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# Racing Start Safety: Head Depth and Head Speed During Competitive Swim Starts Into a Water Depth of 2.29 m

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The head depths and head speeds of swimmers attained following the execution of racing starts during competition have not been well described. To address this, 211 competitive starts were filmed into a starting depth of 2.29 m with a block height of 0.76 m. Starts were stratified according to age, sex, stroke, and swim meet. Dependent measures were maximum depth of the center of the head, head speed at maximum head depth, and distance from the wall at maximum head depth. Significant main effects existed for age for all three measures:  $F(1, 106) = 13.33, p < .001$ ,  $F(1, 106) = 18.60, p < .001$  and  $F(1, 106) = 70.59, p < .001$ , respectively. There was a significant age by sex interaction,  $F(1, 106) = 5.36, p = 0.023$ , for head speed. In conclusion, older swimmers performed starts that were deeper and faster than younger swimmers and nearly all starts exceeded the threshold speeds for injury. As compared to starts previously reported into 1.22 m, starts were deeper, slower, and farther from the starting wall at maximum head depth.

When catastrophic injuries have occurred in competitive swimming, they are virtually all associated with swimmers impacting the pool bottom following the execution of a racing start (Mueller & Cantu, 2007). These incidents primarily have occurred during practice or warm-up prior to a meet and usually have involved some additional contributing factor(s). The injuries that swimmers incurred upon impact were commonly related to hyperflexion, vertical compression, and/or hyperextension of the cervical vertebrae and, as is true for all other diving injuries, impact with the pool bottom often has resulted in para- or quadriplegia (Albrand & Walter, 1975). From the perspective of safety, the extent to which water depth represents a component of the cumulative risk contributing to the catastrophic injuries in competitive swimming remains unclear. Obviously, head velocity, body trajectory (a primary determinant of head depth), body inertia, and other factors contribute to the severity of injury. Very little is known, unfortunately, about swimmers' depths and velocities after the execution of typical racing starts into water depths meeting current regulatory requirements.

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Mean values from the literature for maximum depths following the execution of “noncompetition” racing starts range from 0.56 to 1.22 m and are reported to be dependent upon factors such as water depth, block height, start type, body landmark, and swimmer skill level (Blitvich, McElroy, Blanksby, & Douglas, 1999; Blitvich, McElroy, Blanksby, Clothier, & Pearson, 2000; Counsilman, Nomura, Endo, & Counsilman, 1988; Gehlsen & Wingfield, 1998; Welch & Owen, 1986). The first analysis of head depth and speed following racing starts *during competition* was, to the best of our knowledge, our study of competitive swimmers (5 years to 18 years;  $n = 471$ ) executing starts in a water depth of 1.22 m (Cornett, White, Wright, Willmott, & Stager, 2010). This pool depth is the minimum currently allowable for competition (USA Swimming, 2009). We reported mean values similar to the “noncompetition” data for maximum depth of the center of the head that range from 0.39 to 0.69 m, which was dependent upon the age group of the swimmers and the stroke performed during the first lap of the race. Our findings were (a) approximately 50% of all the starts analyzed showed a maximum depth of the center of the head within 0.5 m of the pool bottom, (b) older swimmers traveled deeper and faster than younger swimmers, (c) virtually all head speeds at maximum head depth exceeded those capable of resulting in catastrophic injuries, and (d) the deepest head depth measured was 1.09 m, which was 13 cm from the bottom of the pool (Cornett et al., 2010).

Previously, Blitvich et al. (2000) had assessed maximum head depth following the execution of simulated racing starts into two water depths (1.2 m and 2.0 m). The swimmers performed shallower starts (by 0.09 m) in shallower water without any measurable performance disadvantage. No instructions were given regarding start depth, although swimmers were aware of the difference in water depth. Nonetheless, the swimmers in their study made depth adjustments when presented with different water depths. Whether or not similar adjustments are made during actual competition remains to be determined.

The purpose of the present study was to describe, from the perspective of start safety, the important underwater characteristics of racing starts proposed to contribute to the severity of injury upon impact with the pool bottom. This information is critical in terms of determining minimum pool depth standards for competitive racing starts. Maximum depth of the head, head speed at maximum head depth, and distance from the starting wall at maximum head depth are the relevant measures when assessing the safety of racing starts and will be evaluated here. Comparisons among age groups, sex, and the competitive strokes will be made. These findings in 2.29 m (7.5 ft) will then be put into context by making comparisons with our previous results obtained from a competition in a shallower pool (1.22 m or 4.0 ft).

## Method

The study took place during two USA Swimming sanctioned meets in the same natatorium in central Indiana: a combined age group and open invitational swim meet (referred to as “open invitational”) and a regional championship meet (referred to as “regional championship”). These two competitive meets were chosen so as to be able to collect data from a broader range of ages and technical abilities without potential differences occurring in the results due to the venue and/or the starting

block design. The competitive facility consisted of an eight lane pool with a starting end depth of 2.29 m (7.5 ft). Starting platforms were standard 0.76 m (30 in) blocks mounted in each lane. A separate diving well was available for swimmers to warm-up and cool-down. The project was previously approved by the university's Human Subjects Committee. Because filming was considered to be "in the public domain" and swimmers' identities were neither recorded nor otherwise obtained, no consent was required from participants.

## Participants

The participants in this study were USA Swimming registered competitive swimmers ranging in age from 6 to 22 years. The regional championship had minimal time standards, while the open invitation did not and as a result, swimmers represented a wide range of skill levels. A total of 99 male and 112 female starts were included within the 211 starts.

Due to required underwater camera positions, only starts performed in lanes four and five were filmed. 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 are likely to be the most skilled performers, meaning that for each heat, the starts of lesser skilled swimmers were not being recorded. Further, the institutional review board prohibited us from knowing the identity of any 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 they participated in more than one event and started multiple times from either lane four or five. Two hundred starts provided useable images for analysis with about 5% of all starts filmed providing nonuseable images because of an obstructed view of anatomic landmarks.

## 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 underwater. For each heat, the underwater portion of the racing start in lanes four and five was recorded using a two-camera system. The start type utilized 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 housing 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 (98.25 ft) and enabled both video signals to be input directly to a single laptop computer (M675, Gateway Inc., Irvine, CA) at the poolside. Video data 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 (39.3 in × 39.3 in × 117.9 in). It was constructed from marine aluminum and painted black. Eighty-four bright yellow closed-cell foam marker balls (0.05 m or 1.97 in 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. Additionally, 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

For each start, the center of the subject's head was digitized from the first recognizable point of entry (below the water surface) through to the maximum depth achieved. It was determined that the completion of digitization took place when the subject's head displayed movement upward vertically toward the surface. This instant was estimated visually by the experimenter, and an additional 10 frames were digitized to make certain that the maximum depth of the center of the head had been recorded. Using the appropriate calibration for the lane, the 3-D coordinates of the head were transformed into the pool-based reference frame for that lane. In addition, the center of the knee and the tips of the fingers and toes were digitized in the same manner as described for the center of the head.

As mentioned previously, data were collected during two different swim meets at the same pool: (a) an open invitational and (b) a regional championship. The three dependent measures of interest at both meets were maximum depth of the center of the head, head speed at maximum head depth, and distance from the wall at maximum head depth. There are a few important points to be made about the dependent measures. First, Blitvich et al. (2000) suggest that the "maximum depth of the center of the head" could underestimate "maximum head depth" by as much as 0.15 m (5.9 in) because the external auditory meatus is approximately 0.15 m from the external surfaces of the head. We report and refer to our measure

as “maximum depth of the center of the head” and will add 0.15 m to our values (maximum head depth = maximum depth of the center of the head + 0.15 m) when making comparisons with the literature reporting “maximum head depth.” Second, we include distance from the wall at maximum head depth as a dependent measure in our analysis because it has been used in some of the more recent literature pertaining to start safety (Blitvich et al., 1999; Blitvich et al., 2000) and because it is an important safety consideration given that pool bottoms are frequently sloped.

The starts from the open invitational were stratified by age group, sex, and stroke. As is customary, the swimmers were grouped during competition into five age groups: 8 years and under (8&U), 9 to 10 years (9–10), 11 to 12 years (11–12), 13 to 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 filmed and analyzed but not included in this project, because when doing a backstroke start, swimmers do not enter the pool from the top of the starting block. Due to technical limitations at this meet (camera battery limits and necessary calibration time), we were unable to collect data during all competitive sessions for each of these age groups. Filming and analysis was thus limited to the younger (8&U, 9–10) and older (15&O) age groups. After running an initial analysis comparing the dependent measures and finding no difference between 8&U and 9–10, we pooled them into one group of swimmers aged 10 yrs and under (10&U) for comparisons with the 15&O swimmers.

In contrast to the open invitational, there were no chronologic age groupings at the regional championship. There were minimum time standards that needed to be achieved in order for a swimmer to be accepted into the meet. As a result, the meet consisted almost exclusively of swimmers older than 15 yrs (15&O), which excluded age group as an independent variable. Starts were still stratified by sex and stroke at this second meet.

The data from the open invitational were analyzed using a three-way (age group by sex by stroke) factorial analysis of variance (ANOVA). 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 test revealed significant interactions, simple effects analyses were conducted using methods previously established (Keppel & Wickens, 2004). For all analyses reported below, an alpha level equal to or less than 0.05 was used to determine statistical significance.

The purpose of filming at the regional championship was to verify the results at the open invitational and to explore possible differences due to competitive level. In order to do so, the results from the regional championship were compared with the 15&O results from the open invitational. Because the literature indicates that factors such as age and stroke can affect maximum depth of the center of the head, head speed at maximum head depth, and distance from the wall at maximum head depth, we matched starts from the two meets in order to obtain samples with equal ages, sexes, and strokes. For every start used from the open invitational, a corresponding start from the regional championship was randomly selected in which the swimmers performing the starts had the same age and sex and competed in a race with the same competitive stroke. A three-way (meet by sex by stroke) ANOVA was conducted to analyze the resulting data set.

## Results

Swimmers used two start types: track (87.7%) and grab (12.3%). Two of the track starts were performed from the side of the pool rather than the starting block. The mean age of the swimmers whose starts were included in the analyses at the open invitational within the 10&U was  $9.2 \pm 1.1$  yr ( $n = 62$  starts; 38 from girls and 24 from boys) while the mean age of the swimmers whose starts were included within the 15&O at this meet was  $17.1 \pm 2.0$  yr ( $n = 56$  starts; 31 from girls and 25 from boys). The group means for maximum depth of the center of the head, head speed at maximum head depth, and distance from the wall at maximum head depth and the range of values for maximum depth of the center of the head are provided in Table 1.

The three-way (age group by sex by stroke) ANOVA for maximum depth of the center of the head showed a significant main effect for age group,  $F(1, 106) =$

**Table 1** Maximum Depth of the Center of the Head (m), Head Speed at Maximum Head Depth ( $\text{ms}^{-1}$ ), and Distance From the Wall at Maximum Head Depth (m) for Racing Starts Performed in Competition in a Water Depth of 2.29 m

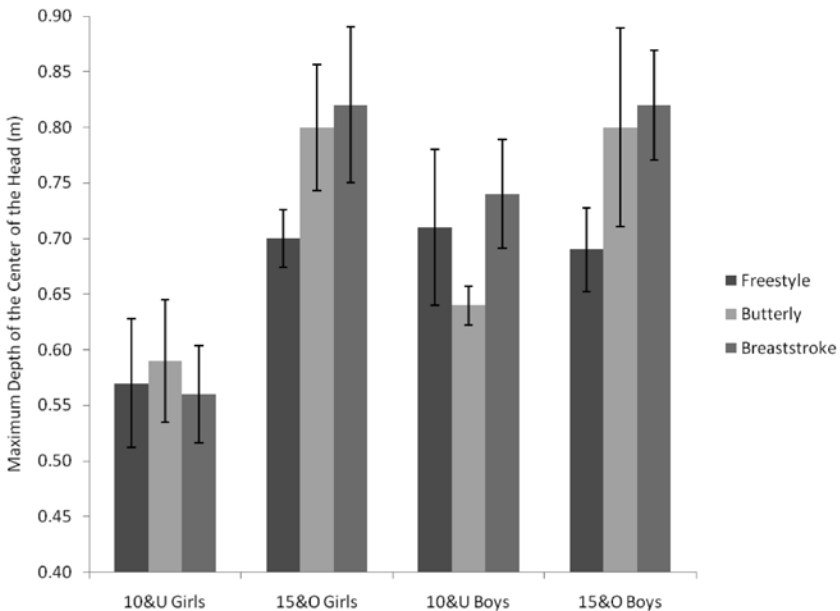
Age Group	Sex	Stroke	<i>n</i>	Maximum Depth of the Center of the Head (m)		Head Speed at Max. Head Depth ( $\text{ms}^{-1}$ )	Distance at Max. Head Depth (m)
				Mean	Range		
10&U	Girls	Freestyle	17	$0.57 \pm 0.24$	0.30–1.29	$2.13 \pm 0.62$	$3.51 \pm 0.92$
		Butterfly	4	$0.59 \pm 0.11$	0.49–0.69	$2.39 \pm 0.62$	$4.12 \pm 0.90$
		Breast-stroke	17	$0.56 \pm 0.18$	0.23–0.91	$1.96 \pm 0.53$	$4.01 \pm 0.81$
	Boys	Freestyle	9	$0.71 \pm 0.21$	0.44–1.07	$2.18 \pm 0.73$	$3.73 \pm 0.48$
		Butterfly	3	$0.64 \pm 0.03$	0.62–0.67	$1.65 \pm 0.23$	$4.63 \pm 0.45$
		Breast-stroke	12	$0.74 \pm 0.17$	0.54–1.09	$1.60 \pm 0.62$	$4.15 \pm 0.80$
15&O	Girls	Freestyle	15	$0.70 \pm 0.10$	0.49–0.86	$2.73 \pm 0.66$	$4.62 \pm 0.54$
		Butterfly	7	$0.80 \pm 0.15$	0.62–1.10	$2.45 \pm 0.41$	$4.95 \pm 0.50$
		Breast-stroke	9	$0.82 \pm 0.21$	0.61–1.29	$2.07 \pm 0.54$	$5.39 \pm 0.63$
	Boys	Freestyle	12	$0.69 \pm 0.13$	0.48–0.93	$3.24 \pm 0.57$	$4.93 \pm 0.65$
		Butterfly	5	$0.80 \pm 0.20$	0.59–1.06	$2.41 \pm 0.71$	$5.83 \pm 0.65$
		Breast-stroke	8	$0.82 \pm 0.14$	0.64–1.00	$2.32 \pm 0.67$	$6.02 \pm 0.59$

*Note.* Values are means  $\pm$  standard deviation. Values for the range are minimum and maximum, respectively. All values are measured at the center of the head.

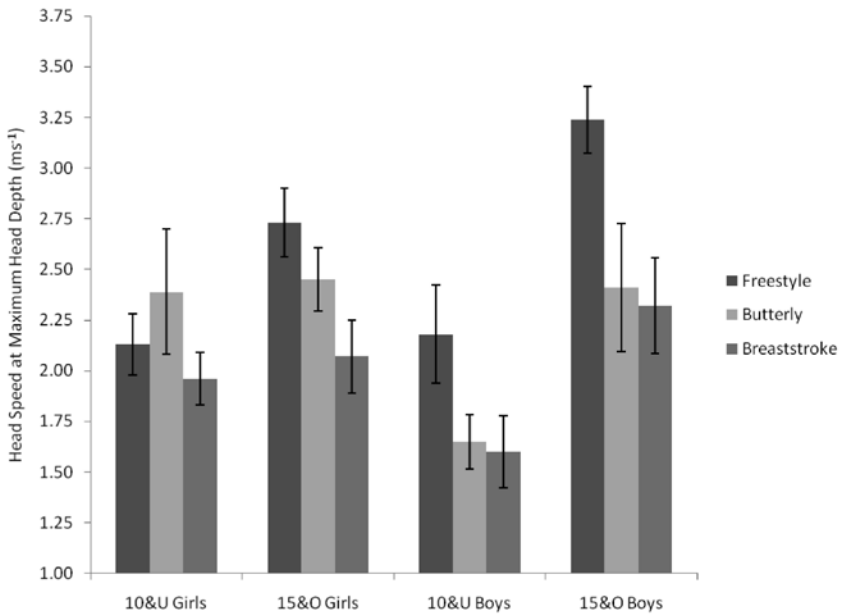
13.33,  $p < .001$ ,  $\eta^2 = 0.10$ , which indicated that maximum depth of the center of the head was significantly greater for 15&O starts than for 10&U starts (Figure 1).

The analyses for head speed at maximum head depth revealed a significant main effect for age group,  $F(1, 106) = 18.60$ ,  $p < 0.001$ ,  $\eta^2 = 0.11$ , which indicated that head speed at maximum depth is greater for 15&O than for 10&U starts. There was also a significant main effect for stroke,  $F(2, 106) = 10.79$ ,  $p < .001$ ,  $\eta^2 = 0.13$ . The pairwise comparisons for stroke showed that head speed at maximum head depth was significantly greater for freestyle and butterfly than breaststroke ( $p < .001$ ). Finally, there was a significant interaction between age group and sex:  $F(1, 106) = 5.36$ ,  $p = 0.023$ ,  $\eta^2 = 0.03$ . Simple effects analysis showed that 15&O boys and girls had significantly greater head speed at maximum head depth than their 10&U counterparts (Boys:  $t_{(47)} = 4.69$ ,  $p < 0.001$ ; Girls:  $t_{(67)} = 2.70$ ,  $p = 0.009$ ). The difference between 15&O and 10&U boys ( $0.96 \text{ ms}^{-1}$ ) was more than twice the difference between 15&O and 10&U girls ( $0.39 \text{ ms}^{-1}$ ; Figure 2).

The three-way ANOVA for distance from the wall at maximum head depth revealed a significant main effect for age group,  $F(1, 106) = 70.59$ ,  $p < .001$ ,  $\eta^2 = 0.30$ , which indicated that distance at maximum head depth was greater for 15&O than 10&U starts. There was also a significant main effect for stroke:  $F(2, 106) = 12.94$ ,  $p < 0.001$ ,  $\eta^2 = 0.11$ . The pairwise comparisons for stroke showed that distance at maximum head depth was significantly greater for butterfly and



**Figure 1** — Maximum depth of the center of the head (m) as a function of age group, sex, and stroke following the execution of racing starts in competition. Water depth at the starting end of the pool was 2.29 m. A significant main effect for age group ( $p < 0.05$ ) was evident indicating that starts for 15&O were deeper than for 10&U. Error bars represent one standard error.



**Figure 2** — Head speed at maximum head depth ( $\text{ms}^{-1}$ ) as a function of age group, sex, and stroke following the execution of racing starts in competition. Water depth at the starting end of the pool was 2.29 m. There were significant main effects for age group and stroke ( $p < 0.05$ ), indicating that head speed was greater for 15&O than 10&U starts and for freestyle and butterfly than breaststroke. There was also a significant age group by sex interaction ( $p < 0.05$ ). Error bars represent one standard error.

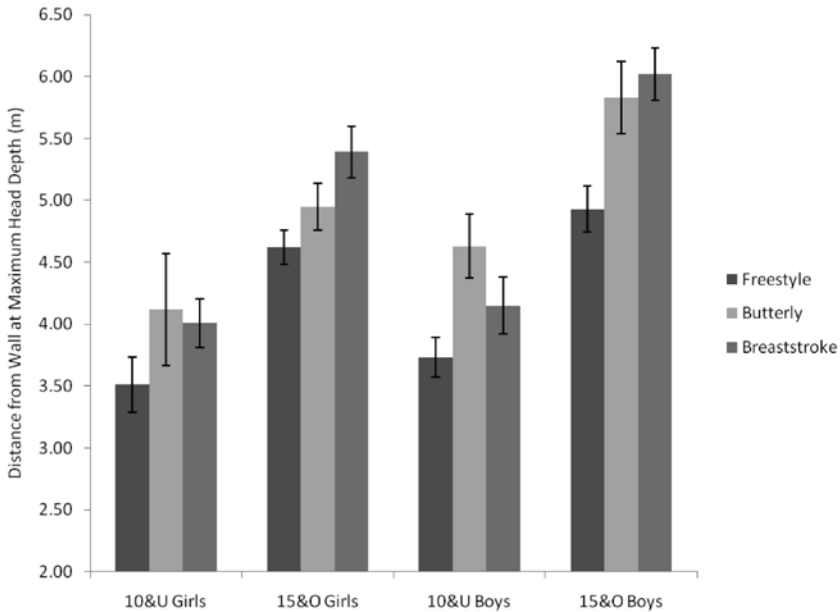
breaststroke than for freestyle ( $p < 0.001$ ). Finally, there was a significant main effect for sex,  $F(1,106) = 8.81$ ,  $p = 0.004$ , which indicated that distance at maximum head depth was greater for males than females (Figures 3).

When comparing the open invitational with the regional championship, there were no significant main effects identified with respect to the meet filmed for maximum depth of the center of the head and speed at maximum head depth. There was a meet main effect for distance at maximum head depth,  $F(1,50) = 12.67$ ,  $p = 0.001$ ,  $\eta^2 = 0.13$ , where the swimmers at the regional championship meet attained a shorter distance at maximum head depth than swimmers at the open invitational: 4.50 m (14.5 ft) vs. 5.14 m (16.8 ft), respectively.

## Discussion

From the perspective of safety, the primary objective of the present study was to describe the maximum depth of the center of the head, head speed at maximum head depth, and distance from the starting wall at maximum head depth of swimmers who are executing racing starts during competition into a water depth of 2.29 m. There is very little literature currently available describing these variables





**Figure 3** — Distance from the wall at maximum head depth (m) as a function of age group, sex, and stroke following the execution of racing starts in competition. Water depth at the starting end of the pool was 2.29 m. There were significant main effects for age group, sex, and stroke ( $p < 0.05$ ), which indicated that distance from wall was greater for 15&O than 10&U, boys than girls, and butterfly and breaststroke than freestyle. Error bars represent one standard error.

obtained during the execution of racing starts and none, to our knowledge, that have assessed starts underwater during competition in this water depth. The most important statistical findings of the present study included differences in maximum depth of the center of the head and head speed at maximum head depth between swimmers of different ages.

## Competition in 2.29 m of Water

**Maximum Depth of the Center of the Head.** Once again, from the perspective of safety, the maximum depth of the center of the head is perhaps the most relevant variable. The literature is relatively incomplete as far as comparable values for head depth among swimmers following racing starts, but there are a few studies with which legitimate comparisons can be made. In the first of these, while they do not report maximum head depth per se, Counsilman et al. (1988) reported a maximum “body depth” of 0.70 m after the execution of a “track start.” Their values were obtained via filmed images of 121 girl and boy swimmers (ages ranged from 10 to 17 yrs) attending a summer stroke camp. We calculated and reported a body depth value of 0.84 m when the maximum depth of the hands, head, knees, and toes are

averaged for 15&O swimmers executing freestyle starts in competition. Our value is significantly deeper ( $p < 0.05$  using an independent sample t-test) than the value from Counsilman et al. (1988). This may be due to a difference in age or it may reflect a difference in technique employed by the swimmers in the two studies which were separated by almost 20 years.

Welch and Owens (1986) report maximum depth of the center of the head for thirty swimmers (12 collegiate women and 18 collegiate men) as being 0.68 m (2.23 ft) following the execution of a “conventional (flat) start” into 3.8 meters (12.45 ft) of water. This value for maximum depth of the center of the head (0.68 m) compares closely to our “freestyle only” value (0.70 m) for 15&O swimmers in the open invitational. It is important to note that this comparison is subjective on our part in that we could not conduct statistical inference because Welch and Owen (1986) did not provide variances for their data.

Blitvich et al. (1999) measured maximum depth of the center of the head for 95 first year university students who executed a start from a standard block into 2.0 m (6.55 ft) pool depth. Their value of 0.64 m in this investigation was not significantly different from our value of 0.70 m ( $p > 0.05$ ; independent samples t-test) despite differences in the competitive skill levels of the athletes in the two studies. Blitvich et al. (2000) report maximum head depths in water depth of 2.0 m as being 0.88 m (2.88 ft) for 36 elite junior swimmers (mean age = 15.3 yr). They added 0.15 m to the depth of each dive because they propose that the maximum depth of the center of the head underestimates maximum head depth by as much as 0.15 m because the external auditory meatus (the anatomical landmark for the center of the head) is approximately this distance to the actual deepest point of the head. When we add the same adjustment to our values for depth of the center of the head, there is not a significant difference ( $p > 0.05$ ; independent samples t-test) between their value (0.88 m) and the value we report (0.85 m) for 15&O freestyle starts in the open invitational. We were unable to find any additional values that would allow appropriate comparisons to be made regarding younger-aged swimmers, shallower or deeper water, and/or other competitive strokes.

**Head Speed at Maximum Head Depth.** The discussion pertaining to head speed at maximum head depth is limited by similar constraints. Only two comparisons with existent literature were appropriate. 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 earlier of these two reports (Blitvich et al., 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  $2.55 \pm 0.64 \text{ ms}^{-1}$ . In the second report (Blitvich et al., 2000), 36 elite junior swimmers executed a start from a standard block into 2.0 m of water with a reported head speed at maximum head depth of  $2.47 \pm 0.36 \text{ ms}^{-1}$ . Our value ( $2.96 \pm 0.66 \text{ ms}^{-1}$ ) for the oldest group of swimmers (15&O) in the open invitational competing in freestyle was significantly greater than the values from both Blitvich et al. reports ( $p < 0.05$ ; independent sample t-test). Our subjects (competitive swimmers) were more skilled than the university students filmed by Blitvich et al. (1999) and were significantly older ( $p < 0.05$ ; 17.1 yr vs. 15.3 yr) than the elite junior swimmers of Blitvich et al. (2000). These factors presumably contribute to greater forces generated from the block and the skill to maintain the resultant speed once in the water.

**Distance From Starting Wall at Maximum Head Depth.** Blitvich et al. (1999) concluded that the horizontal distance traveled underwater at maximum head depth was the best predictor of maximum depth of the center of the head. The best comparison with the results of the present study is, once again, Blitvich et al. (2000). Their value for distance from the wall at maximum head depth in 2.0 m pool depth was  $5.01 \pm 0.61$  m and was not significantly different ( $p > 0.05$ ; independent sample t-test) from our value ( $4.76 \pm 0.60$  m).

**Age Differences.** Within the current data, we identified statistically significant differences between the age groups for all three of the dependent variables. The older swimmers performed starts that were 0.13 m deeper than the younger swimmers. We previously reported similar differences in head depth (0.60 m for 15&O vs. 0.53 m for 10&U) following starts performed in shallower water (1.22 m; Cornett et al., 2010). We also reported head speed for these swimmers to be  $0.82 \text{ ms}^{-1}$  greater for the older swimmers than those for younger swimmers (10&U), a finding similar to that reported in the present study ( $0.63 \text{ ms}^{-1}$  greater in the older swimmers as compared to the younger swimmers). In either case, we cannot know why head depth and head speed were greater in the older swimmers as compared to the younger swimmers. We would speculate that the older swimmers chose to go deeper and that greater head depth was not predetermined by age, size, or experience alone. Head speed, however, may be a function of the interaction among body size, body mass, and the ability to generate greater forces off the block while limiting resistive forces once in the water. Given the present findings, we concluded that from the perspective of safety and risk, competitive starts represent greater risk to the older swimmers as compared to the younger swimmers because of their greater depth and speed.

**Sex Differences.** The literature pertaining to start depths does not address sex differences to any real extent. Counsilman et al. (1988) report separate data for girls and boys but did not run any statistical analytic comparisons. Our analysis (using independent sample t-tests) of their “body depth” data revealed that boys went significantly deeper ( $p < 0.05$ ) than girls for the scoop and flat start, but boys and girls were not significantly different for the track start which is more typical of contemporary starts and the start type utilized for 87.7% of the starts analyzed in this study. In a previous report, we analyzed 471 starts at an open age group invitational in a 1.22 m pool (Cornett et al., 2010). We conducted all statistical analyses with the sexes pooled in this previous report because there were no differences between boys and girls for maximum depth of the center of the head, head speed at maximum head depth, or distance from the wall at maximum head depth for any of the five age groups (8&U, 9–10, 11–12, 13–14, or 15&O; Cornett et al., 2010). The present analysis was similar to the data collected in 1.22 m in that there was not a significant effect for sex for maximum depth of the center of the head. We did detect a significant age group by sex interaction for head speed at maximum head depth.

There is a greater difference in head speed at maximum head depth between the two age groups of boys than the two age groups of girls ( $0.96 \text{ ms}^{-1}$  vs.  $0.39 \text{ ms}^{-1}$ , boys and girls, respectively) even though the boys and girls collectively had similar head speeds. There are likely to be bigger differences in body size (weight and height) between the younger and older boys than between the younger and older girls (Buckler & Wild, 1987). Finally, we found a significant main effect for

sex for distance from the wall which post hoc comparisons indicated that distance was greater for boys than girls. The findings with respect to sex for head speed and distance from the wall are novel. We have not been able to find any previous studies that made sex comparisons. The reason for the differences between the sexes is left to speculation. Maximum depth of the center of the head, it can be argued, is determined by the athlete while speed and distance may be, at least in part, determined by inertia induced by body size (and thus correlate with sex and age). Bigger swimmers (heavier and taller) probably retain more momentum, are moving faster, and are farther from the wall at maximum head depth. From the perspective of safety, collectively, the girls and boys were at equal risk given similar head depths and head speeds in this water depth.

**Meet Differences.** In the current study we were able to compare similarly-aged athletes in the same facility at potentially different competitive levels. Participation in the open invitational was not limited by performance standards or prior-achieved qualification times. The second competition required meeting strict time standards and was a regional championship event. A “meet” main effect for distance at maximum head depth,  $F(1,50) = 12.67$ ,  $p = 0.001$ ,  $\eta^2 = 0.13$ , was identified whereby the swimmers at the regional championship meet attained a shorter distance at maximum head depth than swimmers at the open invitational. No other statistical differences were evident. Although the regional championship meet had time standards, we can not necessarily conclude that there was a higher skill or experience level at this meet, although we presume there was. Regardless of this, from the perspective of safety, maximum depth of the center of the head and head speed did not appear to be influenced by any differences related to better or worse swim performance.

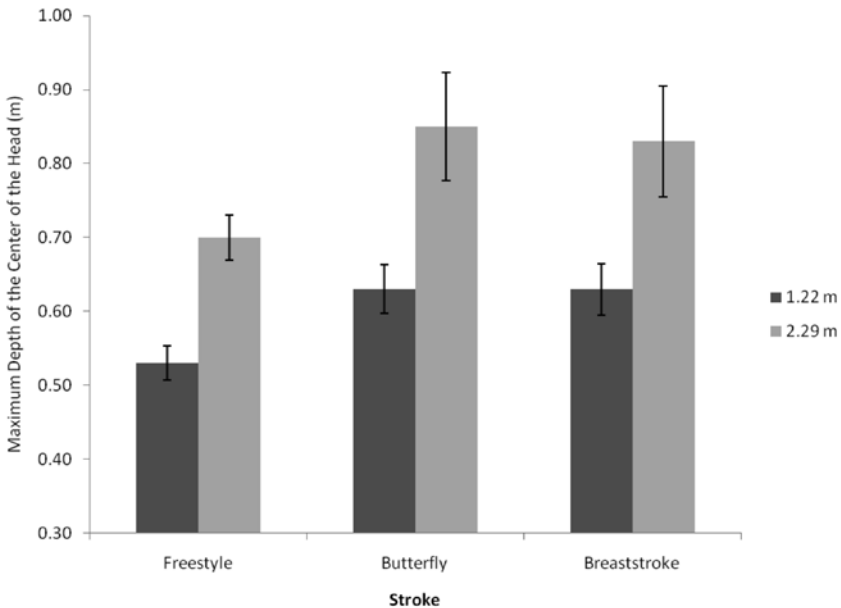
## Competition in 2.29 m vs. 1.22 m of Water

The “start study” authored by Blitvich et al. (2000) compared the maximum head depths achieved by 36 elite junior swimmers following the execution of a racing start into pool depths of 1.2 m (3.94 ft) and 2.0 m (6.56 ft). Maximum head depths achieved differed by 0.09 m (3.5 in) with the shallower pool resulting in shallower starts (1.2 m pool depth, 0.79 m; 2.0 m pool depth, 0.88 m). They also found that distance from the wall at maximum head depth decreased in shallower pools (1.2 m pool depth, 4.72 m; 2.0 m pool depth, 5.01 m). The study presents important information regarding the differences in start depths attained as a function of water depth.

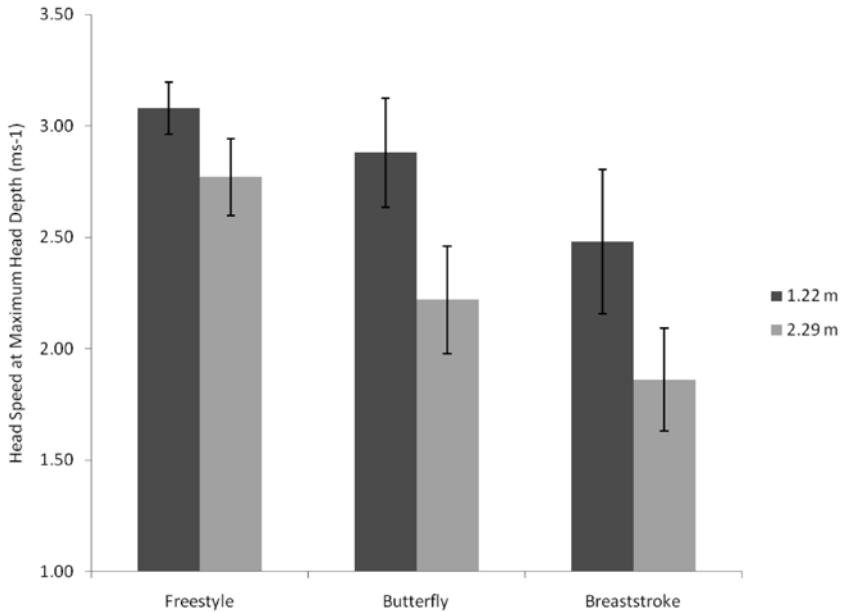
In order to make comparisons similar to those made by Blitvich et al. (2000) we matched 15&O subjects from our previous report (Cornett et al., 2010; starts executed in a pool depth of 1.22 m) with similarly aged subjects from the present study. Each start selected from the data in 1.22 m was randomly matched with a start from the present data in which the swimmers were of the same age and sex competing in the same competitive stroke (see methods). We then ran three-way (meet by sex by stroke) ANOVAs for each of the dependent measures: maximum depth of the center of the head, head speed at maximum head depth, and head distance at maximum head depth. The analysis showed a significant main effect for meet for all three dependent measures, indicating that starts in 2.29 m had deeper

maximum depth of the center of the head,  $F(1,38) = 23.18$ ,  $p < 0.001$ ,  $\eta^2 = 0.27$ ; slower head speed at maximum head depth,  $F(1,38) = 8.01$ ,  $p = 0.007$ ,  $\eta^2 = 0.12$ ; and greater distance at maximum head depth,  $F(1,38) = 16.48$ ,  $p < 0.001$ ,  $\eta^2 = 0.19$  than in 1.22 m (Figures 4-6 and Table 2).

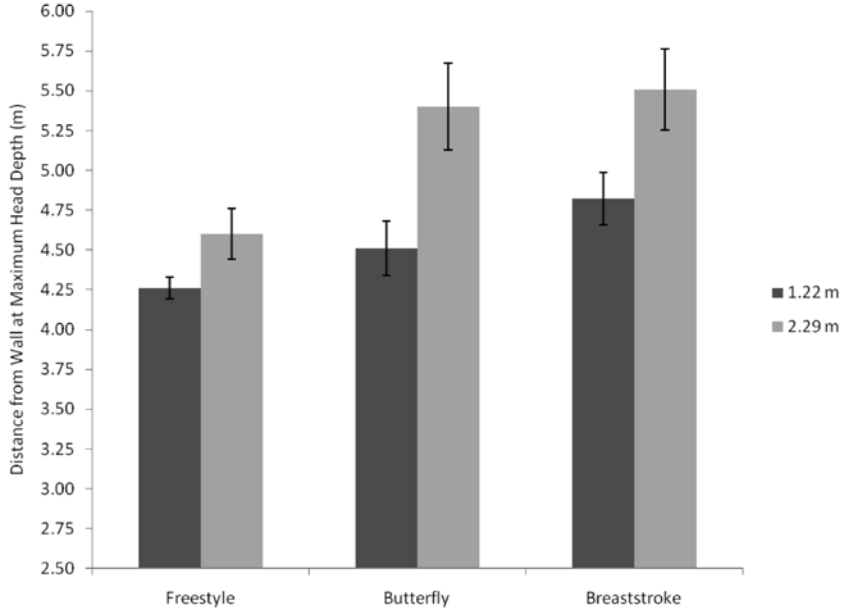
We found head speed at maximum head depth to be faster in the shallower pool (1.22 m pool depth,  $2.93 \text{ ms}^{-1}$ ; 2.29 m pool depth,  $2.49 \text{ ms}^{-1}$ ). This is an appropriate finding as the swimmers presumably traveled through less water both vertically and horizontally in the shallower pool and therefore lost less momentum due to the lower drag forces of the water on the body; however, Blitvich et al. (2000) did not find a difference in head speed at maximum head depth between the two pool depths. Important differences between the two studies are (a) less depth differences between the two trials, (b) the elite nature of their athletes compared to ours, and (c) the noncompetition vs. competition environment. We recognize that to really be able to make the comparison between starts in pools of different depths, the performances of the swimmers in both competitions should be comparable. While we are unable to confirm this, our conclusions are similar to theirs: swimmers adjust start depth as a function of pool water depth essentially without “instruction.”



**Figure 4** — Maximum depth of the center of the head (m) as a function of pool depth and stroke at swim competitions with water depth of 1.22 and 2.29 m. There were significant main effects for meet and stroke ( $p < 0.05$ ), indicating that maximum head depth was deeper for starts in 2.29 m than 1.22 m and for butterfly and breaststroke than freestyle. Error bars represent one standard error.



**Figure 5** — Head speed at maximum head depth ( $\text{ms}^{-1}$ ) as a function of pool depth and stroke at swim competitions with water depth of 1.22 and 2.29 m. There were significant main effects for meet and stroke ( $p < 0.05$ ), indicating that head speed was faster for starts in 1.22 m than 2.29 m and for freestyle than breaststroke. Error bars represent one standard error.



**Figure 6** — Distance from the wall at maximum head depth (m) as a function of pool depth and stroke at swim competitions with water depth of 1.22 and 2.29 m. There were significant main effects for meet and stroke ( $p < 0.05$ ), indicating that distance from the wall was greater for starts in 2.29 m than 1.22 m and for butterfly and breaststroke than freestyle. Error bars represent one standard error.

**Table 2 Maximum Depth of the Center of the Head (m), Head Speed at Maximum Head Depth ( $\text{ms}^{-1}$ ), and Distance From the Wall at Maximum Head Depth (m) at Swim Competitions With Water Depth of 1.22 and 2.29 m**

Pool Depth (m)	Stroke	Maximum Depth of Center of Head (m)	Speed at Maximum Head Depth ( $\text{ms}^{-1}$ )	Distance at Maximum Head Depth (m)
1.22	Freestyle	0.53 $\pm$ 0.09	3.08 $\pm$ 0.46	4.26 $\pm$ 0.27
	Butterfly	0.63 $\pm$ 0.08	2.88 $\pm$ 0.60	4.51 $\pm$ 0.42
	Breaststroke	0.63 $\pm$ 0.07	2.48 $\pm$ 0.65	4.82 $\pm$ 0.33
2.29	Freestyle	0.70 $\pm$ 0.12	2.77 $\pm$ 0.67	4.60 $\pm$ 0.62
	Butterfly	0.85 $\pm$ 0.18	2.22 $\pm$ 0.59	5.40 $\pm$ 0.67
	Breaststroke	0.83 $\pm$ 0.15	1.86 $\pm$ 0.46	5.51 $\pm$ 0.51

*Note.* Values are means  $\pm$  standard deviation.

## Pool Safety

The secondary purpose of this research was to provide information that will help decide the minimum safe water depths required for the execution of racing starts during competition. There are few reports available on the frequency of swimmers attaining various depths following a racing start. Counsilman et al. (1988) relate that 88% of their subjects went deeper than 0.94 m (3.1 ft) and 10% went deeper than 1.37 m (4.5 ft) when swimmers were asked to complete a “scoop” start. This analysis was performed on noncompetitive starts performed in a 4.88 m diving well. Gehlsen and Wingfield (1998) report that none of the swimmers they filmed while performing starts in a 4 m deep pool “went deeper than 1.4 m (4.6 ft)” and conclude minimum water depth should be at least that deep. Blanksby, Wearne, and Elliot (1996) reported that the percentage of semiskilled children in a preliminary swimming program who reached depths greater than 1.00 m (3.3 ft), 1.20 m (3.94 ft), and 1.52 m (5.0 ft) while executing a block dive into 1.8 m of water were 42%, 27%, and 3.5%, respectively. They recommend depths deeper than 1.5 m for children learning to execute “block dives” and “further scrutiny” for the regulation that allows racing starts to be performed in water depth of 1.2 m. Our comparable results are found in Table 3. Of particular note is the fact that nearly 3% of all starts and more than 4% of 15&O starts in the regional championship exceeded a maximum depth of the center of the head of 1.2 m.

In terms of impact velocity, the literature pertaining to the velocity capable of causing spinal injuries includes the following values: 0.60  $\text{ms}^{-1}$  (sufficient momentum to dislocate the adult cervical spine; Stone, 1981 from Blanksby, Wearne, & Elliott, 1996), 1.20  $\text{ms}^{-1}$  (sufficient momentum to crush the cervical spine; Stone, 1981 from Blanksby et al., 1996), 1.90  $\text{ms}^{-1}$  (15% risk of serious neck and head

injury; Viano & Parenteau, 2008), and  $3.40 \text{ ms}^{-1}$  (50% risk of serious neck and head injury; Viano & Parenteau, 2008). Our data for these thresholds are shown in Table 4. The point to be made is that nearly all (>99%) of the starts filmed resulted in head speeds in excess of that suggested as capable of resulting in serious neck injury and four out of five starts filmed present a measurable risk of serious neck or head trauma ( $> 1.9 \text{ ms}^{-1}$ ) if an impact was to occur. It is important to point out here that none of our values are for vertical velocity. At maximum head depth, the swimmer is traveling in the horizontal plane and is about to move back toward the water surface. Nevertheless, head speed at maximum head depth represents a risk “potential” value, an estimate of the head speed possible if the athlete had continued toward the pool bottom.

**Table 3 Proportion of Racing Starts Executed in 2.29 m During Competition With Maximum Depth of the Center of the Head Greater Than Minimum Recommended Water Depths**

Group	% > 1.00 m <sup>a</sup>	% > 1.20 m <sup>a</sup>	% > 1.52 m <sup>b</sup>
10&U Open Invitational	6.5	1.6	0
15&O Open Invitational	7.1	1.8	0
15&O Regional Championship	15.1	4.3	0
Combined	10.4	2.8	0

*Note.* Values are percentages of starts with maximum depth of the center of the head greater than proposed minimum recommended water depths from (a) Werner (1994) and (b) American Red Cross (1992) as cited by Blanksby et al. (1996).

**Table 4 Proportion of Starts Executed in 2.29 m During Competition With Head Speed at Maximum Head Depth Greater Than Proposed Thresholds for Head and Neck Trauma**

Group	% > $3.4 \text{ ms}^{-1a}$	% > $1.9 \text{ ms}^{-1a}$	% > $1.2 \text{ ms}^{-1b}$	% > $0.6 \text{ ms}^{-1b}$
10&U Open Invitational	0	50.0	91.9	98.4
15&O Open Invitational	12.5	85.7	100	100
15&O Regional Championship	21.5	96.8	100	100
Combined	12.8	80.1	97.6	99.5

*Note.* Values are percentages of starts with head speeds at maximum head depth greater than proposed thresholds for head and neck trauma from (a) Viano and Parenteau (2008) and (b) Stone (1981) as cited by Blanksby et al. (1996).



## Conclusion

From the perspective of racing start safety, the first conclusion from the present study would be that in 2.29 m of water, only a very small percentage of swimmers (2.8%) approach within one meter of the pool bottom and none come within 0.50 m from the pool bottom. This is in contrast to our earlier findings filmed in 1.22 m of water where nearly half of the swimmers were within 0.5 m of the pool bottom at maximum head depth. Our second conclusion is that older swimmers are potentially at greater risk than younger swimmers during the execution of competitive racing starts because they consistently attain deeper head depths and greater head speeds. The trajectory of the head, the velocity of the head, and the inertial forces related to speed and body size were clearly contributing variables to the potential for injury. It would appear that greater head speed upon impact and the greater mass of the older swimmers are added factors that put older, larger swimmers at greater risk. In terms of the causes of these differences, we hypothesize that the older swimmers go deeper because they allow themselves to do so while head speed may be more a function of size and mass. In addition, start skill and start proficiency are likely to be contributing factors. Additional measurements of body size (e.g., mass, height) are needed before specific conclusions about their relative importance can be drawn.

Comparisons made between our current data and the data previously-collected in 1.22 m (4.0 ft) indicate that swimmers in competition adjust to pool depth by executing shallower dives in shallower water. This is true regardless of age group, sex, or swim stroke. Because maximum depth of the center of the head is less in 1.22 m, head speed is greater at maximum head depth, a finding that seems initially contradictory; however, the longer the start travel distance underwater, the greater are the cumulative resistive forces causing negative acceleration of the swimmer. Nevertheless, because virtually all analyzed starts (in the present study as well as in our earlier research) resulted in head speeds capable of causing catastrophic injury, head depth relative to water depth appears to be the more important of the two variables. We are in agreement with Blanksby et al. (1996) who suggest that regulations that allow 1.2 m minimum water depth under starting blocks need to be reviewed as the margin of error is small at these speeds and at this depth. While we know that swimmers can make depth adjustments during racing starts, what we do not yet know is how reliably they do so. In other words, we can now conclude that, statistically speaking, swimmers can and do adjust the depth of their starts. But, as individuals, how consistently do they make these depth adjustments? This would seem to be an important initial criterion for allowing a novice swimmer to execute a racing start from a standard starting block during competition in shallow water.

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