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Racing Start Safety: Head Depth and Head Speed During Competitive Starts Into a Water Depth of 1.22 m

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From the perspective of swimmer safety, there have been no quantitative 3-dimensional studies of the underwater phase of racing starts during competition. To do so, 471 starts were filmed during a meet with a starting depth of 1.22 m and block height of 0.76 m. Starts were stratified according to age (8 & U, 9–10, 11–12, 13–14, and 15 & O) and stroke during the first lap (freestyle, breaststroke, and butterfly). Dependent measures were maximum head depth, head speed at maximum head depth, and distance from the wall at maximum head depth. For all three variables, there were significant main effects for age, $F(4, 456) = 12.53$, $p < .001$, $F(4, 456) = 27.46$, $p < .001$, and $F(4, 456) = 54.71$, $p < .001$, respectively, and stroke, $F(2, 456) = 16.91$, $p < .001$, $F(2, 456) = 8.45$, $p < .001$, and $F(2, 456) = 18.15$, $p < .001$, respectively. The older swimmers performed starts that were deeper and faster than the younger swimmers and as a result, the older swimmers may be at a greater risk for injury when performing starts in this pool depth.

The importance of being able to perform a safe racing start is crucial to all ages of competitive swimmers. An analysis of 72 pool accidents in the United States revealed that 53 of the incidents (74%) were associated with head-first diving into a shallow pool, 51 of the incidents (71%) occurred in pools that were less than 1.22 m (4 ft) deep, and 60 (83%) resulted in tetraplegia and/or permanent brain damage (Green, Gabrielsen, Hall, & O'Heir, 1980). A subsequent study (1982–2007) reported 13 catastrophic injuries resulting in "permanent severe functional brain or spinal cord disability" specifically within competitive swimming (high school and college) with all but one incident occurring during the execution of a racing start (Mueller & Cantu, 2007).

The number of catastrophic injuries over this time period for all of age group swimming is not readily available and is difficult to estimate as not all competitive programs and swimmers are registered with USA Swimming or any other recognized organizing body. It is possible to suppose that one catastrophic accident as a result of a racing start is one too many if it was preventable. As participation in the sport of competitive swimming continues to increase and the cost of medical care and litigation increases exponentially, there is an obvious need to understand

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the dangers inherent in the execution of racing starts as a means to minimize the risks and subsequently eliminate or reduce the number of catastrophic injuries.

The risks associated with racing starts are a function of the trajectory of the body upon leaving the starting block and entering the water, the velocity at which the body is traveling in the air and water, the depth of the head during the trajectory underwater, and of course the depth of the water into which the swimmer is entering. Whether an injury occurs upon contact is also affected by the momentum associated with the moving body, which is a function of the velocity and mass of the swimmer. In addition to body size and mass, the velocity of the swimmer's body is related to the forces generated by the swimmer while on the block, the ability of the swimmer to reduce the resistive forces (streamline) once entering the water, and the height of the block above the water surface from which the movement is initiated.

The current rules outlined by the governing bodies of competitive swimming state that block height shall not be higher than 0.76 m (2 ft 6 in) above the surface of the water, and water depth shall not be less than 1.22 m (4 ft; USA Swimming, 2009). Although these current rules are in place to enforce a standard for competition and perhaps a measure of safety, in the later case, these rules are not necessarily supported by data derived through empirical research.

The majority of the competitive swimming start literature has reported the use of biomechanical analysis to improve race performance rather than swimmer safety. While there have been studies that have examined the racing start depths achieved when performing competitive swim starts from varying block heights and pool depths (Blitvich, McElroy, Blanksby, & Douglas, 1999; Blitvich, McElroy, Blanksby, Clothier, & Pearson 2000; Counsilman, Nomura, Endo, & Counsilman, 1988; Gehlsen & Wingfield, 1998; Welch & Owens, 1986), these studies all took place in controlled or "non-competitive" settings. Mean values for maximum head depth following a racing start for these referenced studies range from 0.56 to 1.22 m and are shown to be dependent upon factors such as water depth, block height, start type, body landmark, and swimming skill level. Currently, we are unaware of any studies that have quantitatively analyzed the underwater motion following a competitive racing start during actual swimming competition. Furthermore, we have not been able to find data for starts initiated before different strokes or studies that directly compare start parameters for competitive swimmers of different ages.

The purpose of this study was to identify risk factors in competitive swim starts by describing maximum head depth, head speed at maximum head depth, and distance from the wall at maximum head depth following the execution of racing starts in an actual swim competition. Swimmers ranging in age and competitive skill levels participating in a typical "open" invitational were filmed with the primary focus of the study being upon variables that contribute to the risk of injury.

Method

The study took place during a USA Swimming sanctioned age group and open invitational swim meet at a competitive pool in central Indiana. The facility consisted of an eight-lane competition pool with a starting end depth of 1.22 m. Starting platforms were standard 0.76 m blocks. The project was previously approved by the university's Human Subjects Committee.

Participants

The swimmers participating in this study were USA Swimming registered competitive swimmers. Swimmers ranged in age from five to eighteen years. There were no minimal time standards for participation in the competition, and therefore swimmers represented a wide range of skill levels. Only starts performed in lanes four and five were filmed as a result of the required camera position. One limitation of the study that should be acknowledged is that the swimmers filmed were those with the two fastest entry times of the eight swimmers in each heat. These swimmers were likely to be the most skilled performers meaning that for each heat, the starts of the least skilled swimmers are not being recorded.

"Starts" rather than specific swimmers in each age group were considered the more critical of the two descriptors and thus the exact number of swimmers filmed was not specifically known. Furthermore, limitations imposed by the institutional review board prohibited us from knowing the identity of the swimmers filmed (minors without parental consent in the public domain). For these reasons, a swimmer might be represented in the data set more than once if he or she participated in more than one event and started multiple times from either lane four or five.

Procedures

All filming took place in a competitive pool specifically selected because it had sufficient space outside of the competition area in lanes one and eight for cameras to be positioned. For each heat, the underwater portion of the racing start for the swimmers in lanes four and five was recorded using a two-camera system. The start type used by each swimmer was observed and recorded by an experimenter at poolside.

Video recording began at the start signal of the race and continued until the swimmers passed completely through the field of view. Canon GL2 (Canon Inc., Tokyo, Japan) digital video camcorders, housed in underwater units (Ikelite Underwater Systems, Indianapolis, IN), were placed on the pool bottom on the outer edge of lanes one and eight at an angle of approximately 45° to the pool start wall. Canon wide-angle adapters (WD-58, Canon Inc., Tokyo, Japan) were used to ensure that the field of view included the subjects' underwater motions from water entry to beyond the deepest point of the racing start. Camera zoom and focus were adjusted remotely underwater once the camera unit was in place. Opticis Optical IEEE1394 FireWire Repeaters (M4–100, Opticis North America, Inc., Chatham, Ontario, Canada) extended the range of the video cables to 30 m and enabled both video signals to be input directly to a single laptop computer (M675, Gateway Inc., Irvine, CA) at the poolside. Video sequences were recorded at 60 Hz using motion software (SIMI Reality Motion Systems, Unterschleissheim, Germany), which determined the time offset between the video signals from the two cameras to permit accurate three-dimensional (3D) reconstruction.

Calibration

Separate calibrations were undertaken for lanes four and five. For each, a custom-built calibration frame was placed in the region of the racing start and filmed with both cameras. The dimensions of the frame were 1 m × 1 m × 3 m and it was constructed from marine aluminum, which was painted black. Eighty-four bright yellow closed-cell foam marker balls (0.05 m diameter) served as calibration points.

The calibration frame was placed vertically in line with the center of the starting block and perpendicular to the side of the pool. In addition, a vertical plumb line with three marker balls and three additional balls floating at the surface were included in the field of view and a video image was captured with each camera.

The positions of the 84 marker balls on the frame, the additional marker balls, and reference points on the wall of the pool were digitized in a single video frame from each camera using SIMI Motion. The balls on the frame were used in the 3D direct linear transformation (DLT) procedure to calibrate the area using a frame-based coordinate system. The data on the positions of the additional markers enabled the transformation of position data from the frame-based system to a pool-based reference frame in which the x-axis was horizontal and perpendicular to the wall, the y-axis pointed horizontally to the left, and the z-axis pointed vertically upward. The origin was at water level directly below the center of the starting block for that lane.

Filming and Data Analysis

All competitive starts in lanes four and five were recorded. For each trial, the locations of four landmarks were digitized in each frame from the first recognizable point of entry (below the water surface) through to the instant 10 frames after maximum depth was achieved. The landmarks were the center of the head, the center of the knee joint, and the top of the middle finger and big toe. The frame in which the head reached its maximum depth was first visually estimated by the experimenter, and an additional 10 frames were digitized to ensure that the true instant of maximum depth had been included. When a landmark was obscured or its location could not be determined from both camera angles, the start was excluded from the analysis.

The dependent measures of interest for this study were maximum depth of the center of the head (maximum head depth), head speed at maximum head depth, and distance from the wall at maximum head depth. The starts were stratified according to age group, stroke, and sex. Similar to what others have reported (Counsilman et al., 1988), preliminary comparisons found no differences between boys and girls for the dependent variables. As a result, we limited our comparisons to age group and stroke. The age groups were for swimmers 8 years and under (8 & U), 9–10 years (9–10), 11–12 years (11–12), 13–14 years (13–14), and 15 years and older (15 & O). The stroke variable was determined by the competitive stroke performed on the first lap of the race. The three levels of stroke were front crawl (freestyle), breaststroke, and butterfly. Backstroke starts were not included in this project because swimmers do not enter the pool from the starting block.

A two-way ANOVA was conducted to test for differences for each of the dependent measures. When a significant F-ratio was obtained from the omnibus ANOVA test, post hoc comparisons were performed using Tukey's HSD procedure. When the ANOVA tests revealed significant interactions, simple effects analysis was conducted using methods previously established (Keppel & Wickens, 2004). For all analyses reported below, an alpha level of 0.05 was used to determine statistical significance.

Results

Swimmers used two start types: track (96.1%) and grab (3.9%). Three of the track starts were performed from the side of the pool. For maximum head depth, head speed at maximum head depth, and distance from the wall at maximum head depth (Table 1), two-way ANOVAs showed significant main effects for age group, $F(4, 456) = 12.53$, $p < .001$, $\eta^2 = 0.09$, $F(4, 456) = 27.46$, $p < .001$, $\eta^2 = 0.18$, and $F(4, 456) = 54.71$, $p < .001$, $\eta^2 = 0.30$, respectively, and stroke $F(2, 456) = 16.91$, $p < .001$, $\eta^2 = 0.06$, $F(2, 456) = 8.45$, $p < .001$, $\eta^2 = 0.03$, and $F(2, 456) = 18.15$, $p < .001$, $\eta^2 = 0.05$, respectively.

Table 1 Maximum Head Depths (m), Head speed at Maximum Head Depth (ms^{-1}), and Distance From the Wall at Maximum Head Depth (m)

			Head Depth		Head Speed at Max. Head Depth	Distance at Max. Head Depth
Age Group	Stroke	N	Mean	Range		
8 & Under	Freestyle	18	0.39 ± 0.17	0.09–0.64	1.85 ± 0.70	2.88 ± 0.67
	Breaststroke	10	0.49 ± 0.12	0.29–0.65	1.75 ± 0.38	3.36 ± 0.72
	Butterfly	17	0.47 ± 0.14	0.19–0.67	2.05 ± 0.42	3.10 ± 0.55
	Combined	45	0.44 ± 0.15	0.09–0.67	1.90 ± 0.55	3.07 ± 0.65
9–10	Freestyle	48	0.52 ± 0.16	0.19–0.99	2.09 ± 0.65	3.46 ± 0.56
	Breaststroke	34	0.62 ± 0.19	0.25–1.01	2.02 ± 0.65	3.72 ± 0.69
	Butterfly	33	0.55 ± 0.17	0.23–0.84	2.04 ± 0.56	3.50 ± 0.70
	Combined	115	0.56 ± 0.17	0.19–1.01	2.05 ± 0.62	3.55 ± 0.65
11–12	Freestyle	72	0.53 ± 0.13	0.08–0.77	2.41 ± 0.54	3.79 ± 0.55
	Breaststroke	34	0.63 ± 0.16	0.26–0.88	2.11 ± 0.39	4.21 ± 0.56
	Butterfly	49	0.58 ± 0.15	0.15–0.88	2.39 ± 0.44	3.96 ± 0.65
	Combined	155	0.57 ± 0.15	0.08–0.77	2.34 ± 0.49	3.93 ± 0.60
13–14	Freestyle	52	0.59 ± 0.12	0.32–0.87	2.78 ± 0.60	4.09 ± 0.50
	Breaststroke	29	0.69 ± 0.17	0.36–1.09	2.44 ± 0.52	4.49 ± 0.65
	Butterfly	31	0.62 ± 0.14	0.32–0.96	2.54 ± 0.44	4.26 ± 0.60
	Combined	112	0.62 ± 0.15	0.32–1.09	2.63 ± 0.55	4.24 ± 0.59
15 & Over	Freestyle	21	0.54 ± 0.09	0.41–0.77	3.05 ± 0.45	4.26 ± 0.27
	Breaststroke	11	0.69 ± 0.07	0.60–0.78	2.41 ± 0.41	5.05 ± 0.61
	Butterfly	12	0.62 ± 0.07	0.53–0.77	2.83 ± 0.46	4.53 ± 0.44
	Combined	44	0.60 ± 0.10	0.41–0.78	2.83 ± 0.50	4.53 ± 0.53
Combined	Freestyle	211	0.53 ± 0.14	0.08–0.99	2.44 ± 0.68	3.76 ± 0.64
	Breaststroke	118	0.64 ± 0.17	0.25–1.09	2.16 ± 0.55	4.14 ± 0.78
	Butterfly	142	0.57 ± 0.15	0.15–0.96	2.34 ± 0.53	3.87 ± 0.74
	Combined	471	0.57 ± 0.16	0.08–1.09	2.34 ± 0.61	3.89 ± 0.73

Values are means ± *SD*. Values for the range are minimum, maximum respectively. All values are measured at the center of the head.

Maximum head depth was significantly less for 8 & U than for all other age groups ($p < .001$), 9–10 than for 13–14 ($p = 0.009$), and 11–12 than for 13–14 ($p = 0.011$; Figure 1a). The pairwise comparisons for the stroke groups showed that maximum head depth was significantly less for freestyle than breaststroke ($p < .001$) and butterfly ($p = 0.03$) and butterfly than for breaststroke ($p < .001$; Figure 2a).

The pairwise comparisons for the age groups showed that head speed at maximum head depth was significantly less for 8 & U than 11–12, 13–14, and 15 & O ($p < .001$), 9–10 than 11–12, 13–14, and 15 & O ($p < .001$), and 11–12 than 13–14 and 15 & O ($p < .001$; Figure 1b). The pairwise comparisons for the stroke groups showed that head speed at maximum head depth was significantly less for breaststroke than freestyle ($p < .001$) and butterfly ($p = 0.026$; Figure 2b).

The pairwise comparisons for the age groups showed that the distance from the wall at maximum head depth was significantly different for all comparisons ($p < .05$). In all cases, the distance for the older of the two age groups was significantly greater than the younger (Figure 1c). The pairwise comparisons for the stroke groups showed that distance from the wall at maximum head depth was significantly greater for breaststroke than for freestyle and butterfly ($p < .001$; Figure 2c).

In 14 of 471 filmed racing starts, a swimmer came in contact with the pool bottom. Regardless of body part in contact with the pool bottom, head depth in these cases was not less than 0.23 m (or 9 inches) from pool bottom. The average head distance from the bottom upon contact was 0.46 m (or 18 inches), which is similar to that of the noncontact starts. The racing starts during which the swimmers made contact with the bottom of the pool were categorized in several ways: age group, body part, stroke, and sex (Table 2).

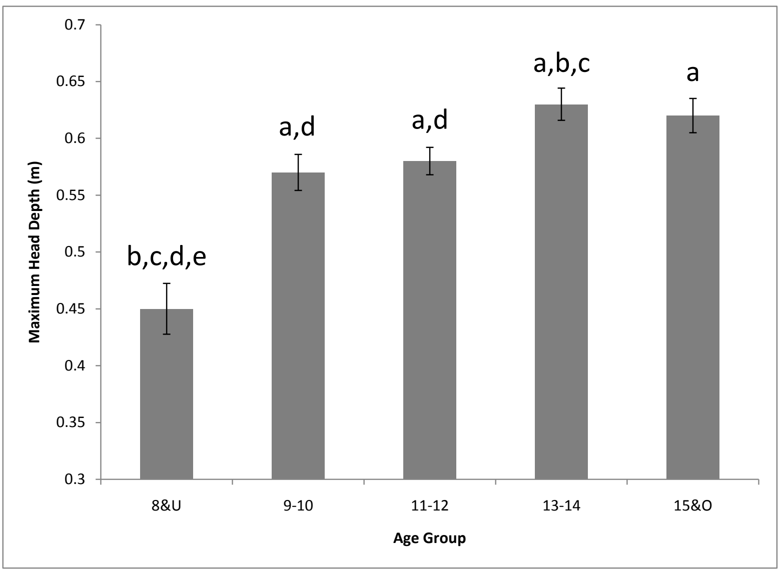

Figure 1a — Maximum head depth (m) as a function of age group (yr; a- 8 & U, b- 9–10, c-11–12, d- 13–14, and e- 15 & O). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

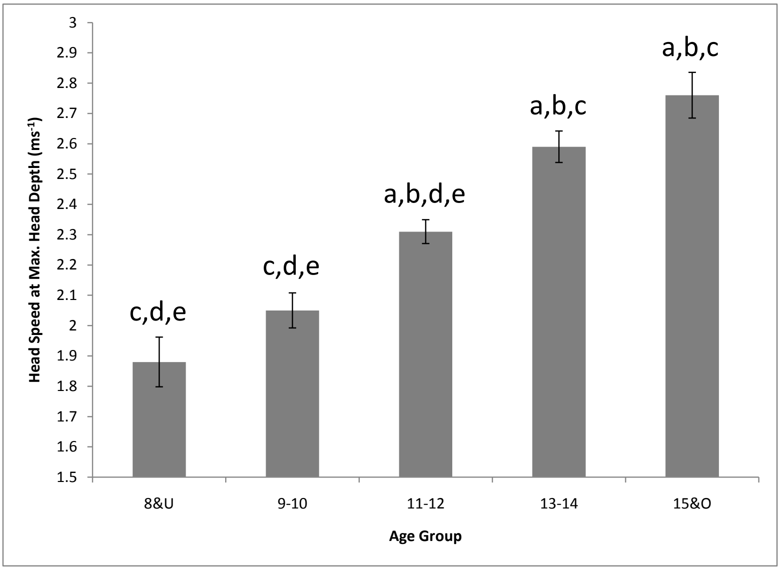

Figure 1b — Head speed at maximum head depth (ms^{-1}) as a function of age group (yr; a: 8 & U, b: 9–10, c: 11–12, d: 13–14, and e: 15 & O). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

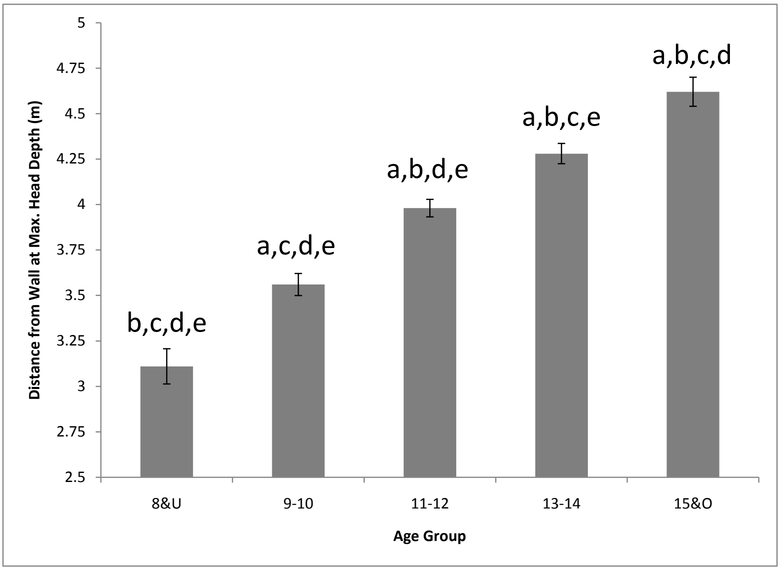

Figure 1c — Distance from the wall at maximum head depth (m) as a function of age group (yr; a: 8 & U, b: 9–10, c: 11–12, d: 13–14, and e: 15 & O). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

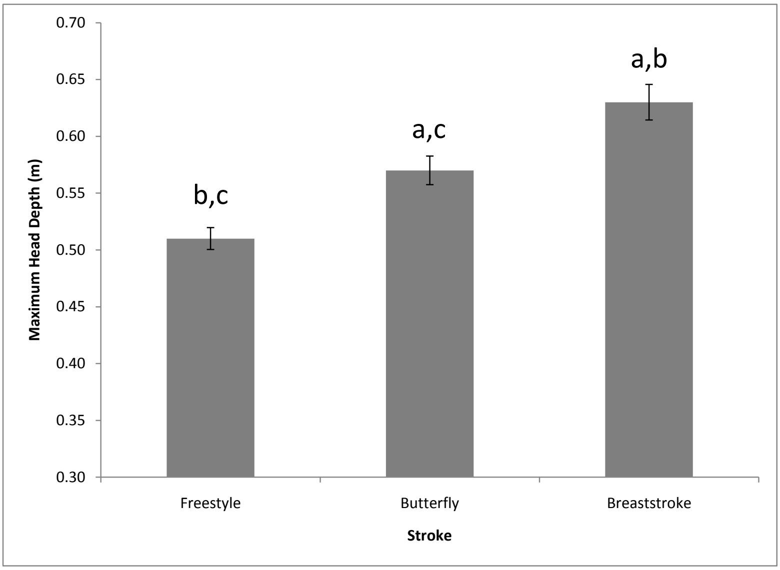

Figure 2a — Maximum head depth (m) as a function of stroke (a: freestyle, b: butterfly, c: breaststroke). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

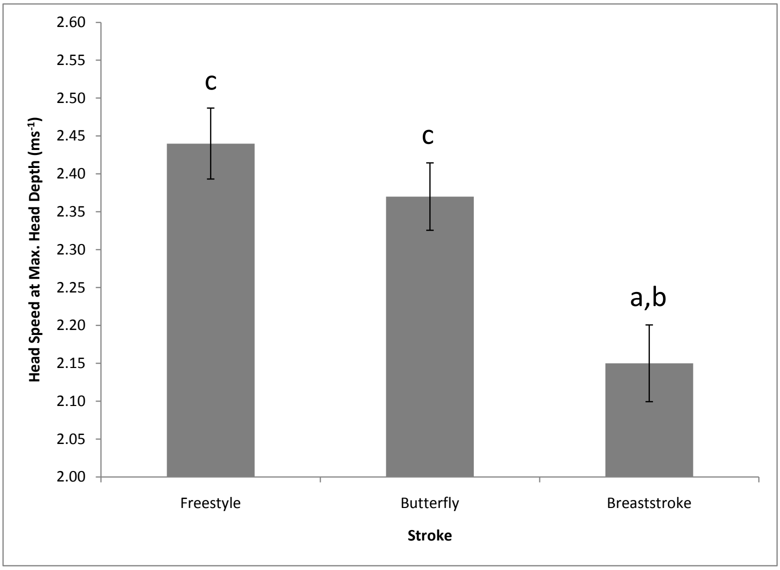

Figure 2b — Head speed at maximum head depth (ms^{-1}) as a function of stroke (a: freestyle, b: butterfly, c: breaststroke). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

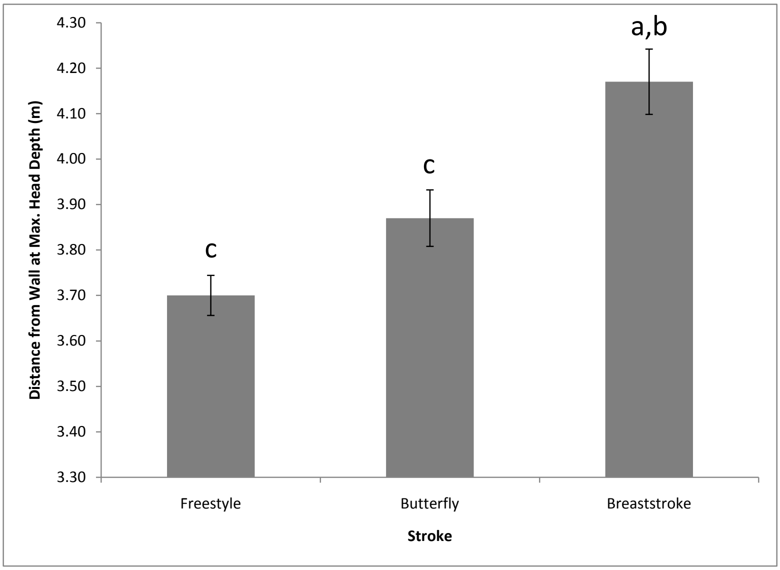

Figure 2c — Distance from the wall at maximum head depth (m) as a function of stroke (a: freestyle, b: butterfly, c: breaststroke). Significant differences ($p < .05$) denoted by letter above each bar. Error bars represent one standard error.

Table 2 Observed Pool Bottom Contacts

Group	Subgroup	Contacts
Age Group	8 & U	0
	9–10	5
	11–12	1
	13–14	4
	15 & O	4
Body Part	Feet only	8
	Hands only	1
	Hands & Feet	4
	Knees & Feet	1
Stroke	Freestyle	4
	Breaststroke	4
	Butterfly	4
	Relays	2
Sex	Boys	8
	Girls	6

Note. Values are frequencies of observed contacts for age group, body part, stroke, and sex.

Discussion

The purpose of this study was to describe the maximum head depth and the head speed at maximum head depth achieved by competitive swimmers following the execution of racing starts during *actual swim competition*. Few comparable data are available in the research literature primarily due to a lack of available imaging technology, the time intensive process involved in analyzing the images once obtained, and a traditional research perspective focused upon swim performance rather than swim safety. The operational hypothesis was that there would be a difference in starts executed during competition as compared with those performed in a practice setting. In addition, we hypothesized that older (and heavier) swimmers would attain deeper head depths and greater head speeds because they leave the starting block with greater velocity and enter the water in a more streamlined position.

Head Depth, Head Speed, and Horizontal Distance at Maximum Head Depth

The scant values from the literature for mean head depths for swimmers following the execution of practice racing starts ranged from 0.56 to 1.22 m and were suggested to be dependent upon factors such as block height, start type, water depth, body landmark, and skill level (Blitvich et al., 1999; Blitvich et al., 2000; Counsilman et al., 1988; Gehlsen & Wingfield, 1998; Welch & Owens, 1986). We report values for mean head depth ranging from 0.39 to 0.69 m, depending on the age group and/or swim stroke. Our data initially suggested that values for head depth collected in competition were not as deep as those reported for starts in practice.

Considering for a moment age and water depth, the closest comparison we can make with values in the literature was with values from Blitvich et al. (2000). They report head depth for 36 elite junior swimmers (mean age = 15.3 yrs) as 0.79 m in a water depth of 1.2 m and 0.88 m in a water depth of 2.0 m. The most appropriate comparison is between the starts from Blitvich et al. in the 1.2 m pool and the 15 & O freestyle starts from the current report. It is important to note that the maximum head depth values reported by Blitvich et al. were adjusted by 0.15 m to account for the distance from the external auditory meatus to the deepest point of the head. As a result, a similar adjustment must be made on our data before making the comparison. Statistical analysis (Independent sample t test) revealed that our values for head depth were significantly less ($p < .05$) by 10 cm. We explain this difference because the athletes in the two studies differed greatly in competitive skill levels (ours were much less skilled) and, of course, our starts were performed in competition rather than practice.

Counsilman et al. (1988) filmed the starts of 121 swimmers attending a summer stroke camp. Girls and boys who ranged in age from 10 to 17 years were asked to perform three different start types: scoop, flat, and track. Given that over 95% of the swimmers in the current study performed track starts, the most appropriate comparison was with their data obtained after the execution of the track start. They reported “the depth to which the subjects penetrated the water” for the girls and boys (mean = 0.70 m) was identical to each other (Counsilman et al., 1988). When our values (boys and girls) for head depth, hand depth, knee depth, and toe depth were collapsed in a similar manner (i.e., 0.57 m, 0.57 m, 0.77 m, 0.89 m, respectively;

unpublished data) and then averaged (the four body parts) to represent a “mean body depth,” it resulted in an identical depth of 0.70 m. Once again to be exacting, Counsilman et al.’s data were obtained in a diving well during a swim practice. Admittedly, the effect of filming “in competition” cannot be interpreted directly from our data due to a limited frame of reference. Hypothetically, the only way to specifically assess this effect would be to film the same swimmers executing the same starts in the same pool during practice and competition.

The discussion pertaining to head speed at maximum head depth is limited by similar issues. Only two comparisons with existent literature could be legitimately made. Blitvich et al. (1999) and Blitvich et al. (2000) provided estimates of head speed at maximum head depth for two groups during the execution of a start. In the first report (1999), 95 first-year university students executed a start from a standard block into 2.0 m of water with a head speed at maximum head depth of 2.55 ± 0.64 ms^{-1}. In the second report, 36 elite junior swimmers executed a start from a standard block into 1.2 m of water (as well as 2.0 m of water) with a reported head speed at maximum head depth of 2.51 ± 0.47 ms^{-1}. Our value (2.76 ± 0.50 ms^{-1}) for similarly-aged swimmers (15 & O) was not statistically different ($p > 0.05$; Independent Sample t test) from either of their values.

The literature pertaining to the velocity capable of causing spinal injuries upon impact include the following: 0.60 ms^{-1} (sufficient momentum to dislocate the adult cervical spine; Blanksby, Wearne, & Elliott, 1996), 1.20 ms^{-1} (sufficient momentum to crush the cervical spine; Blanksby et al., 1996), 1.90 ms^{-1} (15% risk of serious neck and head injury; Viano & Parenteau, 2008), and 3.40 ms^{-1} (50% risk of serious neck and head injury; Viano & Parenteau, 2008). In the present analysis, recorded head speed exceeded 0.60 ms^{-1} in 99% of all starts (469 of 471 starts; Table 3). In contrast, only 5% of all starts exceeded 3.40 ms^{-1} with there being a trend toward higher speed and higher risk as the swimmers’ ages (and presumably body size and mass) increased (Figure 1b). The point to be made is that nearly all of the starts resulted in head speeds in excess of that suggested as capable of resulting in serious neck injury and three out of four starts present a measurable risk of serious neck or head trauma if an impact with the bottom were to occur.

Blitvich et al. (1999) concluded that the horizontal distance traveled underwater at maximum head depth was the best predictor of maximum head depth. The best

Table 3 Proportion of Starts Greater Than Proposed Thresholds for Head and Neck Trauma

Age Group	% > 3.4 ms^{-1}*	% > 1.9 ms^{-1}*	% > 1.2 ms^{-1}+	% > 0.6 ms^{-1}+
8 & U	2.2	51.1	91.1	100
9–10	1.7	55.7	90.4	98.3
11–12	1.9	81.9	100	100
13–14	11.6	92.0	100	100
15 & O	11.4	97.7	100	100
Total	5.1	76.4	96.8	99.6

Note. Values are percentages of starts greater than proposed thresholds for head and neck trauma.
*From Viano and Parenteau (2008). + From Blanksby et al. (1996).

comparison with the current study was, once again, Blitvich et al. (2000). The value reported for distance from the wall at maximum head depth was 4.72 ± 0.62 m and was not significantly different ($p > .05$; Independent Sample t test) from the value we reported here (4.62 ± 0.53 m).

In summary, despite only limited comparisons being possible to make between our values and those existent within the literature, the conclusion seems to be that starts in competition are not necessarily deeper, faster, or farther (from the wall) than starts filmed noncompetitively when similarly aged athletes were compared in pools of similar water depths. This suggested that future research pertaining to start safety, start depth, start velocity, and/or distance from the wall may be valid even when filmed in noncompetitive settings.

Pool Depth and Pool Safety

One of the major reasons for choosing the specific meet filmed in this study was that the depth of the pool starting end was 1.22 m (4.0 ft), the minimum depth allowed in competition where swimmers are still permitted to start from blocks with heights of 0.76 m (USA Swimming, 2009). While the age group and stroke comparisons were significant and interesting, perhaps most important in this regard were the observations pertaining to maximum head depth and head velocity at this depth. The deepest starts (by age group and stroke) averaged slightly less than 0.70 m in depth (about 27.5 in from the surface) or about 0.52 m (approximately 20.5 inches) from the bottom of the pool. When the average distance from the center of the head to the top of the head (15 cm or about 6 inches) is subtracted from the distance from the pool bottom, the average distance is reduced to 0.37 m (approximately 14.5 inches). When the variance around the mean value is then used to compute the scatter among the measurements, 95% of the values for maximum head depth fall within a range of 0.71 m to 0.03 m from the bottom of the pool (between 28.0 in and 1.4 in from the pool bottom). We emphasize that these values are for the deepest starts filmed (breaststroke for the 13–14 and 15 & O) and the variance used for this estimate was the greater of the two (13–14). Thus, although this minimal distance from the bottom represents a "worst case" scenario, it is an index of risk that needs to be fully appreciated.

The racing starts during which the swimmers made contact with the bottom of the pool were categorized in several ways: age group, body part, stroke, and sex. This is depicted in Table 2. With regard to the number of times swimmers who contacted the pool bottom for the different age groups, it is important to note that there were no observed contacts by 8 & U swimmers. There are two possible reasons for this. First, swimmers within this age group do not enter the water with as much momentum as the older, larger swimmers. They have a smaller mass and cannot create as much force, so therefore they are not traveling as fast. Second, 8 & U swimmers are less skillful at performing starts and they typically enter the water less streamlined than more experienced swimmers, resulting in greater drag. The combination of the lack of experience, low speed, and less body mass makes it less likely for these swimmers to reach the bottom of the pool during a competitive start.

With respect to all contacts observed during the swim meet, this was the only discernible pattern. Qualitatively, it appeared as though a number of the swimmers who contacted the bottom did so deliberately. Our observation was that the swimmers who made contact with their hands appeared to reach toward the bottom, perhaps as a means of locating it during the start or cushioning the impact and then pushing off the bottom with their feet. Thus there were four cases in which the hands and feet touched the pool bottom. The majority of the other cases appeared to be as a result of the execution of a dolphin kick before the swim.

As this was the first study of which we are aware that rigorously analyzes the maximum depth of starts during a swimming competition, there were no values from the literature with which to directly compare. Our results suggested that age group and stroke had a significant effect on maximum head depth achieved during a competitive swim start. The data suggested older swimmers tended to go deeper than younger swimmers. We also showed that a small but important number of competitive starts into 1.22 m (4 ft) of water resulted in contact with the bottom of the pool during competition. Head depth during these starts did not differ from the noncontact starts, suggesting that catastrophic injuries were no more likely to occur in the contact starts than the noncontact starts. Furthermore, head speed at maximum head depth at the moment of contact was nearly zero in these "contact" cases.

Conclusion

Approximately 50% of all the starts analyzed showed a maximum head depth (maximum depth of the center of the head plus 0.15 m adjustment) within 0.5 m of the pool bottom. This fact, coupled with the observation that the head was traveling (at maximum head depth) at twice the pool depth (?2.4 ms^{-1}) in a second suggested that the margin of error for starts into 1.22 m (4 ft) water depth was small. The trend was for the older (and presumably heavier) swimmers to attain deeper starts with greater speeds, nearly all at speeds previously estimated to be consistent with serious neck and head trauma. What remains to be determined is whether swimmers competing in pools with greater water depths adjust the depth of their starts to accommodate the additional water as Blitvich et al. (2000) reported in a noncompetitive setting. The alternative view would be that when competing in shallow water, swimmers adjust their starts to accommodate less water. Either way, does head depth increase, or, more importantly, does head distance from the bottom increase if greater water depth is available? To answer these questions, additional assessments of competitive start depths in deeper pools are a necessary next step.

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References

Blanksby, B. A., Wearne, F.K., & Elliott, B.C. (1996). Safe depths for teaching children to dive. *The Australian Journal of Science and Medicine in Sport, 28*(3), 79-85.

Blitvich, J.D., McElroy, G.K., Blanksby, B.A., & Douglas, G.A. (1999). Characteristics of 'low risk' and 'high risk' dives by young adults: Risk reduction in spinal injuries. *Spinal Cord, 37*(8), 553–559.

Blitvich, J.D., McElroy, G.K., Blanksby, B.A., Clothier, P.J., & Pearson, C.T. (2000). Dive Depth and water depth in competitive swim starts. *Journal of Swimming Research, 14,* 33–39.

Counsilman, J., Nomura, T., Endo, M., & Counsilman, B. (1988). A study of three types of grab start for competitive swimming. *National Aquatics Journal, 4*(2), 2-6.

Gehlsen, G.M., & Wingfield, J. (1998). Biomechanical analysis of competitive swimming starts and spinal cord injuries. *Journal of Swimming Research, 13,* 23–30.

Green, B.A., Gabrielsen, M.A., Hall, W.J., & O'Heir, J. (1980). Analysis of swimming pool accidents resulting in spinal cord injury. *Paraplegia, 18,* 94–100.

Keppel, G., & Wickens, T.D. (2004). *Design and analysis: A researcher's handbook* (4th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Mueller, F.O., & Cantu, R.C. (2007). *Catastrophic sports injury research. Twenty-Fifth annual report: Fall 1982 to Spring 2007*. University of North Carolina at Chapel Hill: National Center for Catastrophic Sports Injury Research.

Swimming, U.S.A. (2009). *2009 USA Swimming Rules and Regulations*. Colorado Springs, CO: USA Swimming.

Viano, D.C., & Parenteau, C.S. (2008). Analysis of head impacts causing neck compression injury. *Traffic Injury Prevention, 9,* 144–152.

Welch, J., & Owens, V. (1986). Water depth requirements of competitive racing starts. *Journal of Swimming Research, 2*(3), 5–7.