Kinematic Differences in Shoulder Roll and Hip Roll at Different Front Crawl Speeds in National Level Swimmers

Andersen , J., Sinclair, P., McCabe, C., & Sanders, R. (2020). Kinematic Differences in Shoulder Roll and Hip Roll at Different Front Crawl Speeds in National Level Swimmers. *Journal of Strength and Conditioning Research*, *34*(1), 20-25. https://doi.org/10.1519/JSC.0000000000003281

Published in:
Journal of Strength and Conditioning Research

Publication Status:
Published (in print/issue): 01/01/2020

DOI:
10.1519/JSC.0000000000003281

Document Version
Author Accepted version

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Running head: Shoulder and hip roll during front crawl swimming at different speeds

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No funding was received for this work.

Title: Kinematic differences in shoulder roll and hip roll at different front crawl speeds~~:~~

~~Implications for torso muscle demands and dry-land strength training in swimming~~

Running head: Shoulder and hip roll during front crawl swimming at different speeds

Dry-land strength training is a common component of swimming programs; however, its efficacy is contentious. A common criticism of dry-land strength training for swimming is a lack of specificity. An understanding of movement patterns in swimming can enable dry-land strength training programs to be developed to elicit adaptations that transfer to improvements in swimming performance. This study aimed to quantify the range and velocity of hip roll, shoulder roll, and torso twist (produced by differences in the relative angle between shoulder roll and hip roll) in front crawl at different swimming speeds. Longitudinal torso kinematics were compared between sprint and 400m pace front crawl using 3D kinematics of thirteen elite Scottish front crawl specialists. The range (sprint: 78.1°; 400m: 61.3°) and velocity of torso twist (sprint: 166.3°/s; 400m: 96.9°/s) were greater at sprint than 400m pace. These differences were attributed to reductions in hip roll (sprint: 36.8°; 400m: 49.9°) without corresponding reductions in shoulder roll (sprint: 97.7°; 400m: 101.6°) when participants swam faster. Shoulder roll velocity (sprint: 190.9°/s; 400m: 139.2°/s) and hip roll velocity (sprint: 75.5°/s; 400m: 69.1°/s) were greater at sprint than 400m pace due to a higher stroke frequency at sprint pace (sprint: 0.95 strokes/s; 400m: 0.70 strokes/s). These findings imply that torques acting to rotate the upper torso and the lower torso are greater at sprint than 400m pace. Dry-land strength training specificity can be improved by designing exercises that challenge the torso muscles to reproduce the torques required to generate the longitudinal kinematics in front crawl.

Keywords: torso twist, biomechanics, sprint, middle-distance, performance

INTRODUCTION

To maximise the probability that strength training adaptations will transfer to improvements in performance, training must be based on the demands of a sport (12, 13). The lack of effectiveness of many dry-land strength training programs in improving swimming performance is often attributed to a lack of specificity in training (11, 32, 33). Transference of strength training gains to performance can be enhanced by designing exercises that match the demands associated with the movement patterns used within a sport (37). Dry-land strength training specificity for swimming can therefore be improved with a better understanding of the movement patterns used in swimming.

Longitudinal body rotation is essential for maximising performance in front crawl swimming (6, 17). Rotation of the shoulders and hips about the body's longitudinal axis, known respectively as shoulder roll and hip roll, depend on swimming speed (27). Some characteristics of shoulder roll and hip roll remain consistent across different front crawl speeds; for example, the shoulders roll through a greater range of motion than the hips regardless of swimming speed (3, 35). The effect of swimming speed on several features of longitudinal rotation in front crawl, however, remain unclear. For example, it is unknown how torso twist produced by differences in the relative angles of hip roll and shoulder roll varies with swimming speed. Further, the influence of swimming speed on the rate of change (or velocity) of hip roll, shoulder roll, and torso twist has never been reported. Considering the association between torso muscle activity and the magnitude and speed of twisting motions of the spine (16, 19), differences in the range and velocity of torso twist in front crawl may influence the demands on the torso muscles. Our understanding of the torso muscle requirements in front crawl may therefore be limited by the lack of evidence of torso twist characteristics in front crawl swimming.

Total hip roll, a measurement of the range of hip roll from one side to the other, tends to decrease as swimming speed increases while total shoulder roll, which is the range of shoulder roll from one side to the other, does not seem to change with increasing speed as much as total hip roll. McCabe and Sanders (21) reported a total hip roll of 57 degrees at 1.50 m/s during a 400m maximal effort while Psycharakis and Sanders (26) reported a total hip roll of 44 degrees at 1.68 m/s in the first 50m of a 200m maximal front crawl test. Psycharakis and McCabe (25) reported an even lower total hip roll of 39 degrees at 1.81 m/s during a maximal 25m sprint. Despite the 18 degrees difference in total hip roll between 400m pace and sprint front crawl swimming, total shoulder roll remained between 105 and 111 degrees across all three studies. Differences in the range and/or timing of hip roll and shoulder roll require twist within the torso. Data from the studies by McCabe and Sanders (21), Psycharakis and Sanders (26), and Psycharakis and McCabe (25) indicate that the range of torso twist is likely to increase with swimming speed; however, differences in torso twist from the same group of swimmers swimming at different front crawl speeds have never been examined.

The time for the hips and shoulders to roll from one side to the other and back again is determined by the duration of the arm stroke cycle (28, 34). The velocities of hip roll and shoulder roll are therefore influenced by the range of hip roll and shoulder roll, respectively, and the number of stroke cycles per unit of time, or stroke frequency. It is well documented that stroke frequency increases as swimming speed increases (4, 7, 29, 30); however, the influence of swimming speed on hip roll velocity and shoulder roll velocity is unknown. Changes in the relative angle between hip roll and shoulder roll and differences in stroke frequency across front crawl speeds suggest that torso twist velocity may also change with swimming speed, but torso twist velocity has yet to be quantified in the scientific literature.

Although twist of the shoulders and hips relative to each other is influenced by the torques produced by the actions of the upper and lower limbs, it may be hypothesised that the differences between shoulder and hip rotation, manifest in changing torso twist angles, is also influenced by the actions of the torso muscles connecting the shoulders and hips. Therefore, it is likely that differences in torso twist rates of change, that is, torso twist velocities, may reflect differences in demands on the torso muscles to control posture and maintain stability of the swimmer’s torso. Further, if there are differences in the relative magnitudes and velocities of shoulder and hip roll between paces, demands on the torso muscles are likely to differ between swimming speeds. Therefore, insights into these demands may be gained by quantifying the differences in the range and velocity of torso twist at different swimming paces.

While the ranges of hip roll and shoulder roll at different swimming speeds have been examined in separate studies, the differences in the velocities of hip roll and shoulder roll between swimming speeds have never been reported. Moreover, the range and velocity of torso twist produced by differences in hip and shoulder roll at different front crawl speeds have never been examined to our knowledge. These gaps in swimming research present a barrier to understanding the movement patterns in front crawl swimming that can be used to improve the specificity of dry-land strength training for swimmers. Therefore, the purpose of this study was to quantify the range and velocity of hip roll, shoulder roll, and torso twist in front crawl at different swimming speeds. The differences in the longitudinal kinematics between speeds will further our understanding of the movement patterns in front crawl swimming which can be used to develop insight into the demands on the torso muscles in front crawl swimming.

METHODS

Experimental Approach to the Problem

This cross-sectional study of three-dimensional kinematics enabled analysis of the movement patterns of high level front crawl swimming for two different event distances (i.e. 50m and 400m freestyle). National and international level swimmers were recruited because of their ability to produce movement patterns that can provide insights into the requirements for high level swimming performance. While experienced swimmers are known to reliably produce consistent swimming technique, multiple trials at both swimming paces were collected to account for individual variability inherent of human movement.

Subjects

Three-dimensional coordinate data of a 15 segment whole-body model of thirteen national and international level male Scottish front crawl specialists (age: 17.54 ± 1.98 years, range 15 to 22 years; height: 181.18 ± 4.98 cm; weight: 71.58 ± 6.26 kg) were analysed from a data set that was previously utilized in the studies of McCabe, Psycharakis and Sanders (20) and McCabe and Sanders (21). Participants had specialized in front crawl for a minimum of two years, were not currently injured or recovering from injury, and held a short course personal best time of either less than 24.60s for 50m or less than 4min10s for 400m. The protocols and procedures were approved by the university ethics committee. All participants were informed of the risks and benefits of the study and provided written consent prior to data collection. For participants under the age of 18, participants and a parent or guardian provided written consent.

Procedures

The data collection by McCabe was conducted in an indoor 25m pool. Participants were marked to enable identification of the following anatomical landmarks: the vertex of the head (on top of the swim cap), the left and right: tip of the 3rd distal phalanx of the finger, wrist axis, elbow axis, shoulder axis, hip axis, knee axis, ankle axis, lateral aspect of the 5th metatarsophalangeal joint, and tip of 1st phalanx of the foot (big toe). After an individualized warm up, participants swam 4x25m at sprint pace and one 400m effort at a pace that would result in the fastest time possible. After each sprint trial, participants swam back to the start position at recovery pace and rested in-water for two minutes before beginning the next trial. The order of swimming pace was randomized and participants swam for at least five minutes to recover after completing the first pace, then exited the pool for an additional ten minute rest before warming up again and completing the second pace.

As participants swam through a calibration volume (4.5m long, 1.0m wide, and 1.5 in height) located 15.25m from the starting wall, their motion was captured by six synchronized JVC KY32 CCD cameras (four below and two above the water surface) at a frame rate of 50 Hz. Each trial began from a push start and participants were required to not breathe as they swam through the calibration volume to avoid any effect of the breathing actions on their swimming technique (25, 30). Swimmers familiarized themselves with the breath-holding requirement during warm up. All participants used a six-beat flutter kick at both swimming paces.

Data Processing

One stroke cycle (SC) was defined as the moment the tip of the third digit of one hand entered the water to the subsequent entry of that digit on the same hand performed completely within the calibrated space. At sprint pace, one SC was analysed for each of the four 25m trials. During the 400m effort, one SC was recorded from the first 25m length of each 50m lap. SCs from laps 2, 3, 4 and 5 during the 400m effort were analysed, totaling four observations per swimmer at 400m pace. These laps were selected to align with previous findings that laps 1, 7, and 8 were consistently different from laps 2-6 (21). Lap 6 was excluded to further minimize the effect of fatigue on swimming technique. Due to marker occlusion during data collection that prevented digitization of landmarks over several consecutive frames, one trial from one participant at 400m pace (P4) was discarded. Data were retained for all four trials at both paces from every other participant.

Three-dimensional reconstruction from manual digitization of the anatomical landmarks was conducted using the Ariel Performance Analysis System (direct linear transformation algorithms from Abdel-Aziz and Karara (1)). Errors due to digitization for the variables used in the current study were considered small from digitization reliability tested in a previous study (20). To prevent data loss during filtering, an additional 30 frames were extrapolated by reflection. Fourier truncation was used to filter the position data of the body landmarks. This filtering strategy was deemed appropriate because the cyclic nature of movements in front crawl swimming results in periodic data (2). Residual analysis indicated that a 6 Hz cut-off was suitable to smooth the data. SC length was then standardized to 201 points using a Fourier transform and inverse transform so that each datum represented a half percentage of the SC (i.e. 0-100%).

The filtered anatomical landmark data were entered into a bespoke MATLAB (Mathworks, Inc.) analysis program written by the last author. The orthogonal external reference system was defined by the horizontal X-axis pointing in the swimming direction, the Y-axis pointing vertically up, and the horizontal Z-axis pointing to the swimmer’s right. Shoulder roll and hip roll were calculated independently for each percentile of the SC as the angle, expressed in degrees, between the Z-axis and vectors connecting the shoulders and hips, respectively, projected onto the YZ plane.

Data Analysis

Average swimming velocity, calculated by dividing the horizontal component of the centre of mass displacement by SC time, was 1.81 ± 0.06 m/s at sprint pace and 1.47 ± 0.06 m/s at 400m pace.

Stroke frequency was determined using the inverse of the time to complete one SC (stroke/s). Torso twist was the difference in the relative angles of shoulder roll and hip roll and was calculated for each percentile of the SC in degrees. Hip roll velocity, shoulder roll velocity, and torso twist velocity were the rate of change of hip roll, shoulder roll, and torso twist, respectively, and were expressed as angular velocities (in degrees per second) using the time derivatives of hip roll, shoulder roll, and torso twist with the central difference method.

Range of hip roll, range of shoulder roll, and range of torso twist were determined separately for each trial by summing the maximum magnitude of hip roll, shoulder roll, and torso twist, respectively, to the left side and to the right side. Averages for hip roll velocity, shoulder roll velocity, and torso twist velocity were calculated using the mean of the absolute values of hip roll velocity, shoulder roll velocity, and torso twist velocity, respectively, over each entire SC.

Statistical Analyses

Statistical tests were performed using IBM SPSS Statistics 24 ($\alpha = 0.05$), with the exception of effect sizes which were calculated manually (10). Intra-class correlations between swimming trials were determined using a single-rating, absolute agreement, two-way mixed random effects model analysis (14) for stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity at sprint pace and 400m pace.

Means and 95% confidence intervals (i.e. the *t*-value for the sample size (*n* = 13) multiplied by the standard error of the sample mean) were calculated at both swimming paces for stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity. Confidence intervals improved our ability to compare and interpret differences between swimming paces by providing a range about the mean of each kinematic variable in which the true mean was likely to fall for either pace. The Shapiro-Wilk test indicated that all variables were normally distributed. Separate paired *t*-test were conducted to evaluate the differences in stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity between sprint pace and 400m pace. Effect sizes were determined using Cohen’s *d* and interpreted with the following recommendations: small 0.2, moderate 0.5, and large 0.8 (5). *Post hoc* power analysis was conducted using open-source software (G*Power 3.1) (9).

RESULTS

Intra-class correlations were high for stroke frequency (sprint pace: 0.93; 400m pace: 0.98) range of hip roll (sprint pace: 0.90; 400m pace: 0.93), range of shoulder roll (sprint pace: 0.85; 400m pace: 0.94), range of torso twist (sprint pace: 0.82; 400m pace: 0.91), average hip roll velocity (sprint pace: 0.90; 400m pace: 0.91), average shoulder roll velocity (sprint pace: 0.83; 400m pace: 0.96), and average torso twist velocity (sprint pace: 0.84; 400m pace: 0.89) at both paces.

Time series for ensemble averages of hip roll, shoulder roll, and torso twist are shown in Figure 1 and time series for ensemble averages of hip roll velocity, shoulder roll velocity, torso twist velocity are shown in Figure 2 for one SC at sprint and 400m pace.

[INSERT FIGURE 1 NEAR HERE]

[INSERT FIGURE 2 NEAR HERE]

Table 1 shows means, 95% confidence intervals using the *t*-distribution of the sample mean, effect sizes, and statistical power for comparisons between paces of stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average hip roll velocity, average shoulder roll velocity, and average torso twist velocity. Stroke frequency was greater at sprint pace than at 400m pace ($t(12) = 12.27$, $p < 0.01$) with a large effect size. Range of hip roll was greater at 400m pace than at sprint pace ($t(12) = 6.77$, $p < 0.01$) with a large effect size while range of shoulder roll was similar between paces ($p = 0.14$). Range of torso twist ($t(12) = 6.88$, $p < 0.01$), average shoulder roll velocity ($t(12) = 9.17$, $p < 0.01$), and average torso twist velocity ($t(12) = 12.30$, $p < 0.01$) were greater at sprint pace than at 400m pace with large effect sizes. Average hip roll velocity was also greater at sprint pace than at 400m pace ($t(12) = 2.98$, $p < 0.05$) but with a moderate effect size.

[INSTERT TABLE 1 NEAR HERE]

DISCUSSION

The purpose of this study was to quantify the range and velocity of hip roll, shoulder roll, and torso twist in front crawl at different swimming speeds. The differences in hip roll and shoulder roll that contributed to the changes in the range and velocity of torso twist between paces will further understanding of the demands on the torso muscles in front crawl swimming. The findings from this study contribute to the knowledge of movement patterns in front crawl that can be used to improve the specificity of dry-land strength training for swimmers.

The larger range of torso twist at sprint pace than at 400m pace seemed to be the result of a reduction in hip roll without a corresponding reduction in shoulder roll when participants were swimming faster. The range of hip roll and range of shoulder roll observed in the current study are consistent with trends of total hip roll and total shoulder roll across different swimming speeds from previous findings (26). The similar range of shoulder roll between paces and the higher stroke frequency at sprint pace than at 400m pace meant the swimmers rolled their shoulders faster as swimming speed increased. This was reflected in an average shoulder roll velocity that was 37% greater at sprint pace than at 400m pace (Table 1). Despite the smaller range of hip roll at sprint pace than at 400m pace, the higher stroke frequency resulted in an increase in hip roll velocity as swimming speed increased; however, average hip roll velocity was only 9% greater at sprint pace than at 400m pace. Moreover, the effect size of the difference in average hip roll velocity was moderate while all other statistically significant differences between paces had large effect sizes (Table 1). The difference in torso twist velocity between swimming paces therefore seemed to be the result of the swimmers' ability to maintain their range of shoulder roll, despite an increase in stroke frequency, and to reduce their range of hip roll as they increased swimming speed.

The patterns of hip roll, shoulder roll, and torso twist in Figure 1 suggest the magnitude of rotation between the upper and lower torso was greater at sprint pace than at 400m pace. Furthermore, the difference in torso twist velocity between swimming paces implies the swimmers in this study rotated their upper torso with respect to their lower torso more rapidly at sprint pace than at 400m pace. Increases in the magnitude and speed of rotation between the upper and lower torso are associated with higher torso muscle activity (18, 19). These findings suggest that the demands on the torso muscles are likely to be higher at faster swimming speeds but this cannot be stated with confidence without further research measuring the muscle activity at different paces.

Torques that produce rotation of the upper torso must have been higher at sprint pace than at 400m pace in order for the swimmers to achieve a similar range of shoulder roll at both paces considering the increase in stroke frequency as swimming speed increased. Hydrodynamic and buoyancy torques associated with the arm stroke produce longitudinal body rotation (23, 34, 36) and could have contributed to the differences in shoulder roll velocity observed in the current study. Though the shoulders and hips roll somewhat independently in front crawl (28), longitudinal rotation is likely transferred from the shoulders to the hips. For example, motion can be transferred along the torso during twisting motions of the spine through passive mechanisms (e.g. via connective tissue and intervertebral discs) (15, 16) or with the assistance of muscle torques (19, 24, 31). Greater torque acting to rotate the lower torso, separate from the torques acting to rotate the upper torso, may have therefore been required to reduce the range of hip roll as swimming speed increased. Sanders and Psycharakis (28), for instance, hypothesized that hip roll is “dampened” compared to shoulder roll from torques associated with the flutter kick. Considering swimmers tend to increase kicking frequency as swimming speed increases (4, 8, 22), torques from the flutter kick acting on the lower torso may have been greater at sprint pace than at 400m pace, which could have contributed to the reduction in hip roll as swimming speed increased. The differences in the longitudinal kinematics presented here indicate that the torques acting to rotate the upper torso and the torques acting to rotate the lower torso may be greater at sprint pace than at 400m pace. This may also indicate that the demands on the torso muscles increase as swimming speed increases. Quantification of the torques acting on the upper torso and lower torso in front crawl is required to test this hypothesis.

PRACTICAL APPLICATIONS

This is the first study to investigate the velocity of hip roll, shoulder roll, and torso twist in front crawl swimming. Coaches can use these findings to guide recommendations for changes to swimming technique between sprint and middle-distance swimming. For example, swimmers can be encouraged to maintain their range of shoulder roll as stroke frequency increases with swimming speed. From the differences in the range and velocity of torso twist between swimming paces, torques acting to produce rotation of the upper torso and the lower torso are likely to increase as swimming speed increases. Dry-land strength training specificity may be improved by designing exercises that challenge the torso muscles to generate torques that produce or resist longitudinal rotation of the upper torso and the lower torso. Coaches are encouraged to consider the differences in the demands placed on swimmers competing over different distances when designing dry-land strength training. For instance, torques required from the torso muscles may be greater at faster swimming speeds than at slower swimming speeds. ~~As swimming speed increases, exercises should increase the amount of torque required from the torso muscle. This~~ Acknowledgement of the differences in demands between swimming speeds could increase the likelihood that benefits from dry-land strength training will transfer to improvements in swimming performance.

ACKNOWLEDGMENTS

The authors would like to thank the swimmers and coaches for their participation in data collection. There are no conflicts of interest to declare.

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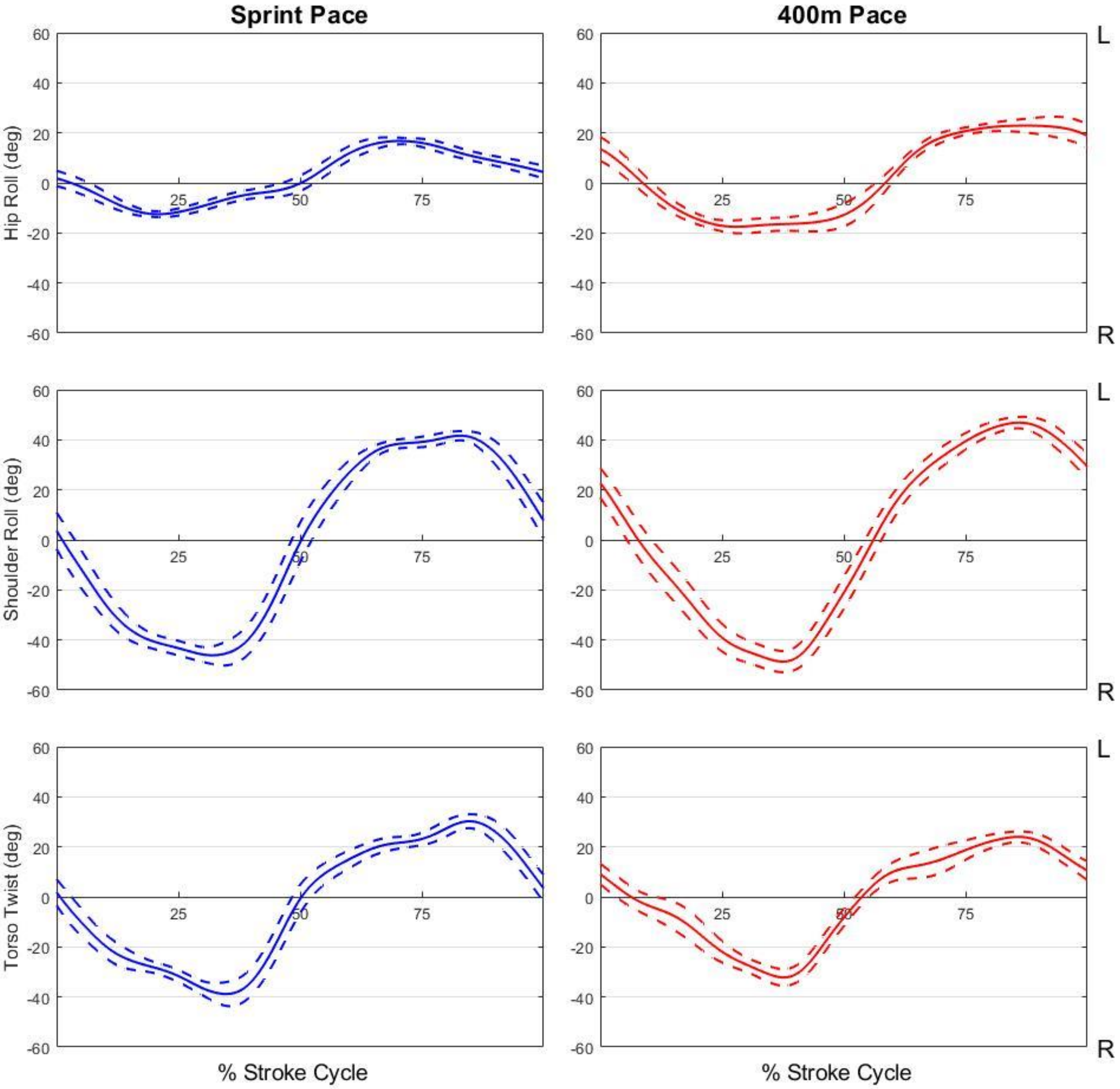
FIGURES

Figure 1. Time series with ensemble averages for hip roll, shoulder roll, and torso twist at sprint pace and 400m pace. Dashed lines represent 95% confidence intervals calculated using the *t*-value and standard error of the sample mean. Positive values indicate rotation to the swimmer's left (i.e. in the anticlockwise direction when viewing the swimmer from behind) and negative values indicate rotation to the swimmer's right (i.e. in the clockwise direction when viewing the swimmer from behind). Swimmers began these SCs with the right hand. Time series for SCs beginning with the left hand were similar to this figure.

Figure 2. Time series with ensemble averages for hip roll velocity, shoulder roll velocity, and torso twist velocity at sprint pace and 400m pace. Dashed lines represent 95% confidence intervals calculated using the *t*-value and standard error of the sample mean. Positive values indicate rotation to the swimmer's left (i.e. in the anticlockwise direction when viewing the swimmer from behind) and negative values indicate rotation to the swimmer's right (i.e. in the clockwise direction when viewing the swimmer from behind). Swimmers began these SCs with the right hand. Time series for SCs beginning with the left hand were similar to this figure.

Figures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400m Pace
Hip Roll (deg)
Shoulder Roll (deg)
Torso Twist (deg)
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20
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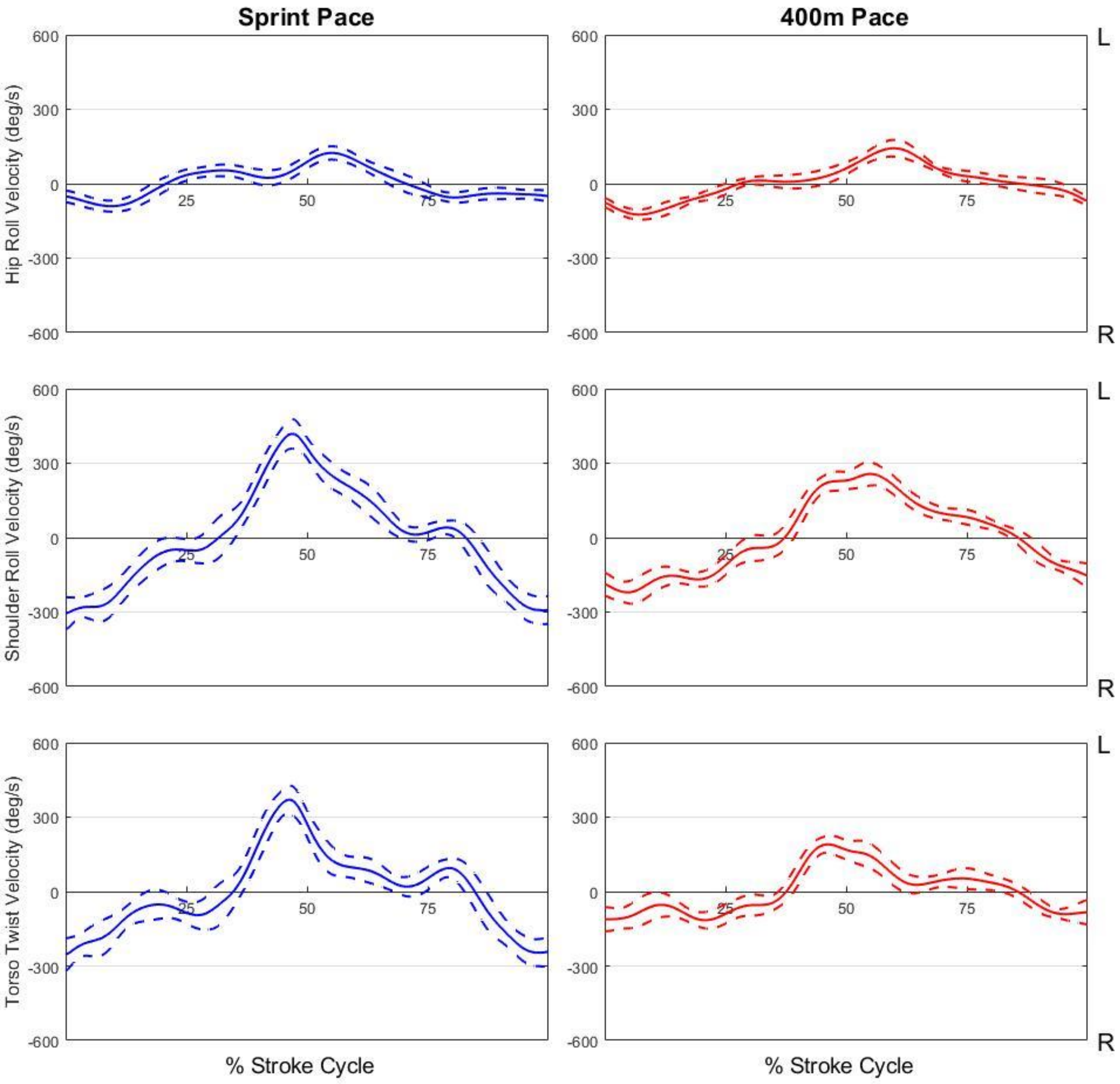
Sprint Pace
400m Pace
Hip Roll Velocity (deg/s)
Shoulder Roll Velocity (deg/s)
Torso Twist Velocity (deg/s)
600
300
0
-300
-600
25
50
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% Stroke Cycle

Table 1. Stroke frequency, range of hip roll, range of shoulder roll, range of torso twist, average absolute hip roll velocity, average absolute shoulder roll velocity, and average absolute torso twist velocity at sprint pace and 400m pace.

	Sprint Pace		400m Pace		Effect Size (Cohen's *d*)	Power (*n* = 13)
	Mean	95% CI	Mean	95% CI		
Stroke Frequency (stroke/s)	0.95**	0.04	0.70	0.04	3.73	1.0
Range of Hip Roll (^{o})	36.8**	*3.1*	49.9	*5.6*	-1.58	1.0
Range of Shoulder Roll (^{o})	97.7	*3.1*	101.6	*5.9*	-0.46	0.40
Range of Torso Twist (^{o})	78.1**	*3.4*	61.3	*4.7*	2.23	1.0
Average Absolute Hip Roll Velocity (^{o}/s)	75.5*	7.1	69.1	7.9	0.52	0.66
Average Absolute Shoulder Roll Velocity (^{o}/s)	190.7**	9.9	139.2	11.5	2.92	1.0
Average Absolute Torso Twist Velocity (^{o}/s)	166.3**	*10.0*	96.9	*8.2*	4.13	1.0

Significantly different from 400m pace (*$p < 0.05$, **$p < 0.01$).