International Journal of Aquatic Research and Education, 2011, 5, 32-41

Water Depth Influences the Head Depth of Competitive Racing Starts

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Recent research suggests that swimmers perform deeper starts in deeper water (Blitvich, McElroy, Blanksby, Clothier, & Pearson, 2000; Cornett, White, Wright, Willmott, & Stager, 2011). To provide additional information relevant to the depth adjustments swimmers make as a function of water depth and the validity of values reported in prior literature, 11 collegiate swimmers were asked to execute racing starts in three water depths (1.53 m, 2.14 m, and 3.66 m). One-way repeated measures ANOVA revealed that the maximum depth of the center of the head was significantly deeper in 3.66 m as compared to the shallower water depths. No differences due to water depth were detected in head speed at maximum head depth or in the distance from the wall at which maximum head depth occurred. We concluded that swimmers can and do make head depth adjustments as a function of water depth. Earlier research performed in deep water may provide overestimates of maximum head depth following the execution of a racing start in water depth typical of competitive venues.

Minimum water depths at the starting end of competitive swim pools are regulated by several different organizations dependent upon geographic location and the details of the specific competitive event. On a global basis, Federation Internationale de Natation (FINA) requires water depth to be 2.0 m for international competitions primarily due to performance considerations (FINA, 2010). In the United States, the National Federation of State High School Associations (NFHS) and USA Swimming require a minimum water depth of 1.22 m (4 ft) in order to ensure the safety of swimmers executing competitive racing starts (NFHS, 2009; USA Swimming, 2010). Few, if any, of these water depth regulations are based upon empirical observations of the depth of swimmers completing competitive racing starts. Thus, the water depth regulations currently enforced are based more on opinion, coaching experience, and/or existing pool configurations than on scientific data.

Of the research studies that exist, many have taken place in diving wells, or as compared to typical competitive swim venues, relatively deep water. The water depth for studies that took place in diving wells ranged from 3.81 m to 4.88 m

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(Counsilman, Nomura, Endo, & Counsilman, 1988; Gehlsen & Wingfield, 1998; Welch & Owens, 1986). While the findings from these "start studies" provide important information, in light of the more recent research suggesting that swimmers perform deeper starts in deeper water (Blitvich, McElroy, Blanksby, Clothier, & Pearson, 2000; Cornett, White, Wright, Willmott, & Stager, 2011), values for head depth obtained in diving wells might overestimate head depth in typical competitive venues (e.g., 1.22 to 2.14 m depth). If so, then these existent values obtained for starts performed in deep water might be inappropriate for use in determining appropriate regulations for safe starting depths.

Previously, 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 and 2.0 m. Maximum head depths achieved differed by 9 cm with the shallower pool resulting in shallower starts. The study presented important information regarding differences in start depths attained as a function of water depth in that swimmers without specific instructions adjusted the depths of starts to accommodate less water.

In order to make comparisons similar to those made by Blitvich et al. (2000), Cornett et al. (2011) analyzed racing starts at two different swimming competitions: an open age group invitational in 1.22 m and an open age group invitational in 2.29 m. Their analysis showed that boy and girl swimmers (15 years of age and older) in 2.29 m had significantly deeper maximum depths of the center of the head, slower head speeds at maximum head depth, and greater distances at maximum head depth than starts in 1.22 m (Cornett et al., 2011). The only caveats were that the comparisons were made with different swimmers performing at different venues. Nevertheless, the study again suggested that swimmers performed shallower starts in shallower water, or conversely, deeper starts in deeper water.

The purposes of the present study are twofold. The first is to extend the findings of Blitvich et al. (2000) and Cornett et al. (2011) by investigating the effect of water depth on racing starts executed by experienced swimmers from a standardized starting block within the same aquatic venue. The second purpose is to make comparisons between starts performed in typical competitive pool depths and deeper water depths similar to the depths used by most prior studies pertaining to racing start variables. This information will aid in making appropriate regulations pertaining to minimum water depths as well as to validate the values available in the research literature.

Method

Participants

Prior to the initiation of the study, the project was approved by the university's Human Subjects Committee and informed consent was obtained from each participant after written and verbal explanations of the study were provided. The participants were all members of collegiate swim teams and USA Swimming registered. No other criteria were used in the selection process other than these memberships. Eleven swimmers (5 females and 6 males) participated in this study with a mean age of 20.1 ± 1.2 years, height of 1.79 ± 0.08 m, and mass of 74.5 ± 8.9 kg.

Experimental Procedure

The testing took place in a competitive swim venue (22.86 m by 13.70 m, or 25 ft by 45 ft) with six lanes and a separate diving well (12.83 m by 10.96 m, or 42 ft by 36 ft). No other activity took place in the facility during testing. The competition pool had a depth of 1.53 m (5 ft) at one end and a depth of 2.14 m (7 ft) at the other. The diving well depth was 3.66 m (12 ft) in the location that the swimmers executed their starts. A portable starting block with a platform height of 0.76 m above the water surface was custom-designed and specifically built for this project (Adolph Kiefer and Associates, Zion, IL). The block was mounted on a steel platform that provided the ability to easily move the starting block to any location desired. The start platform was inclined at an angle of 10° from horizontal and had a surface area of 0.39 m^2.

All swimmers performed a competitive start into three water depths: 1.53 m, 2.14 m, and 3.66 m. Due to calibration and setup constraints, testing in each water depth took place on a separate day and thus the order of the trials was not randomized. Swimmers mimicked a competitive situation and were asked to step onto the block and after a standard verbal command ("Swimmers take your mark"), a conventional audio signal ("Beep") from a commercial starting system (Daktronics, Brookings, SD) initiated the start. The swimmers were not aware of the purpose of the study so as to not affect their behavior. The swimmers followed each start with a front crawl (freestyle) sprint midway across the pool. Based on the sprint swim, the subjects most likely believed that speed and/or time to mid-pool was the purpose of the study.

Video Recording

A Canon GL2 digital video camcorder (Canon Inc., Tokyo, Japan) was utilized for video recording. The camera was placed in a sealed housing unit (Ikelite Underwater Systems, Indianapolis, IN) mounted on a heavy tripod (Hercules model, Quick-Set Inc., Northbrook, IL) placed on the bottom of the pool. The camera was aligned perpendicular to the direction of the racing start, and a Canon WD-58 wide-angle adapter (Canon Inc., Tokyo, Japan) was used to ensure that the field of view included the swimmers' underwater motions from entry until farther than the deepest point of the racing start. Camera zoom and focus were adjusted underwater once the tripod/camera unit was in place. An Opticis Optical IEEE1394 FireWire Repeater (M4-100; Opticis North America, Inc., Chatham, Ontario, Canada) extended the range of the video cable to 30 m and enabled the video signal to be input directly to a Gateway (model #: M675, Gateway Inc., Irvine, CA) laptop computer at the poolside. The video signal was captured using SIMI Motion software (zFlo Inc., Quincy, MA).

Calibration

The dive area in front of each block location was calibrated using the 2D direct linear transformation (DLT) procedure in SIMI Motion. A custom-built 1 m × 3 m aluminum frame was placed vertically in line with the center of the starting block, perpendicular to the side of the pool and with the top of the frame about 0.1 m below the surface of the water. The frame was painted black and 30 bright yellow spheres (marker balls), approximately 0.05 m in diameter, were located at regular intervals around it.

A number of additional cues were included in the same image as the calibration frame: two points on the wall/block, a vertical plumb line with three marker balls, and three further marker balls floating at the water surface. These were used in the rotation and translation of the calibration frame coordinate system to give a pool-based coordinate system in which the kinematic data would be expressed. The origin of the latter system was at water level directly below the center of the starting block, and the axes were oriented such that the x-axis pointed horizontally and perpendicular to the wall and the y-axis pointed vertically upward.

Video Analysis

Following the calibration of the dive area, the competitive dives were recorded and analyzed using SIMI Motion. In each dive, the center of the swimmer's head was digitized from the frame in which it was first visible below the surface through to 10 frames after the instant at which qualitative analysis of the video suggested that the head had reached its maximal depth and was beginning to move back towards the surface. The (x,y) position was calculated using SIMI Motion and the coordinate system transformation described above. Along with the maximum head depth reached in each trial, the speed of the head at this instant and the distance of the head from the wall were determined.

Data Analysis

Fisher's Least Significant Difference (LSD) test was utilized to analyze the data. Briefly, this procedure consists of two steps. First, the equality of means is tested using an α-level analysis of variance (ANOVA) F test. If the null hypothesis for the omnibus F test was rejected, pairwise comparisons were conducted using a-level *t* tests. If the null hypothesis for any *t* test was rejected, the corresponding means were declared unequal (Hayter, 1986). A major criticism of the LSD procedure is that maximum familywise error is known to increase above the nominal level as the number of groups gets large. Hayter (1986) found that the maximum familywise error rate is maintained at the nominal level a when the number of groups is equal to three. Since we have three groups in this study, we can utilize this procedure without it resulting in maximum familywise error inflation.

For the F tests, the sphericity assumption was tested using Mauchly's Test of Sphericity. If the sphericity assumption was violated, the Greenhouse-Geisser sphericity correction was used to alter the degrees of freedom and thus raise the significance of the F-ratio. For all analyses reported below, an alpha level of 0.05 was used to determine statistical significance.

Results

The results for the three water depths and head variables are shown in Table 1. The one-way repeated measures ANOVA yielded a significant main effect, $F(2, 20) = 6.12$, $p = 0.008$, across water depths for maximum depth of the center of the head. Follow-up procedures indicated that the maximum depth of the center of the head was significantly deeper for racing starts in 3.66 m of water than for starts in 1.53 m ($p = 0.018$) and 2.14 m ($p = 0.012$) of water (Figure 1). No additional significant differences were detected between the three water depths for head speed at maximum head depth or distance from the wall at maximum head depth (Figures 2 & 3).

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

Water Depth (m)	n	Depth of the Center of the Head (m)		Head Speed at Maximum Head Depth (ms^{-1})	Distance from the Wall at Maximum Head Depth (m)
		Mean	Range		
1.53	11	0.83 ± 0.13	0.67–1.08	2.80 ± 0.60	5.34 ± 0.66
2.14	11	0.85 ± 0.22	0.49–1.26	2.81 ± 0.47	5.27 ± 0.61
3.66	11	1.00 ± 0.21	0.73–1.32	2.97 ± 0.45	5.55 ± 0.49

Note. Values are means ± standard deviation for dependent measures as well as the range of values for maximum depth of the center of the head. All values are measured at the center of the head.

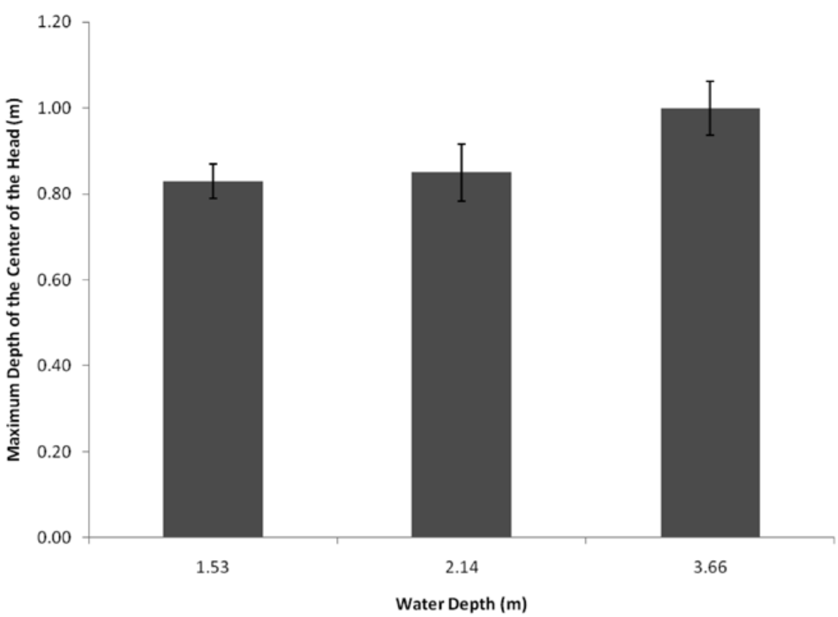

Figure 1 — Maximum depth of the center of the head (m) as a function of water depth following the execution of racing starts. The omnibus ANOVA revealed a significant main effect for water depth ($p < 0.05$) and follow-up procedures indicated that starts were deeper in a water depth of 3.66 m than in 1.53 m and 2.14 m. Error bars represent one standard error.

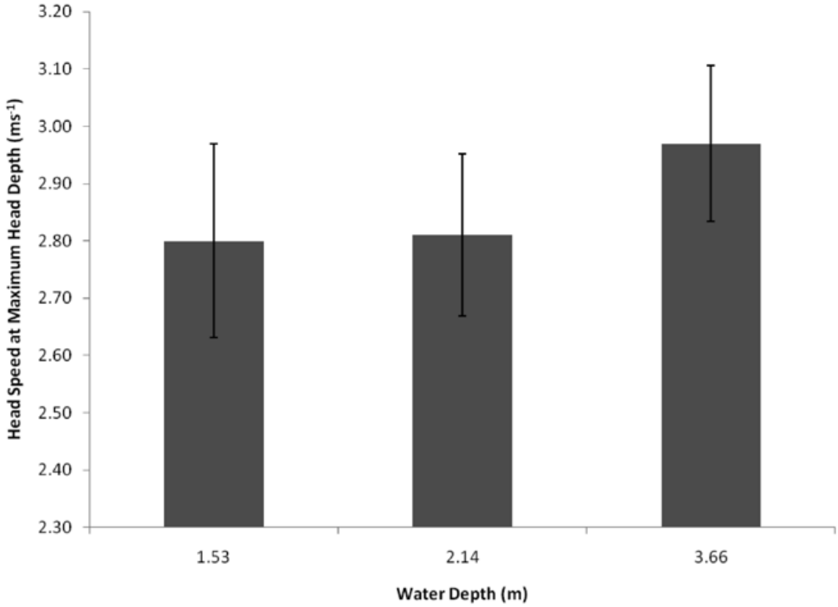

Figure 2 — Head speed at maximum head depth (ms^{-1}) as a function of water depth following the execution of racing starts. There was not a significant main effect for water depth ($p > 0.05$) indicating that head speed was not different for the three water depths. Error bars represent one standard error.

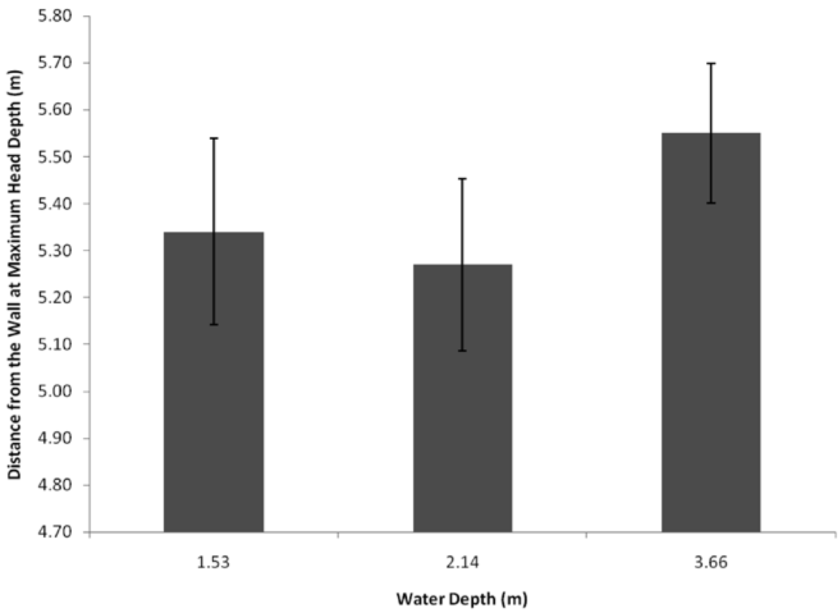

Figure 3 — Distance of the center of the head from the wall at maximum head depth (m) as a function of water depth following the execution of racing starts. There was not a significant main effect for water depth ($p > 0.05$) indicating that distance from the wall was not different for the three water depths. Error bars represent one standard error.

Discussion

One purpose of this study was to extend the findings of Blitvich et al. (2000) and Cornett et al. (2011) by investigating start parameters when experienced swimmers execute competitive racing starts from the same starting block into three different water depths. All of the swimmers participating in the study were familiar with the pool and the depths at each test site. No specific instructions or information about the pool depths were given to the swimmers prior to filming. Therefore, changes in head depth or speed were as a result of decisions made by the athlete during the racing start. Consistent with the earlier research findings, then, the most important statistical result of the present study was that swimmers performed the deepest starts in the deepest water.

Maximum Depth of the Center of the Head

Our current results are in partial agreement with Blitvich et al. (2000), who reported that for elite junior swimmers, maximum depth of the center of the head was deeper in deeper water. Blitvich et al. examined the depths achieved by 36 junior swimmers while executing racing starts into pool depths of 1.2 m and 2.0 m. Head depths achieved differed by 9 cm, with the shallower pool resulting in shallower depths (1.2 m pool depth, 0.79 m; 2.0 m pool depth, 0.88 m). When considering the head depth values, it is important to note that Blitvich et al. adjusted head depth by adding 0.15 m to the maximum depth of the center of the head in order to prevent underestimating the maximum depth of the head. The importance of their study was in showing that swimmers adjusted their start depths without requiring any specific instruction to do so. In their study, the swimmers warmed up in the pool and were therefore familiar with the depth but no information concerning water depth and no instructions relating to head depth were provided to the swimmer. Their findings and our findings are comparable in that experienced swimmers were shown to adjust head depth when presented with different water depth.

The current data were also in partial agreement with our previous findings (Cornett et al., 2011), whereby we concluded that swimmers adjust maximum depth of the center of the head as a function of water depth. Comparisons between competitive events held in two different pool depths (1.22 m and 2.29 m) resulted in starts where swimmers attained shallower maximum depth of the center of the head in shallower water (0.53 m and 0.70 m for freestyle starts, respectively). The difference in maximum depth of the center of the head for these starts (17 cm) was almost twice the difference found by Blitvich et al. (2000). Important differences between the two studies include the research design (independent groups versus repeated measures) and the homogeneity of the swimmers.

Despite finding the deepest starts in the deepest water, it is important to note that we did not find a significant difference in maximum depth of the center of the head between the two shallower pool depths (1.53 m and 2.14 m). Thus, while we can state that "swimmers dive deeper in the deepest water," we cannot state that "swimmers dive deeper in deeper water" without clarification. We can only speculate as to why there was not a significant difference between the two shallower depths. The most likely explanation is that the difference between the water depths was less (0.61 m) than in other reports that found maximum depth of the center of the head to change as a function of water depth. For instance, the difference between the depths in other studies was 0.80 m (Blitvich et al., 2000) and 1.07 m (Cornett et al., 2011). Another consideration might be the absolute depth in which the starts were completed. It is possible that differences in head depth might have been observed if the pool depths had been 1.22 m and 1.83 m rather than 1.53 and 2.14 m. The swimmers participating in the present study were familiar with the pool because most, if not all, trained in the pool at some point in time. Furthermore, most were accustomed to competing in pools with shallower water depth, specifically 1.22 m. Additionally, there may be a threshold at greater depths whereby head depth is no longer perceived as relevant to the swimmer from the perspective of swim performance or personal safety. More research is required in order to develop a complete understanding of the relationship between the maximum depth of the center of the head and the pool water depth.

Head Speed at Maximum Head Depth

Cornett et al. (2011) found head speed at maximum head depth to be faster in a shallower pool (2.93 ms^{-1} in 1.22 m water depth vs. 2.49 ms^{-1} in 2.29 m water depth). Because starts in 1.22 m were also significantly shallower than the starts in 2.29 m, faster starts in shallower water seemed likely. Cornett et al. reasoned that because the swimmers traveled through less water both vertically and horizontally in the shallower pool, less momentum was lost due to the reduction in drag forces of the water on the body.

Despite correlations between head depth and head velocity ($r = -0.60$, $p = 0.05$ at 1.53 m), no significant differences in head speed at maximum head depth for the three water depths were observed in the current study even though significantly deeper starts in 3.66 m were recorded. Similarly, Blitvich et al. (2000) found deeper starts in 2.0 m than 1.2 m but did not find an associated difference in head speed at maximum head depth between the two water depths (2.51 ms^{-1} in 1.2 m water depth vs. 2.47 ms^{-1} in 2.0 m water depth). One critical difference between the three studies may have been that the values reported by Cornett et al. (2011) were obtained during actual swimming competitions while the other two studies took place in controlled, noncompetitive settings. All three studies provide values for speeds within a similar range, averaging between 2.47 and 2.97 ms^{-1} with the fastest speeds recorded by the oldest, taller, heavier swimmers.

Distance From the Wall at Maximum Head Depth

Previous research on the effect of water depth on racing start parameters has demonstrated a shorter distance from the wall at maximum head depth when swimmers perform shallower starts (Blitvich et al., 2000; Cornett et al., 2011). This is a logical outcome of a shallower start because the swimmer reaches maximum head depth faster and thus does not have as much time to move horizontally. Blitvich et al. analyzed the starts of 36 elite junior swimmers in two different pool depths. They found distance from the wall at maximum head depth was significantly shorter for starts in shallower water (4.72 m in 1.2 m water depth vs. 5.01 m in 2.0 m water depth). Similarly, Cornett et al. found distance from the wall to be significantly shorter for starts in shallower pools (4.26 m in 1.22 m water depth vs. 4.60 m in 2.29 m water depth) when the starts from each water depth were matched for age, sex, and stroke. In the present analysis, significant correlations were observed between head depth and distance for two of the three water depths ($r = 0.67$, $p = 0.02$ in 1.53

m and r = 0.79, $p < 0.01$ in 3.66 m) although we did not find significant differences in distance from the wall at maximum head depth between any pair of pool depths.

Pool Safety

A secondary purpose of this study was to provide information that will put values from the prior literature into context given that most of this earlier research was performed in diving wells. This may help swimming regulatory organizations determine the minimum safe water depths required for the execution of racing starts performed during competition.

There are few reports available on the frequency of swimmers attaining various depths following a racing start during competitive or noncompetitive scenarios. Counsilman et al. (1988) related that in noncompetitive scoop starts performed in a 4.88 m diving well 88% of swimmers went deeper (body depth) than 0.94 m (3.1 ft) and 10% went deeper than 1.37 m (4.5 ft). Gehlsen and Wingfield (1998) report that none of the swimmers they filmed while performing starts in a 4.0 m deep pool "went deeper (center of head) than 1.4 m (4.6 ft)" and conclude minimum water depth should be at least that deep. The current findings include two starts (18%) in 1.53 m with a maximum head depth deeper than 1.0 m, three starts (27%) in 2.14 m deeper than 1.0 m, and five starts (45%) in 3.66 m deeper than 1.0 m. A total of four starts (12%) filmed (one in 2.14 m and three in 3.66 m) exceeded 1.22 m in head depth with the deepest start filmed being 1.32 m deep (in 3.66 m of water) at the center of the head. While these values represent the extremes within this sample of starts, they are important to consider in the context of the rules pertaining to permissible water depths during teaching starts and swim competitions. Our values support the contention by Blanksby, Wearne, and Elliott (1996) that "further scrutiny" may be advisable for rules allowing starts in 1.2 m. Regardless, the current values are seemingly in line with values provided by the literature, keeping in mind that the starts performed in the deepest water were deeper than the two shallower depths. Thus, the values from the previous literature performed in diving wells appear to overestimate the head depth attained in typical competitive venues.

Finally, from the perspective of head speed and swimmer safety, most likely because all of the swimmers filmed were experienced, mature collegiate swimmers, the head speeds all exceeded proposed thresholds (Stone, 1981 as cited in Blanksby et al., 1996) for severe head and neck trauma should an impact occur. Water depth does not appear to appreciably alter this aspect of racing starts. The assumption that deeper starts are faster starts was not supported by these findings. In fact, the tendency observed suggested that slower head speeds (at maximum head depth) were consistent with deeper starts. Coaches and athletes need to recognize that head speed following the feet leaving the blocks during a racing start depends to a great extent upon minimizing resistive forces that are encountered once the swimmer enters the water. Dependent upon the underwater trajectory (and all other factors held constant) the longer the underwater pathway, the slower the swimmer's speed prior to initiating propulsive forces.

Conclusion

The present study confirmed earlier findings reporting swimmers can and do adjust the depth of their starts as a function of water depth. There may be a depth threshold below which and above which additional adjustments cannot or are not made because we did not find differences in head depth between the two shallower depths. All values reported were within the range of values previously reported for racing starts as far as head depth, head speed, and distance from the wall were concerned. Our findings showed that prior studies in which swimmers' starts were filmed in diving wells appeared to provide overestimates of maximum head depth in water depths typical of competitive venues. In terms of head speed at maximum head depth, all starts filmed in the present study were determined to exceed proposed threshold speeds (Stone, 1981 as cited in Blanksby et al., 1996) for severe injury if an impact occurred and that this speed was independent of water depth. Additional research is needed to fully understand the relationships between racing start parameters and additional variables such as water depth, block height, competitive experience, and swimmer age, height, mass, and skill level.

Acknowledgments

Financial support for the project was received from a grant from *United States* Sports *Insurance* Company (USSIC) to USA Swimming. We would like to thank John Petersen of Risk Management Services, Inc., and Ron Van Pool, Murray Stevens, and Carol Zaleski of USA Swimming, who were fundamental in providing support and important input. Dr. Paul B. Sigfusson, DDS, deserves special recognition as liaison with USSIC and USA Swimming and important project advisor.

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