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Human Kinetics
ORIGINAL RESEARCH REPORT

Is Real-Time Poolside Assessment of Upper Limb Errors in Front Crawl Swimming Technique Reliable and Equivalent to Video Analysis?

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Context: Swimming technique is widely believed to influence performance, but this relationship has rarely been tested objectively using a real-time poolside assessment. ***Objective:*** To determine the (1) test–retest reliability, interrater reliability, and criterion validity (live vs video) of real-time poolside assessment of upper limb (UL) errors in front crawl (FC) swimming technique and (2) the relationship between UL errors and FC swimming performance. ***Design:*** Cross-sectional reliability, validity, and correlational study. ***Setting:*** Swim team practice at a college natatorium. ***Participants:*** Thirty-nine Division III college swimmers (21 women and 18 men, age = 19 [1] y, swimming experience = 11 [3] y). ***Main Outcome Measures:*** Seven UL errors in FC swimming technique, many of which involved unnecessary vertical and mediolateral motions, were assessed in real time from outside the pool during swim practice. Test–retest reliability, interrater reliability, and criterion validity were calculated using Cohen kappa (κ) and weighted kappa (κ_w). Swimming performance was determined by the participants' best FC events relative to the conference records. The correlation between total UL errors and FC swimming performance was assessed with Pearson *r*. ***Results:*** Cohen κ and κ_w were moderate for the majority of errors, with the following ranges: 0.46 to 0.90 (test–retest), −0.01 to 1.00 (interrater), and 0.36 to 0.66 (criterion validity). There was a significant correlation between total UL errors and FC swimming performance: $r(24) = -.59$ ($P = .001$, $R^2 = .35$). ***Conclusions:*** Reliability and validity were moderate for the majority of errors. The fewer UL errors swimmers made while practicing FC, the faster their best FC race times tended to be relative to the conference record. UL errors in FC swimming technique explained 35% of the variance in performance.

Keywords: stroke mechanics, performance, validity, biomechanics, coaching

Swimming performance is dictated by the multifactorial interplay of anthropometric, physiological, psychological, tactical, and biomechanical factors.[1,2] Of these factors, biomechanics tends to receive the most attention during a typical training session.[3] Methods for addressing swimmers' biomechanics in training range from drills (eg, closed-fist swimming, catch-up drill, the "swim golf" game) to attentional focus while swimming (eg, "distance per stroke," "long and strong") and individual coaching instructions.[1] Previous studies have used a variety of tools to quantify swimming biomechanics, from 2- and 3-dimensional motion capture[4] and inertial measurement units[5] to computational fluid dynamics.[6] At the most fundamental level, studies of kinematics have established that long stroke lengths and high stroke rates maximize speed.[7] Studies of swimming kinetics demonstrate that fast swimming requires maximal propulsive forces and minimal drag.[8]

For coaches and swimmers, practical application of these kinematics and kinetics findings can be limited.[9,10] Most swim coaches have neither the equipment nor the expertise to undertake sophisticated quantitative biomechanical analyses.[3] In addition, the insights that such studies provide are mostly on a macroscopic, whole-body scale.[11] What would be most useful for practitioners would be an objective system for qualitatively assessing proper segmental kinematics, known in sports vernacular as "swimming technique."[10,11] Examples of such parameters include a high elbow and lateral (away from the midline) hand path during the underwater pull-through phase of the stroke (Figure 1).[6]

Few qualitative assessments of competitive swimming technique have been published.[12–14] One was an interrater reliability study, which found significant differences between 2 evaluators' technique ratings of 20 adolescent swimmers.[14] Two studies measured the prevalence of technique errors during front crawl (FC) swimming.[12,13] Prevalence of errors ranged from one-third to two-thirds in age group swimmers[13] as well as college swimmers.[12] Virag et al[12] designed their assessment based on injury risk to the shoulder. They suggested that technique errors may impair performance, but they did not test this relationship.

To our knowledge, only 3 English language studies have directly reported on the relationship between swimming technique and performance.[15–17] In two of the studies, better FC technique was associated with faster swimming times in 12 state-level and national-level Australian swimmers ($r = -.75$)[15] and 67 adolescent swimmers ($r = -.32$).[16] However, in both studies, technique was rated subjectively on 10- or 20-point scales (from "poor" to "excellent" or "near perfect") with no objective scoring criteria. Silva et al[17] also found correlations between FC technique and performance ranging from .40 to .51 in a sample of 73 adolescent female swimmers. Interestingly, though, Silva et al[17] did not find these same relationships in the 65 males in their study. Although Silva et al[17] did report using objective scoring criteria, they did not describe those criteria in detail. Moreover, Silva et al[17] and

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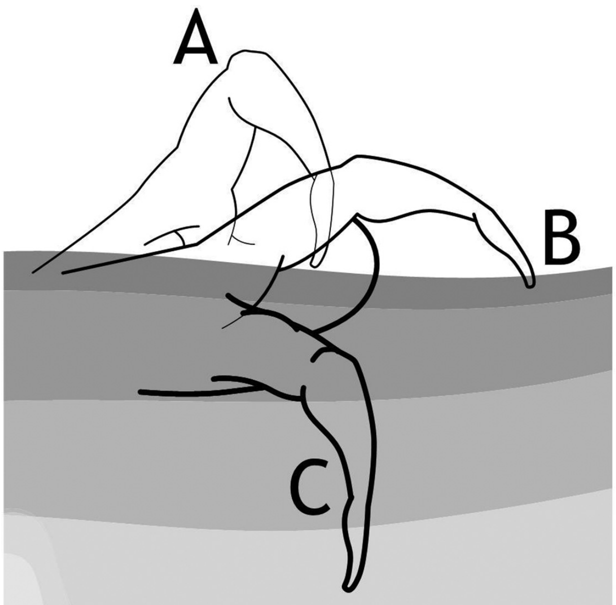

Figure 1 — Phases of the front crawl swimming stroke: (A) recovery, (B) hand entry, and (C) underwater pull through.

Sacilotto et al[15] used above water and underwater video, which limits feasibility as some coaches do not have access to this technology.[3] In the Virag et al[12] study, the investigators rated only 1 stroke cycle. Given the variability between strokes, 1 stroke likely is not sufficient to fully represent technique.[5] For a technique assessment to be representative, field expedient, and timely in terms of feedback for the athlete, coaches should be able to administer it in real time from outside the pool.

Thus, a reliable and valid real-time poolside method for objectively assessing swimming technique relative to performance is needed. Such a tool could remove technological barriers and add rigor to technique assessment by reducing subjectivity in identifying errors and facilitating documentation and progress tracking.[3] To this end, this study had 2 objectives. The primary objective was to determine the test–retest reliability, interrater reliability, and criterion validity (live vs video) of real-time poolside assessment of upper limb (UL) errors in FC swimming technique. Of the 4 competition strokes, we chose FC because it predominates racing and training volume. We focused on the UL because it provides upward of 85% of the propulsion in FC.[1] The secondary objective of the study was to examine the relationship between UL errors and FC swimming performance. Based on previous reliability data and correlation magnitudes,[12,14–17] we hypothesized that the UL errors would have at least moderate reliability and be moderately correlated with performance. For the assessment to be practically useful, minimums of moderate reliability and correlation with performance have been recommended.[18]

Methods

Design

This was a cross-sectional reliability, validity, and correlational study. It was conducted in conjunction with a prospective study investigating intrinsic and extrinsic risk factors for injury in swimmers.[19,20]

Participants

Thirty-nine National Collegiate Athletic Association Division III college swimmers (Table 1) provided informed consent to participate in this study in accordance with the Declaration of Helsinki. This study was approved by the Drexel University Institutional Review Board. Swimmers were included if they were at least 18 years of age, members of a Division III swim team, and medically cleared to participate in sport. An a priori power analysis for a correlation between errors and performance suggested a sample size of 29 (input parameters of $\alpha = .05$, power = 0.8, and $r = .5$) (G*Power, version 3.1).[21]

Assessment of UL Errors in FC Swimming Technique

Seven UL errors in FC swimming technique were assessed during the various phases of the stroke (Figure 1). We adapted these errors from a previous study that focused on injury risk to the shoulder.[12] To ensure that the assessment was comprehensive, we also interviewed 5 current or former National Collegiate Athletic Association Division I swim coaches. The coaches were a mean (SD) of 40 (8) years old and had a mean (SD) of 18 (8) years of coaching experience. In the interviews, the coaches unanimously endorsed the errors from the previous study and did not propose any additional errors.[12] Compared with that previous study, we modified rating criteria for some errors or defined them more specifically in an effort to improve reliability. Many of the techniques that we considered errors were characterized by unnecessary vertical and mediolateral motions that did not directly contribute to forward propulsion.[6,8] Descriptions and images of the errors are provided in Table 2 and Figure 2, respectively. We observed 6 of the 7 errors bilaterally, resulting in a maximum total UL error score of 13.

Procedures

During the first month of the swimmers' college season, the principal investigator (a biomechanist and former college swimmer with 6 y of movement analysis experience) assessed the swimmers' FC for UL errors. The investigator was naïve to the swimmers and their technical and performance abilities. The rater observed from the end of a short-course, 25-yard pool during normal swim practice while participants swam FC at a moderate speed (ie, FC that was not warm-up, drill, sprint, or cooldown). To minimize the observer effect, we did not inform participants when we were assessing them. To consider an error present, the rater had to detect it on an estimated 51% or more of the strokes in a lap (ie, more than half). The rater concentrated on 1 error each lap (both left and right sides simultaneously) but was allowed to observe as many laps as necessary, which usually totaled to 8 to 12 laps per swimmer (200–300 yards). Our data collection sheet for the UL errors in FC swimming technique is available in the Supplementary Material (available online).

For test–retest reliability, we selected 30 participants at random and rated them a second time. The mean (SD) time between ratings was 16 (5) days. Team logistics dictated the length and variability of time between ratings. Due to a finite volume of moderate-pace FC training, we could rate a mean (SD) of only 5 (2) swimmers per day, and some swimmers only trained FC occasionally. For interrater reliability, a second rater (a swim coach with 8 y of experience) underwent two 1-hour training sessions. The purpose of the first training session was to familiarize the second rater with the errors. The second session consisted of practice ratings

Table 1 Participant Demographics

Category	Value
Sex	21 women and 18 men
Age, y, median (IQR)	19 (3)
Height, m, median (IQR)	1.73 (0.18)
Body mass, kg, mean (SD)	70.0 (11.0)
Body mass index, kg/m^2, mean (SD)	22.8 (2.3)
Dominant hand	34 right and 5 left
Weekly training volume, km, mean (SD)	24.2 (3.4)[20]
Competitive swimming experience, y, median (IQR)	11 (3)
Months/year swum, median (IQR)	10 (4)
Self-reported training group	19 sprint 8 middistance 12 distance

Abbreviation: IQR, interquartile range.

with feedback. In the reliability study, the second rater assessed 28 randomly selected participants poolside at the same time as the first rater assessed them. The raters were blinded to each other's scores.

For criterion validity, a professional videographer video recorded 4 nonconsecutive laps of FC swimming from above water for 30 randomly selected participants. We pulled participants out from normal practice and put them into an end lane of the pool for approximately 2 minutes of filming. The videographer recorded from the front and back (transverse plane view) (HC-V770 camcorder, Panasonic) as well as while walking alongside the swimmer (sagittal plane view) (EOS 5D Mark IV camera, Canon Inc). The swimmers' mean (SD) pace per 25-yard lap was 14 (1) seconds. The principal investigator rated the videos, documenting and tallying errors on each stroke individually. The rater was blinded to the name of the swimmer on video. The rater was able to slow the videos down and watch them as many times as necessary. The same 51% threshold was imposed for an error to be considered present on video. The video ratings served as the standard against which

Table 2 Description of Upper Limb Errors in Front Crawl Swimming Technique

Stroke phase	Technique parameter	Error(s)	Description	Viewing angle	Location of error	Laterality
Recovery	Arm recovery	Straight arm	Recovering with wrist higher than elbow	Back	Above water	Both sides
Recovery	Shoulder roll	Flat or excessive	Flat (<30°) or excessive rotation (>60°)	Back	Above water	Both sides
Hand entry	Hand position	Crossover	Hand crossing over midline of body instead of in line with shoulder	Front	Above water	Both sides
Hand entry	Hand orientation	Thumb first	Hand entering water with thumb first instead of fingertips	Front	Surface of water	Both sides
Pull through	Elbow position	Dropped elbow	Failure to maintain high elbow	Front	Below water	Both sides
Pull through	Hand path	Cross under	Hand crossing over midline of body instead of pulling straight back	Front	Below water	Both sides
Throughout	Head orientation	Up or down	Looking up toward wall or looking down toward feet	Back	Surface water	—

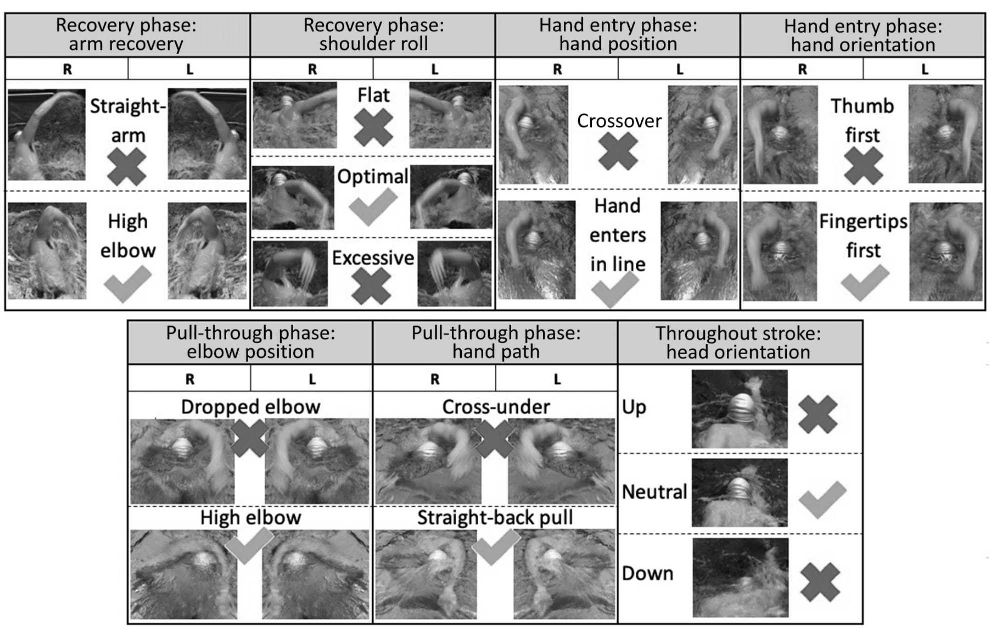

Figure 2 — Images of UL errors assessed in FC swimming technique. FC indicates front crawl; L, left; R, right; UL, upper limb.

we compared live ratings for criterion validity.[4] To confirm video as the reference standard, we rated a random subset of 10 participants' videos twice and found 87% agreement across errors between ratings.

For FC swimming performance, we extracted race times from end-of-season championship meet results (approximately 5 mo after the start-of-season assessment of UL errors) for the 50-, 100-, 200-, 500-, 1000-, and 1650-yard FCs.[22] To synthesize data across distances and sexes in a fair and consistent manner, we calculated percentages relative to the conference record in each race (conference record time divided by participant's time). For example, we would divide a conference record of 23.45 seconds in the women's 50-yard FC by a participant's time of 24.38 seconds to yield a score of 96.2%. If a participant raced multiple FC events, we used their highest percentage score.

Statistical Analyses

We calculated UL error prevalence as the number of swimmers who committed the error divided by the total number of swimmers that the primary investigator observed during the first test session. We evaluated reliability and criterion validity with percent agreement and Cohen kappa coefficient (κ) for dichotomous errors or quadratic weighted kappa coefficients (κ_w) for trichotomous errors (shoulder roll and head orientation). We interpreted these κ and κ_w as follows: <0 (no agreement), 0 to 0.20 (slight agreement), 0.21 to 0.40 (fair agreement), 0.41 to 0.60 (moderate agreement), 0.61 to 0.80 (substantial agreement), and 0.81 to 0.99 (almost perfect agreement).[18] We calculated a total UL error score as the sum of the errors with at least moderate test–retest agreement. From the test and retest total UL error scores, we calculated an intraclass correlation coefficient (ICC(3,1)) along with a minimum detectable difference 95%. We interpreted the ICC as follows: <.5 (poor), .5 to .75 (moderate), .75 to .90 (good), and >.9 (excellent).[18]

To assess the relationship between UL errors in FC swimming and performance, we correlated the total UL error scores from the principal investigator's first rating session with performance relative to conference record using Pearson correlation coefficient (r). We interpreted the correlation as follows: little to none (0–.25), fair (.25–.50), moderate to good (.50–.75), and good to excellent (>.75).[18] We set statistical significance at $\alpha = .05$, and we conducted analyses in SPSS (version 25, IBM Corp).

Results

Prevalence, Reliability, and Criterion Validity of Technique Errors

The 39 participants made a mean (SD) of 3 (2) total UL errors (range from 0 to 7) in FC swimming technique. We did not observe 1 technique error (dropped elbow pull through) in any of the swimmers' strokes on their left or right sides. Prevalence for the other 11 errors ranged from 5% to 39% (Table 3). For test–retest reliability, interrater reliability, and criterion validity, mean percentage agreements were 86%, 82%, and 79%, respectively. Of the 11 errors with nonzero prevalence, all of the test–retest reliability κ and κ_w indicated moderate, substantial, or almost perfect agreement. The test–retest reliability ICC for the total UL error score was moderate: ICC(3,1) = .68 (95% confidence interval, 0.43 to 0.83) with a corresponding minimum detectable difference 95% of 2 errors. Seven of those 11 interrater reliability κ and κ_w achieved moderate agreement or better; the other 4 errors ranged from no agreement to fair agreement (Table 3). Poolside live rating exhibited at least moderate agreement with video (ie, criterion validity) for 9 out of 11 errors, with agreement on the remaining 2 errors considered fair (Table 3).

Relationship Between UL Errors and FC Swimming Performance

Of the 39 study participants, 27 swam individual FC races at the end-of-season championship meets. Of those 27 swimmers, we excluded one from the correlation analysis due to a late-season

Table 3 Prevalence, Reliability, and Criterion Validity (Live Versus Video) of UL Errors in FC Swimming Technique

		Test–retest reliability (n = 30)		Interrater reliability (n = 28)		Criterion validity (n = 30)	
Technique parameter (side)	Prevalence, %	Agreement, %	$\kappa_{(w)}$ (95% CI)[a]	Agreement, %	$\kappa_{(w)}$ (95% CI)[a]	Agreement, %	$\kappa_{(w)}$ (95% CI)[a]
Arm recovery (R)	37	93	0.84 (0.63 to 1.05)	89	0.75 (0.48 to 1.02)	73	0.48 (0.19 to 0.76)
Arm recovery (L)	25	80	0.46 (0.10 to 0.81)	93	0.79 (0.51 to 1.07)	87	0.66 (0.36 to 0.96)
Shoulder roll (R)	26	83	0.55 (0.19 to 0.90)	64	0.16 (−0.11 to 0.43)[b]	80	0.46 (0.13 to 0.79)
Shoulder roll (L)	39	67	0.54 (0.28 to 0.80)	57	−0.01 (−0.40 to 0.38)[b]	57	0.36 (0.07 to 0.66)[b]
Hand position (R)	38	83	0.65 (0.38 to 0.91)	82	0.63 (0.34 to 0.92)	77	0.52 (0.21 to 0.83)
Hand position (L)	37	87	0.71 (0.46 to 0.97)	86	0.65 (0.34 to 0.96)	73	0.44 (0.12 to 0.75)
Hand orientation (R)	36	80	0.57 (0.27 to 0.87)	75	0.44 (0.09 to 0.79)	73	0.43 (0.09 to 0.76)
Hand orientation (L)	24	83	0.56 (0.21 to 0.90)	79	0.48 (0.12 to 0.83)	77	0.38 (0.00 to 0.76)[b]
Elbow position (R)	0	N/A	N/A	N/A	N/A	N/A	N/A
Elbow position (L)	0	N/A	N/A	N/A	N/A	N/A	N/A
Hand path (R)	11	93	0.71 (0.35 to 1.08)	89	0.34 (−0.23 to 0.92)[b]	93	0.63 (0.16 to 1.10)
Hand path (L)	17	97	0.90 (0.71 to 1.09)	100	1.00 (1.00 to 1.00)	90	0.52 (0.04 to 0.99)
Head orientation	5	97	0.67 (0.07 to 1.26)	89	0.00 (−0.07 to 0.07)[b]	93	0.50 (−0.10 to 1.10)

Abbreviations: CI, confidence interval; FC, front crawl; κ, Cohen kappa coefficient; κ_w, Cohen weighted kappa coefficient; L, left; N/A, not applicable; R, right; UL, upper limb.
[a]κ_w for shoulder roll (right and left) and head orientation, κ for all other technique parameters. [b]$\kappa_{(w)} < 0.40$, indicating less than moderate agreement.

injury that affected their ability to train and compete. Of the remaining 26 participants, based on their best FC event, 11 were sprinters (50- and 100-yard FCs), 10 were middle-distance swimmers (200-yard FC), and 5 were distance swimmers (500- and 1000-yard FCs). They performed at a mean (SD) of 94.0% (3.4%) relative the conference record (range from 87.0% to 99.1%). There was a significant negative correlation of moderate strength between the total UL error score and FC swimming performance: $r(24) = −.59$ ($P = .001$, $R^2 = .35$) (Figure 3).

Discussion

The objectives of this study were to determine (1) the test–retest reliability, interrater reliability, and criterion validity of real-time poolside assessment of UL errors in FC swimming technique and (2) the relationship between UL errors and FC swimming performance. Our hypotheses were confirmed: The total UL error score had moderate reliability (ICC(3,1) = .68; 95% confidence interval, 0.43 to 0.83) and was moderately correlated with FC swimming performance ($r = −.59$).

Prevalence, Reliability, and Criterion Validity of Technique Errors

The prevalence of 2 of the errors, crossover hand entry position and thumb first hand entry orientation, was similar to previously reported data for 31 college swimmers.[12] The prevalence of the other errors differed substantially from Virag et al's[12] findings, likely due to differences in rating criteria, vantage point, and number of strokes assessed. We live rated several laps of swimming from the pool deck, whereas Virag et al[12] rated above water and underwater video footage of 1 stroke. In this study, we did not observe the dropped elbow error during the underwater pull through in any of the participants (ie, a floor effect). Given that high-level swimmers tend to pull with a higher elbow compared with novice swimmers,[23] it is possible that no participant made this error. However, it could also be that we could not view this portion of the stroke accurately from above the water.[4] This challenge reflects the tradeoff between field expedience and optimal viewing conditions.

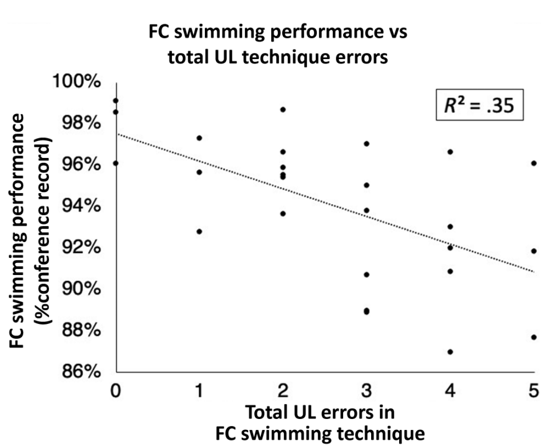

Figure 3 — Correlation between number of UL errors in FC swimming technique and FC swimming performance (the swimmer's best FC event relative to the conference record). FC indicates front crawl; UL, upper limb.

As stated in our hypothesis, moderate reliability and criterion validity are minimum thresholds for an assessment tool to be used in practice. Assessments with moderate reliability can be considered preferable to no formal rating system; however, caution should be applied in decision making derived thereof.[18] Based on our test–retest reliability data, a knowledgeable rater can assess moderate-pace FC technique from poolside between days with moderate agreement or better. In terms of interrater reliability, 2 knowledgeable raters can observe 7 of the errors with at least moderate agreement. This finding is consistent with a previous interrater reliability study, which found that 2 raters agreed on the frequency of approximately 60% of FC errors.[14] The measures with lower agreement were shoulder roll (bilaterally), cross-under hand path (right side), and head orientation. The difficulty in rating shoulder roll could have been due to the trichotomous rating system as well as high variability in shoulder roll with respect to breathing. Swimmers tend to roll their shoulders more on breathing strokes than nonbreathing strokes.[24] Between-rater agreement for shoulder roll was also low in a previous study ($\kappa < 0.40$).[12] In the present study, agreement may have been low on the right side for the cross-under hand path due to high variability in this aspect of the stroke as a swimmer approaches the wall. During practice, swimmers in the United States always swim down the right side of the lane. As they near the wall, they steer toward the center of the lane before performing a flip turn. This repositioning may increase the likelihood of committing the cross-under hand path error on the right side. Disregarding the last 2 stroke cycles of each lap could improve agreement for the right side cross-under hand path. Agreement statistics for the right side cross-under hand path and head position were also hindered by low error prevalence (11% and 5%, respectively) in a relatively small sample size. Additional procedural training and practice beyond the 2 sessions provided in this study may improve interrater reliability.

Live versus video agreement was lower than both test–retest and interrater for almost half of the errors. The errors for which this agreement was lowest were shoulder roll (left side) and thumb first hand entry orientation (left side). Although criterion validity failed to reach moderate agreement on the left side for both of these errors ($\kappa_w = 0.36$ and $\kappa = 0.38$, respectively), it did on the right side ($\kappa_w = 0.46$ and $\kappa = 0.43$, respectively). The lower agreement for live versus video may be due to the different testing conditions between live and video. We conducted test–retest and interrater observations in the flow of practice, during which time we observed many consecutive laps of swimming and estimated the 51% threshold for errors. The raters were able to change position to optimize viewing angle. Conversely, we standardized video recording to have 1 swimmer in a lane by themselves, swimming 1 lap at a time and resting briefly after each lap. We stationed the video camera for transverse plane viewing in the middle of the lane. Despite instruction to swim down the middle, swimmers often swam down the right side of the lane to the right of camera (based on habit as 38 out of 39 participants were from the United States). This slightly off-center viewing angle may have impacted video rating. In addition, video provided a limited sample of strokes for observation (as few as 5 per arm per viewing angle), and we counted the 51% threshold exactly. Finally, and perhaps most importantly, participants knew they were being filmed, which could have caused them to alter their technique despite our instruction to swim normally (ie, the Hawthorne effect). Whereas we prioritized standardized video recording procedures in this study, future studies should record swimmers in the flow of normal practice.

Relationship Between UL Errors and FC Swimming Performance

The fewer UL errors swimmers made while practicing FC, the faster their best FC race times tended to be relative to the conference record. This finding is consistent with age-old coaches' intuition: better technique corresponds with better performance.[11] This study is one of the first to support that commonly held belief using objective criteria that coaches can easily employ, which coaches rank as a top requirement for adoption.[3] The magnitude of the relationship between UL errors and FC swimming performance that we observed in the present study ($r = -.59$) is consistent with previous studies, falling about halfway between the extrema of previously observed correlations ($r = .32$ and $r = .75$).[15,16] UL errors in FC swimming technique explained 35% of the variance in FC swimming performance. In a sport where split seconds can differentiate between podium placements, this contribution is practically meaningful.

The remaining variance in performance may be explained by anthropometric, physiological, psychological, tactical, and other biomechanical factors that we did not assess in this study.[1,2] In terms of these other biomechanical factors, there are aspects of the stroke that we did not investigate as well as phases of racing separate from the stroke itself. Within the stroke, performance is likely affected by the position of the hand when exiting the water; trunk and breathing mechanics; pelvis, hip, and kicking mechanics; horizontal body position (ie, angle of attack); and coordinative timing of arm strokes.[25] Some of these technique aspects would be best captured with underwater video. These aspects fall outside the scope of this study, which focused on the UL errors that are most accessible to coaches poolside in real time.[3] Apart from the stroke, a swimmer's start, flip turns, and underwater kicking impact race performance. In a short-course pool, these phases of the race account for as much as 30% to 35% of the total race time.[26] The relationship between technique and performance may be stronger if performance measures come from long-course meters races, which have fewer turns than short-course yards races. In addition to stroke technique, future assessments could include qualitative ratings of start, flip turn, and underwater kicking technique.

"Textbook technique" posits that what is optimal for sprinters and distance swimmers differs;[27] however, there is evidence that disputes this claim.[28,29] One aspect of stroke technique in particular that may differ across distance specializations is shoulder roll, with sprinters tending to roll their shoulders less than distance swimmers.[30] However, in the present study we considered the entire range of shoulder rolls observed in previous studies (45–60°) to be optimal. Calculating the correlation between UL errors and FC swimming performance separately for sprinters (n = 11) and middle-distance/long-distance swimmers (n = 15) in this study, we found $r(9) = -.32$ ($P = .34$, $R^2 = .10$) for sprinters and $r(13) = -.49$ ($P = .06$, $R^2 = .24$) for middle-distance and distance swimmers. Although the sample sizes for these subgroups are small, the lower correlation for sprinters could underscore the relative importance of the start in shorter distance races. Another disputed aspect of FC swimming technique is arm recovery.[31] In keeping with previous research,[12] we considered a high elbow recovery to be correct. With that said, there are examples of elite swimmers who exhibit a straight-arm recovery (eg, Janet Evans). Thus, although most errors can be considered incontrovertible, arm recovery may be optimized on an individual basis.[31]

This study had a number of limitations. As previously stated, we observed floor effects for elbow position as well as head orientation due to low prevalence and a small sample, and the UL errors we assessed are only a subset of the biomechanical factors that affect FC swimming performance. Future work is needed to refine the assessment of those errors as well as expand the assessment to the trunk and lower-extremity. In addition, we assessed for UL errors in FC swimming technique at the beginning of the competitive season during practice with swimmers training at a moderate pace. Conversely, we drew performance data from end-of-season championship meets (approximately 5 mo later) in which swimming was at race pace. It is possible that participants' technique changed in the time between the start-of-season assessment of UL errors and the championship meets. It is also possible that their race technique differed from their moderate-pace practice technique.[32] Moreover, to rate all participants within the confines of normal practice time (during which there was a finite volume of moderate-pace FC training), we could not control for fatigue. In summary, the correlation between actual race technique and race performance may differ from the correlation we observed. Furthermore, given the cross-sectional design of this study, although we observed a correlation between UL errors and performance, we cannot infer causation. Although it seems logical that improving technique (ie, reducing UL errors) would result in faster swimming performance, we need intervention studies to investigate such a cause and effect relationship. Additional research is also needed to weight errors and total error scoring based on the magnitude of the errors' effects on performance (as opposed to a simple arithmetic sum). Lastly, this study was conducted with Division III college swimmers and raters with ample swimming and coaching experience. Our results cannot necessarily be generalized to other competition levels or raters with differing experience.

This study has important implications for swim coaches, sports rehabilitation professionals, and future research. The newly refined assessment of UL errors in FC swimming technique is a low-technology, field-expedient tool. It removes the barriers that above water and underwater cameras introduce, requires no sophisticated biomechanical expertise, and may have practical implications for swimming instruction. Based on our reliability data, a knowledgeable rater can assess FC swimming technique to objectively detect, document, and track UL errors with moderate between-day reliability. In the presence of pain or for return to sport decision making, sports rehabilitation professionals may find utility in comparing UL errors with a baseline assessment. More research is needed to improve interrater reliability and criterion validity for several of the errors. Importantly, the relationship we observed between technique and performance supports the emphasis that coaches place on technique in training.[3] Given the observed correlation, additional work is also needed to determine whether correcting UL errors in FC swimming technique would improve performance. Given the minimum detectable difference 95%, a 2-point improvement in total UL error score would exceed measurement error.

Conclusion

Swimming technique is considered a key determinant of performance. This study was one of the first to investigate this relationship using an objective, real-time, poolside assessment of technique. Our reliability and validity data showed moderate agreement for the majority of errors. The fewer UL errors swimmers made while practicing FC, the faster their best FC race times tended to be relative to the conference record. UL errors explained 35% of the variance in FC swimming performance.

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References

1. Toussaint HM, Beek PJ. Biomechanics of competitive front crawl swimming. *Sports Med*. 1992;13(1):8–24. doi:10.2165/00007256-199213010-00002
2. McGibbon KE, Pyne D, Shephard M, Thompson K. Pacing in swimming: a systematic review. *Sports Med*. 2018;48(7):1621–1633. doi:10.1007/s40279-018-0901-9
3. Mooney R, Corley G, Godfrey A, et al. Analysis of swimming performance: perceptions and practices of US-based swimming coaches. *J Sports Sci*. 2016;34(11):997–1005. PubMed ID: 26359951 doi:10.1080/02640414.2015.1085074
4. Mooney R, Corley G, Godfrey A, Osborough C, Quinlan L, ÓLaighin G. Application of video-based methods for competitive swimming analysis: a systematic review. *Sports Exerc Med*. 2015;1(5):133–150. doi:10.17140/SEMOJ-1-121
5. Guignard B, Rouard A, Chollet D, Seifert L. Behavioral dynamics in swimming: the appropriate use of inertial measurement units. *Front Psychol*. 2017;8:383. PubMed ID: 28352243 doi:10.3389/fpsyg.2017.00383
6. Wei T, Mark R, Hutchison S. The fluid dynamics of competitive swimming. *Annu Rev Fluid Mech*. 2014;46:547–565. doi:10.1146/annurev-fluid-011212-140658
7. Craig A, Pendergast D. Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Med Sci Sports*. 1979; 11(3):278–283. PubMed ID: 522640
8. McMaster WC, Troup JP. Competitive swimming biomechanics: freestyle. *Int SportMed J*. 2001;2(6):1–8.
9. Keskinen K. Measurement of technique in front crawl swimming. *Med Sport Sci*. 1994;39:117–125. doi:10.1159/000423716
10. Glazier PS, Robins MT. Comment on "Use of deterministic models in sports and exercise biomechanics research" by Chow and Knudson (2011). *Sports Biomech*. 2012;11(1):120–122. doi:10.1080/14763141.2011.650189
11. Lees A. Technique analysis in sports: a critical review. *J Sports Sci*. 2002;20(10):813–828. PubMed ID: 12363297 doi:10.1080/026404102320675657
12. Virag B, Hibberd EE, Oyama S, Padua DA, Myers JB. Prevalence of freestyle biomechanical errors in elite competitive swimmers. *Sports Health*. 2014;6(3):218–224. PubMed ID: 24790691 doi:10.1177/1941738114527056
13. Arellano R, López-Contreras G, Sánchez-Molina J. Qualitative evaluation of technique in international Spanish junior and pre-junior swimmers: an analysis of error frequencies. In: Chatard JC, ed. *Biomechanics and Medicine in Swimming IX*. Institute for Applied Training Science; 2002:87–92.
14. Soares S, Fernandes R, Carmo C, Santos Silva J, Vilas-Boas J. Qualitative evaluation of technique in swimming: analyses of the consistency of results produced by evaluators with similar experiences and theoretical backgrounds. *Rev Port Ciências do Desporto*. 2001;1(3):22–32. doi:10.5628/rpcd.01.03.22
15. Sacilotto GB, Clothier PJ, Mason BR, Ball N. Variability in coach assessments of technique in front crawl sprint swimming. In: Mason BR, ed. *XIIth International Symposium for Biomechanics and Medicine in Swimming*. Institute for Applied Training Science; 2014: 222–226.
16. Gómez-Bruton A, Matute-Llorente A, Pardos-Mainer E, et al. Factors affecting children and adolescents 50 meter performance in freestyle swimming. *J Sports Med Phys Fitness*. 2016;56(12):1439–1447. PubMed ID: 26398204
17. Silva AJ, Costa AM, Oliveira PM, et al. The use of neural network technology to model swimming performance. *J Sports Sci Med*. 2007;6(1):117–125.
18. Portney L, Watkins M. *Foundations of Clinical Research*. 3rd ed. Davis Company; 2015.
19. Pollen TR, Warren M, Ebaugh D, Taylor JA, Silfies SP. Intrinsic risk factors for non-contact musculoskeletal injury in college swimmers: a prospective cohort study. *J Athl Train*. Published online March 10, 2022. doi:10.4085/1062-6050-0658.21
20. Pollen TR, Ebaugh D, Warren M, Milner CE, Taylor JA, Silfies SP. The relationship between workload and non-contact musculoskeletal injury in college swimmers: a prospective cohort study. *J Athl Train*. 2022;57(5):470–477. doi:10.4085/1062-6050-0135.21
21. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39(2):175–191. PubMed ID: 17695343 doi:10.3758/bf03193146
22. CollegeSwimming.com. Swimcloud. 2019. www.collegeswimming.com.
23. Suito H, Ikegami Y, Nunome H, Sano S, Shinkai H, Tsujimoto N. The effect of fatigue on the underwater arm stroke motion in the 100-m front crawl. *J Appl Biomech*. 2008;24(4):316–324. PubMed ID: 19075300 doi:10.1016/S0021-9290(07)70760-1
24. McCabe CB, Sanders RH, Psycharakis SG. Upper limb kinematic differences between breathing and non-breathing conditions in front crawl sprint swimming. *J Biomech*. 2015;48(15):3995–4001. PubMed ID: 26456423 doi:10.1016/j.jbiomech.2015.09.012
25. Seifert L, Komar J, Barbosa T, Toussaint H, Millet G, Davids K. Coordination pattern variability provides functional adaptations to constraints in swimming performance. *Sports Med*. 2014;44(10): 1333–1345. doi:10.1007/s40279-014-0210-x
26. Thayer A, Hay J. Motivating start and turn improvement. *Swim Tech*. 1984;20:17–20.
27. Maglischo E. *Swimming Fastest*. Human Kinetics; 2003.
28. McCabe CB, Psycharakis S, Sanders R. Kinematic differences between front crawl sprint and distance swimmers at sprint pace. *J Sports Sci*. 2011;29(2):115–123. PubMed ID: 21120744 doi:10.1080/02640414.2010.523090
29. McCabe CB, Sanders RH. Kinematic differences between front crawl sprint and distance swimmers at a distance pace. *J Sports Sci*. 2012; 30(6):601–608. PubMed ID: 22315962 doi:10.1080/02640414.2012.660186
30. Vezos N, Gourgoulis V, Aggeloussis N, Kasimatis P, Christoforidis C, Mavromatis G. Underwater stroke kinematics during breathing and breath-holding front crawl swimming. *J Sports Sci Med*. 2007; 6(1):58–62.
31. Sanders R. Beyond race analysis. Proceedings of the XVIII International Symposium on Biomechanics in Sports; 2000:3–14.
32. de Jesus K, Sanders R, de Jesus K, et al. The effect of intensity on 3-dimensional kinematics and coordination in front-crawl swimming. *Int J Sports Physiol Perform*. 2016;11:768–775. PubMed ID: 26658832 doi:10.1123/ijspp.2015-0465