investigating the use of sample entropy to detect fatigue. *ISBS Proceedings Archive*, *35*(1), 124.

Wojdala, G., Trybulski, R., Bichowska, M., & Krzysztofik, M. (2022). A Comparison of Electromyographic Inter-Limb Asymmetry during a Standard versus a Sling Shot Assisted Bench Press Exercise. *Journal of Human Kinetics*, *83*(1), 223-234. https://doi.org/10.2478/hukin-2022-0084

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