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INVITED REVIEW

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Competitive Swim Start Safety

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It could be argued that the only component of competitive swimming that is associated with any appreciable risk to the swimmer is the execution of the racing start from a starting block into shallow water. Recently, the Centers for Disease Control and Prevention (CDC) collected and considered input as a means to formulate guidelines for minimum water depths for the installation of starting blocks. Because there are only limited data on the depths and the velocities swimmers attain while executing starts, the data that are available need careful consideration. Insight into the central question, "how deep is deep enough?" involves consideration of values for maximum head depths, maximum head velocities, and the ability to control trajectory during racing starts. This review considers the literature pertinent to the key variables that, in general, stratify risk and determine successful, safe start outcomes.

The affiliates of The Counsilman Center are uniquely positioned within the swimming community as both researchers and practitioners. Center faculty and students conduct research on swimming and swimmers, sponsor and administer a USA Swimming club, and coach age group and high school swim teams. Part of the mission of The Counsilman Center is to provide empirical data upon which competitive regulations and safety mandates can be formulated and evaluated. What follows is a comprehensive review detailing the logical sequence of studies the Center has completed over the last decade pertaining to one specific dilemma within the competitive swimming environment: minimum pool water depth for racing starts.

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On November 27, 2001, the National Federation of State High School Associations (NFHS) announced a rule change "effective immediately" that stipulated a 1.22 m (4 ft) minimum water depth for swim competitions where starting blocks are used (Drew, Stager, & Jamieson, 2002). Before this ruling, a swimmer was permitted to execute a racing start from a 0.46 m (18 in) starting block into water as shallow as 1.07 m (3.5 ft), although a minimum water depth of 1.22 m was required to perform a start from a standard 0.76 m (30 in) starting block (NFHS, 2000). The NFHS's presumption, though not explicitly stated at the time, was that this new mandate would (1) reduce the number of pool bottom collisions occurring when swimmers execute racing starts and (2) act to lessen the severity of injuries when such collisions do occur.

At the time, we were not convinced that the rule change would have the intended effects. The assumption made by the NFHS seemed to be that water depth, or lack thereof, was a contributing factor in the number and severity of the accidents during competitive swim starts. And while that may or may not be the case, we questioned the extent to which an extra 15 cm (6 in) of water depth would provide additional protection to an athlete on a trajectory toward the pool bottom, especially given the momentum swimmers are capable of generating when performing racing starts. While it seemed logical to suggest that the number of incidents of catastrophic head and neck injury from pool bottom collisions would decrease because of the NFHS minimum water depth rule change in certain situations, we reasoned that any reduction would be difficult to verify as the incidence rate is already low and very little empirical data specific to this problem existed in the literature at that time to support or refute our hypothesis.

In terms of water depth at the starting end of a competitive pool, we recognized that two questions were most important and relevant in this regard: "how deep is deep enough?" and, the associated question, "deep enough for what?" In considering these two questions, it became clear that we could not answer the first question until we had an answer for the second one. In other words, before the appropriateness of the minimum water depth rules could be evaluated, the intended purpose of the rules needed to be clearly stated. Was the purpose to *eliminate the possibility* of catastrophic injuries due to pool bottom collisions during the racing start or rather to *minimize the risk* to a reasonable and acceptable level?

The aim of this review is to address the above questions as well as to develop a better understanding of the factors that influence the risk of injury during the execution of a racing start. By doing so, we provide an empirical basis for formulating valid regulations that will help to either reduce or eliminate the risk of injury when swimmers execute competitive racing starts.

Unintended Consequences of Minimum Water Depth Rule Changes

When the NFHS initially made their rule change back in November of 2001, we were curious about the impact the new rule would have on swim programs and aquatic facilities. In an effort to investigate this, we sent questionnaires pertaining to facility usage and swimming pool configuration to 1290 swim coaches (Drew, Stager, & Jamieson, 2002). A total of 369 (29.2%) of the questionnaires were

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returned and analyzed. Approximately two thirds of the respondents indicated that their school corporation owned the facility where they practiced and competed while the remainder used community, college, or YMCA pools. The pools owned by the school corporations served a variety of purposes such as community recreational swimming, youth swimming lessons, physical education classes, and USA Swimming meets. About 9 out of 10 respondents indicated that their pool currently complied with the NFHS 1.22 m (4 ft) rule, meaning that their pools were at least 1.22 m deep at the starting end. When not in compliance, there were a variety of approaches reportedly used: moving starting blocks to the deep end of the pool, continuing without the starting blocks, increasing pool water depth at the starting end, building a new pool, and eliminating the swimming program. Survey respondents also indicated that nearly one fourth of pools would no longer be in compliance if the NFHS further increased the minimum water depth to 1.52 m (5 ft). Three percent of the respondents predicted their swimming program would be eliminated if such a rule went into effect and over 8% could not predict how the school corporation would respond to such a change.

While logic suggests that increased water depth would help to decrease the frequency and severity of injury from pool bottom collisions, our survey of high school swim coaches on facilities usage indicated that it is not as simple as just increasing minimum water depth standards because there are likely to be unintended consequences. The most obvious unintended consequence of the increased minimum water depth rules is decreased opportunities for participation and practice. Responses of schools to the NFHS rules included eliminating swimming programs and removal of starting blocks. This meant that swimmers would have fewer possible swim teams to join and fewer opportunities to practice swim starts from starting blocks.

There is another, perhaps less obvious, *potential* consequence of increasing minimum water depth rules: increased incidence of drowning. The majority of swimming pools are multiuse facilities; they serve as locations for events such as community recreational swimming and youth swimming lessons. And, the deeper the pool, the less likely it is that recreational swimmers and young children in beginning swim classes will be able to stand with their heads above water. Thus, in trying to eradicate one problem (i.e., head and neck injuries due to pool bottom collisions), we could potentially bring about an increase in another one (i.e., fatal or nonfatal drownings). Because of the potential for unintended consequences, we thought it critical to assess whether or not the rules were likely to have the *intended result* before risking an increase in these unintended consequences. Before making any specific determination, there was a need to first carefully review and critically examine the literature on competitive swim start safety.

Early Competitive Swim Start Safety Literature

At the time of the NFHS rule change (late 2001), the existent literature, specifically on the maximum head depth attained when swimmers executed racing starts, was limited. There was only a handful of studies available: Welch and Owens (1986); Counsilman, Nomura, Endo, and Counsilman (1988); Blanksby, Wearne, and Elliott (1996); Gehlsen and Wingfield (1998); Blitvich, McElroy, Blanksby, and Douglas

(1999); Blitvich, McElroy, Blanksby, Clothier, and Pearson (2000); and Blitvich, McElroy, and Blanksby (2000). These studies examined the effect of start entry type, pool water depth, and starting block height on maximum head depth during the racing start; analyzed different predictors of maximum head depth; and assessed the effectiveness of intervention programs on reducing start depth.

Broad conclusions drawn from the cited swim start safety studies include: (1) the entry type used during the competitive swim start affects the maximum head depth reached (Welch & Owens, 1986; Counsilman et al., 1988; Gehlsen & Wingfield, 1998); (2) both starting block height (Welch & Owens, 1986; Gehlsen & Wingfield, 1998) and water depth (Blitvich et al., 2000a) impact maximum head depth when executing racing starts, (3) the horizontal distance the swimmer is away from the wall at maximum head depth is the strongest predictor of maximum head depth (Blitvich et al., 1999); and finally, (4) intervention programs can help swimmers develop skills necessary to decrease their maximum head depth during racing starts (Blitvich et al., 2000b). The authors of these studies seemed to agree with Counsilman et al. (1988) that there is "potential hazard" when swimmers start in water 1.22 m deep and with Blanksby et al. (1996) that the "regulation of 1.2 m minimum water depth under starting blocks requires further scrutiny."

The literature available at the time of the NFHS rule change provided important information that aided our understanding of the competitive swim start and led to some valuable conclusions regarding start safety. As we critically reviewed the findings in the literature, we began to develop research questions of our own that we felt needed to be answered. The remainder of this section presents our observations based upon the available research findings *at the time* (i.e., the pre-2001 competitive swim start safety literature) and the subsequent research questions that arose:

Observations and Research Questions

Observation #1. All of the pre-2001 start safety studies were 'staged,' meaning they were not part of actual practices or swimming competitions. Thus, it was unclear how deep and fast swimmers go when executing swim starts 'in the field,' outside of an experimentally-controlled environment.

Research Question #1. How deep and fast do swimmers go when executing racing starts in actual swimming competitions?

Observation #2. Blitvich et al. (2000a) demonstrated that swimmers executed deeper starts in a water depth of 2.0 m than in a water depth of 1.2 m. Because roughly half of the available studies were conducted in deep diving wells, the extent to which the depths of the starts analyzed were influenced by the water depth in which these experimental starts were executed was unclear.

Research Question #2. Does start depth increase as water depth increases and is there a depth threshold beyond which this ceases to be observed?

Observation #3. When Blitvich et al. (2000a) found that swimmers started deeper in a 2.0 m water depth than in a 1.2 m water depth, they explained the finding by saying that the swimmers "automatically" adjusted the depth of their starts to the water depth based on a direct perception-action paradigm. It was unclear whether swimmers were capable of adjusting or modifying the depth of their starts in response to being told to do so.

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Research Question #3. Can swimmers control maximum head depth when requested to do so and how consistent are these modifications?

Observation #4. Welch and Owens (1986) and Gehlsen and Wingfield (1998) concluded that swimmers perform significantly deeper starts from a standard (0.76 m) starting height than from lower starting heights (0.38–0.46 m). But, the exact nature of the relationship between starting height and maximum head depth remained unclear. Specifically, it was unknown whether there was a difference in maximum starting depth when swimmers executed starts from the poolside as compared with higher starting heights, such as those used by Welch and Owens (1986) and Gehlsen and Wingfield (1998).

Research Question #4. Is maximum starting depth different when swimmers perform starts from the poolside as compared with a low starting block (0.46 m) and a standard starting block (0.76 m)?

Observation #5. Blitvich et al. (2000b) demonstrated that intervention programs aimed at improving diving skills can help swimmers learn to perform shallower starts. Although their intervention program was effective, it was unclear what skills professional swim coaches regard as important and actually teach to swimmers learning to execute competitive swim starts.

Research Question #5. What characteristics of a racing start are recognized by coaches as being "safe," and conversely, what elements are recognized as being "unsafe?" In consideration of these safe and unsafe elements, what skills do professional coaches consider essential for a novice competitive swimmer to develop to execute a safe shallow-water racing start?

Procedures

We designed a series of studies in an effort to answer the stated research questions. Below we divide these studies into five projects, with each project aimed at answering one of the questions we have outlined. Before we begin our description of the five projects, we would like to make a brief note about chronology. The five projects described below were designed following our review of the pre-2001 start safety literature and took nearly a decade to design and fully implement. Although we list the projects from one to five, data collection and analysis for the different projects overlapped to a great extent and was not necessarily chronologically sequential. There were occasions when the results of one study led to additional research questions on a related topic. The questions that arose and the studies designed to address those questions are described below as well.

Project #1: Swim Starts During Actual Competitions

The first swimming competitions at which we filmed starts were endorsed by USA Swimming and took place in a pool with a water depth of 2.29 m (7.5 ft) at the starting end (Cornett, White, Wright, Willmott, & Stager, 2011a). Due to required camera positions, only starts in lanes four and five could be filmed and analyzed with acceptable accuracy. In all, 211 starts were analyzed and the swimmers that executed these starts fell into one of two age groups: 10 years and younger and

15 years and older. When comparing means for the starts executed by younger swimmers and older swimmers (Table 1), we found that the older swimmers performed starts with significantly greater maximum head depths (0.76 m v. 0.63 m) and head velocities at maximum head depth (2.61 $m \cdot s^{-1}$ v. 1.98 $m \cdot s^{-1}$). Although the group mean was deeper for older swimmers, there were starts in both age groups with head depths in excess of 1.22 m, the minimum allowable water depth in USA Swimming and NFHS competitions. Of all the starts analyzed, six had a maximum depth of the center of the head greater than 1.22 m. Importantly, the depths we analyzed were for the maximum depth of the *center* of the head. When we added 15 cm to the depth of the center of the head as a means to estimate the *deepest* part of the head during the starts (Blitvich et al., 1999), the adjusted value indicated that the deepest part of the head was deeper than 1.22 m for 13 (or about 6%) of starts. Because we observed starts in this study with head depths deeper than the minimum mandated allowable water depth, we decided that it was necessary to complete an additional analysis performed during actual competition, but this time, the study needed to take place in a pool with the minimum allowable water depth at the starting end (i.e., 1.22 m).

As a result, we arranged to film swim starts at an open, USA Swimming invitational in a pool with a water depth of 1.22 m (4 ft) at the starting end (Cornett, White, Wright, Willmott, & Stager, 2010). Once again, the required camera positions prevented us from analyzing all the starts at the meet, so we had to focus on the starts occurring in the center two lanes (i.e., lanes four and five). Nevertheless, we were still able to record and analyze 471 racing starts from this competition and found the overall mean value for the maximum depth of the center of the head to be 0.57 m. The maximum depth of the center of the head was a function of age; swimmers eight years and younger performed starts that were significantly shallower (0.44 m) than all other age groups (9–10 year olds, 0.56 m; 11–12 year olds, 0.57 m; 13–14 year olds, 0.62 m; and 15 years and older, 0.60 m; Table 1) and swimmers 13–14 years old executed starts that were significantly deeper than the three younger age groups. The mean head velocity at maximum head depth was 2.34 $m \cdot s^{-1}$, but as was the case for maximum head depth, head velocity was a function of age. The youngest two age groups, 8 years and younger and 9–10 years, performed starts that were significantly slower at maximum head depth (1.90 and 2.05 $m \cdot s^{-1}$, respectively) than the three older age groups (2.34, 2.63, and 2.83 $m \cdot s^{-1}$, for the 11–12, 13–14, and 15 years and older age groups, respectively). And, the older two age groups executed starts that were significantly faster than the younger three age groups at maximum head depth. The deepest observed start was performed by a 13-year-old and, as a result of having an estimated maximum depth of the *center of the head* of 1.09 m (in 1.22 m water depth), the swimmer was obviously close to making contact with the pool bottom. There were two other starts that had maximum head depths in excess of 1.0 m and 10-year-old swimmers executed them both. Thus, while group mean depth seems to be a function of age, the deepest starts executed within each group was not necessarily related to age grouping.

Of the starts executed in a water depth of 1.22 m, five swimmers had a maximum depth of the center of the head within a quarter of a meter of the pool bottom. And again, this value was for the center of the head. When we added 15 cm to each maximum depth of the center of the head as an estimate of the deepest part of the head, 26 starts (5.5%) had maximum head depth values within a quarter of a meter of the

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pool bottom. Although none of these swimmers actually contacted the pool bottom with their head, 14 swimmers did come in contact with the pool bottom with one or more body parts (e.g., hands, knees, feet). These findings caused us to join other researchers (Welch & Owens, 1986; Counsilman et al., 1988; Blanksby, Wearne, & Elliott, 1996; Gehlsen & Wingfield, 1998) in questioning whether 1.22 m was an appropriate minimum water depth for the execution of competitive swim starts.

Based solely on the group means for maximum head depth and head velocity at maximum head depth, we concluded from our studies of racing starts during competition that the older swimmers were at a greater relative risk of injury from pool bottom collisions due to their executing deeper and faster starts. We were also aware that there are some problems with basing risk solely upon group means for head depth and velocity. First, cases of swimmers contacting the pool bottom during racing starts are rare occurrences, very atypical. Thus, it is questionable to use the mean, or typical, value to assess risk. Second, head velocity was measured *at* maximum head depth and so vertical head velocity was zero at this point. As a result, using this head velocity value as an indicator of impact velocity is problematic. And finally, our assessment of relative risk using head depth and velocity does not include any consideration of the swimmers' ability to control or modify trajectory. Despite these problems, we felt at the time, and still do now, that our reports of competitive swimmers executing racing starts during actual swimming competitions addressed a major gap in the swim start safety literature. We also believe, however, that there is more work that needs to be done. Our data were collected at competitions with water depths of 1.22 m (4 ft) and 2.29 m (7.5 ft) at the starting end. For appropriate mandates and water depth recommendations to be made, similar studies conducted during competitions taking place in water depths between 1.22 and 2.29 m, such as 1.52 m (5 ft), 1.83 m (6 ft), and 2.13 m (7 ft) are necessary and highly recommended.

Project #2: The Effect of Pool Water Depth on Start Depth

Blitvich et al. (2000a) conducted an important study that first demonstrated the effect of pool water depth on maximum head depth during a competitive swim start. They had 36 elite junior swimmers perform two racing starts, one into the shallow end of a pool, which had a water depth of 1.2 m, and another into the deeper end of the *same* pool, which had a water depth of 2.0 m. Importantly, the participants were not given any instructions regarding how deep to make their starts, but they did swim warm-up lengths in the pool before the starts and so were *presumably* aware of the difference in water depth at the two ends. Blitvich et al. found that the swimmers had significantly greater maximum head depths when starting into the deeper water depth than when starting into the shallower water depth (0.88 m in the 2.0 m water depth v. 0.79 m in the 1.2 m water depth; Table 2), but there was no difference in head velocity at maximum head depth for the two water depths (2.47 $m{\cdot}s^{-1}$ in the 2.0 m water depth and 2.51 $m{\cdot}s^{-1}$ in the 1.2 m water depth). Blitvich et al. explained that the swimmers "apparently automatically adjusted the depth of their dives to the shallower water" (p. 37). This was of practical significance because it demonstrated that swimmers, at least at this skill level, can and do modify their trajectory in response to changes in the external environment without specific 'instructions' to do so.

Table 1 Maximum Depth of the Center of the Head (MHD) and Velocity at Maximum Head Depth (VEL) for Swim Starts in Competitions With Water Depths of 1.22 and 2.29 m at the Starting End

Authors	Participants	Age Group (yrs)	Pool Depth (m)	MHD (m)		VEL ($m \cdot s^{-1}$)	
				Mean	Max.	Mean	Max.
Cornett et al. (2010)*	45 swimmers	8 & U	1.22	0.44 ± 0.15	0.67	1.90 ± 0.55	3.46
	115 swimmers	9–10		0.56 ± 0.17	1.01	2.05 ± 0.62	3.67
	155 swimmers	11–12		0.57 ± 0.15	0.77	2.34 ± 0.49	3.95
	112 swimmers	13–14		0.62 ± 0.15	1.09	2.63 ± 0.55	4.22
	44 swimmers	15 & O		0.60 ± 0.10	0.78	2.83 ± 0.50	3.8
Cornett et al. (2011a)#	62 swimmers	10 & U	2.29	0.63 ± 0.20	1.29	1.98 ± 0.63	3.35
	56 swimmers	15 & O		0.77 ± 0.18	1.29	2.85 ± 0.66	4.12

Note: Mean values for MHD and VEL are mean ± *SD*.

* MHD was significantly shallower for 8 & U starts than for the four older age groups and deeper for 13–14 starts than for the three younger age groups ($p < .05$). VEL was significantly greater for 13–14 and 15 & O starts than the three younger age groups and faster for 11–12 starts than for the two younger age groups ($p < .05$). # MHD and VEL were significantly greater for 15 & O starts than for 10&U starts ($p < .05$).

The finding that swimmers inherently execute deeper starts in deeper water was both important and problematic. The problem was that most of the early studies on start safety were conducted in relatively deep water, water ranging from 2–4 m deep (Welch & Owens, 1986; Counsilman et al., 1988; Gehlsen & Wingfield, 1998). And if swimmers dive deeper in deeper water, then many of these early studies might provide maximum head depth values that are greater than what would occur in more traditional competitive starting water depths. As a result, the conclusions pertaining to minimum water depth regulations drawn specifically from these early studies in deeper water may not necessarily be valid. Before we could know this, though, we felt it necessary to extend the results of Blitvich et al. (2000a) by adding a condition in deeper water allowing us to interpret more accurately the results of the earlier research.

We addressed this question by having 11 collegiate swimmers execute competitive swim starts into three different water depths: 1.52 m (5 ft), 2.13 m (7 ft), and 3.66 m (12 ft; Cornett, White, Wright, Willmott, & Stager, 2011b; Table 2). In doing so, and as hypothesized, we found that the starts in the deepest water were significantly deeper than the starts in the two shallower water depths (mean depth in 3.66 m water depth was 1.00 m versus mean depths of 0.83 and 0.85 m in water depths of 1.52 and 2.13 m, respectively; Cornett et al., 2011b). Similar to Blitvich et al. (2000a), the water depth swimmers executed starts into did not influence the head velocity at maximum head depth (2.80, 2.81, and 2.97 $m \cdot s^{-1}$ in the 1.52, 2.13, and 3.66 m water depths, respectively). Because swimmers appear to intuitively adjust the depth of their start to the pool water depth, we concluded that this must be considered when evaluating the research supporting the rules requiring a minimum water depth of 1.22 m for the execution of racing starts.

Project #3: Start Depth Modification

The previous section describes the two pivotal studies that demonstrate the effect of pool water depth on the maximum head depth attained during the competitive swim start (Blitvich et al., 2000a, and our follow up study, Cornett et al., 2011b). These studies showed that swimmers intuitively decrease their start depth in response to a decreased pool water depth, or conversely, increase their start depth in response to an increased pool water depth. Blitvich et al. commented that this 'depth adjustment' was done "automatically" by the swimmer without any prompting by coaches or researchers. This led us to wonder whether swimmers could adjust start depth when requested to do so. And if so, would some groups of swimmers be better at adjusting start depth than others?

We designed a study to specifically address these questions. The study included two groups of competitive swimmers, experienced and inexperienced, and the swimmers in both groups performed two racing starts (White, Cornett, Wright, Willmott, & Stager, 2011). The inexperienced swimmers were defined as those having less than one year of competitive swimming experience. For the first start, the swimmers were instructed to perform their "typical" or "normal" racing start followed by a sprint across the pool. Before the second start, the swimmers were instructed to perform a "shallower start." We found that both groups performed starts with significantly shallower maximum head depth when asked to start shallow (0.63 m) as compared with when executing a normal start (0.82 m; Table 3).

Table 2 Maximum Depth of the Center of the Head (MHD) and Velocity at Maximum Head Depth (VEL) for Swim Starts With Different Water Depths at the Starting End

Authors	Participants	Age (yr)	Pool Depth (m)	MHD (m)		VEL ($m \cdot s^{-1}$)	
				Mean	Max.	Mean	Max.
Blitvich et al. (2000a)*	36 elite junior swimmers	15.3 ± 2.4	1.2	0.79 ± 0.13	0.93	2.51 ± 0.47	3.63
			2.0	0.88 ± 0.17	1.23	2.47 ± 0.36	3.00
Cornett et al. (2011b)#	11 collegiate swimmer	20.1 ± 1.2	1.52	0.83 ± 0.13	1.08	2.80 ± 0.60	3.69
			2.13	0.85 ± 0.22	1.26	2.81 ± 0.47	3.69
			3.66	1.00 ± 0.21	1.32	2.97 ± 0.45	3.79

Note. Mean values for MHD and VEL are mean ± *SD*.

* MHD was significantly deeper for starts into a 2.0 m water depth than into a 1.2 m water depth ($p < .05$). MHD values presented in this study had 0.15 m added on them to estimate the deepest part of the head. # MHD was significantly deeper for starts into a 3.66 m water depth than into 1.52 and 2.13 m water depths ($p < .05$).

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Further, there was not an experience by start type interaction which we interpreted to mean that the experienced and inexperienced swimmers were not different in their ability to modify racing start depth when instructed to do so. While *the groups* were not different in the extent to which they modified start depth, *the individual* experienced swimmers were more consistent in successfully modifying their depth than the inexperienced swimmers. All of the experienced swimmers executed a shallower start upon request whereas 3 of the 13 inexperienced swimmers failed to do so (White et al., 2011). Given that swimmers who experience catastrophic injuries following the execution of a start are, in effect, 'outliers' and their actions are not necessarily reflected by group means, we decided that this latter finding needed further analysis.

In our first study on depth modification during the competitive swim start, all of the swimmers were of at least high school age (White et al., 2011), and while this was useful and relevant for evaluating NFHS minimum water depth rules, it was not quite as applicable for USA Swimming rules. USA Swimming *does* have swimmers who are of high school age, but it also has swimmers who are considerably younger than this. Thus, we wanted to expand our results by performing a second study on depth modification using younger competitive swimmers (Cornett, White, Wright, Willmott, & Stager, 2012a). The competitive swimmers in the second depth modification study were grouped according to their USA Swimming age groups: 10 years and younger, 11–12 years, and 13–14 years (mean ages for the three groups were 7.9, 11.3, and 13.5 years, respectively). The swimmers were again asked to execute two racing start in the same manner as was done by White et al. (2011): a "typical" or "normal" start and a "shallow" start. Once again, we found that the swimmers performed starts with significantly shallower maximum head depths when asked to "start shallow" (0.46 m for the shallow starts v. 0.56 m for the normal starts; Table 3). And just as we observed in our first depth modification study, the groups were not different in their ability to modify depth (i.e., there was not an age group by start type interaction). When looking at the percentage of swimmers who successfully executed shallower starts upon request, we found that 76% of the swimmers were successful, a value that closely matched the success rate of the inexperienced swimmers (77%) in our first study on depth modification.

In terms of stratifying risk, then, our work on swim starts during actual competitions told a very different story from the one told by our work on depth modification. When considering starts in competition, we concluded that the older swimmers were at greater relative risk than the younger swimmers based on the fact that they routinely performed starts that had significantly greater maximum head depth and head velocity at that depth. When studying depth modification, however, the conclusion was the opposite: the younger, less experienced swimmers seemed to be at greater relative risk due largely to their greater inconsistency in controlling depth. Although all groups studied significantly decreased start depth when told to start shallow, there were young and/or inexperienced individual swimmers who failed to do so. And, presumably, having the ability to control dive trajectory is a fundamentally important skill in terms of avoiding pool bottom collisions and catastrophic injury.

But simple depth modification is only one parameter pertaining to a swimmer's capacity to control start depth. Another aspect of it relates to the intraindividual variability of the trajectory when a swimmer performs multiple starts under the

Table 3 Maximum Depth of the Center of the Head (MHD) and Velocity at Maximum Head Depth for Swim Starts (VEL) When Swimmers Are Instructed to Perform a "Normal" Start and a "Shallow" Start

Authors	Participants	Age (yr)	Pool Depth (m)	Instructed Shallow?	MHD (m)		VEL ($m \cdot s^{-1}$)	
					Mean	Max.	Mean	Max.
White et al. (2011)*	13 inexperienced swimmers	14.8 ± 1.1	3.66	No	0.63 ± 0.19	0.97	1.79 ± 0.37	2.37
				Yes	0.48 ± 0.19	0.79	2.18 ± 0.46	3.23
	12 experienced swimmers	20.1 ± 1.2		No	1.03 ± 0.23	1.38	2.94 ± 0.45	3.79
				Yes	0.79 ± 0.12	1.10	3.20 ± 0.47	4.30
Cornett et al. (2012a)#	14 competitive swimmers	7.9 ± 1.3	1.8	No	0.50 ± 0.20	0.82	1.69 ± 0.58	2.75
				Yes	0.35 ± 0.18	0.74	1.89 ± 0.83	2.97
	10 competitive swimmers	11.3 ± 0.5		No	0.58 ± 0.24	1.19	2.37 ± 0.55	2.75
				Yes	0.45 ± 0.07	0.55	2.86 ± 0.86	3.98
	18 competitive swimmers	13.5 ± 0.5		No	0.61 ± 0.11	0.83	2.75 ± 0.51	3.61
				Yes	0.56 ± 0.14	0.81	3.08 ± 0.49	3.86

Note. Mean values for MHD and VEL are mean ± *SD*.

* Significant main effect for instruction ($p < .05$), which indicated that MHD was significantly shallower and VEL significantly faster when swimmers were instructed to execute a shallow start. # Significant main effect for instruction ($p < .05$), which indicated that MHD was significantly shallower and VEL significantly faster when swimmers were instructed to execute a shallow start.

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same conditions. Given our findings from the depth modification studies, we hypothesized that younger and/or less experienced swimmers would be associated with greater maximum head depth variability. We tested this hypothesis by having competitive swimmers (with a wide range of ages, experience levels, heights, and masses) execute five racing starts under the same experimental conditions (Cornett, Naganobori, & Stager, 2012c). Then, we computed the standard deviation for maximum head depth for the five trials for each swimmer. We unexpectedly found that our measure of intraindividual variability was not correlated with any of the participant characteristics (i.e., age, experience level, height, or mass). It was, however, positively correlated with the average depth that swimmers attained, meaning that as swimmers went deeper, on average, their maximum head depth became more variable.

Despite the fact that we failed to confirm our hypothesis concerning intraindividual start depth variability, we still concluded that the youngest and most inexperienced swimmers were at the greatest risk of injury from pool bottom collisions *from the perspective of the ability to control start depth*. This conclusion was based on our studies of depth modification (White et al., 2011 and Cornett et al., 2012a) that found, once again, younger and inexperienced swimmers could not always be relied upon to successfully modify start depth when asked to do so.

Project #4: The Effect of Starting Height on Start Depth

Before November of 2001, the NFHS rules were such that swimmers were permitted to execute racing starts from 0.46 m (18 in) starting block heights when water depth was less than 1.22 m (4 ft), but were not allowed to perform starts into this same water depth from a 0.76 m (30 in) starting block (NFHS, 2000). When the NFHS changed their rules in November of 2001, swimmers were no longer permitted to perform racing starts from starting blocks of any height into water less than 1.22 m deep. They were still allowed to perform racing starts from the side of the pool into water less than 1.22 m deep (NFHS, 2002). USA Swimming endorsed a similar rule at the time which also allowed swimmers to execute racing starts from the poolside into water less than 1.22 m deep (USA Swimming, 2001). Given these rules regarding starting block height and water depth at the time, we were anxious to examine the literature to determine whether or not these rules pertaining to starting block height were supported by scientific studies of swimmers executing racing starts.

It turned out that two studies existed in the literature at the time of the NFHS rule change that compared maximum head depth during starts from a standard starting height (0.76 m) to the depth of starts from lower starting heights (Welch & Owens, 1986; Gehlsen & Wingfield, 1998). Welch and Owen performed the first of these two studies. They had male and female collegiate swimmers perform starts from starting blocks with heights of 0.38 m (15 in) and 0.76 m (30 in). The mean maximum head depth value was 0.61 m from the 0.38 m block and 0.68 m from the 0.76 m block (Table 4). They did not, however, report whether a main effect for block height was detected. And, since the variances for the conditions were not provided, we were unable to conduct statistical analyses on their data to determine whether the difference between the means was statistically significant.

Gehlsen and Wingfield (1998) also investigated the effect of starting block height on swim start parameters. They had male and female collegiate swimmers perform starts with two different types of entry (pike and flat) from four different starting heights (0.46, 0.56, 0.66, and 0.76 m). Their conclusion from their findings was that the maximum head depth increased as the starting height increased. Although they reported a significant main effect for starting height, the results of pairwise comparisons for the different starting block heights were not provided. Judging from the graphical display they provided of their data, their statistical interpretation and stated conclusions seemed inconsistent. The "mean underwater head vertical displacement values at the lowest point in the dive" appeared equivalent for the lowest (0.46 m) and highest (0.76 m) starting heights. Only head depths from the 0.56 m starting height appeared to be shallower than those from the other block heights. Thus, while there may have been statistical differences between some groups, their claim that maximum depth increased with each increase in block height does not seem to be supported by the data and graphs they provided.

Because of the weaknesses in the existing literature at the time, the true nature of the relationship between starting height and maximum head depth during the racing start seemed to us to be unclear. As a result, we designed an investigation whereby competitive swimmers were asked to perform three starts from each of three starting heights: the poolside (0.21 m), an intermediate starting block (0.46 m), and a standard starting block (0.76 m; Cornett, White, Wright, Willmott, & Stager, 2011c). With this design, the intent was to address two issues. First, we wanted to compare maximum head depth for starts from the intermediate starting height and standard starting height. In other words, we wanted to verify the findings of Welch and Owens (1986) and Gehlsen and Wingfield (1998) because of the concerns mentioned earlier regarding their analyses and conclusions. Second, we felt it was critically important to include the condition in which swimmers started from the poolside, so we could compare maximum head depth during starts from the poolside with those from the higher starting heights. At the time, according to NFHS and USA Swimming rules, starting from the poolside into water less than 1.22 m was still an option (NFHS, 2002; USA Swimming, 2001). We found that maximum head depth and the velocity at maximum head depth was significantly greater from the poolside (0.93 m and 2.88 $m \cdot s^{-1}$) and the standard starting block (1.00 m and 2.97 $m \cdot s^{-1}$) than from the intermediate starting block (0.83 m and 2.43 $m \cdot s^{-1}$) but the poolside and standard starting block conditions were not different from each other (Table 4). The finding of deeper starts from the standard block than the intermediate block seems to be in agreement with the findings of Welch and Owens (1986) and Gehlsen and Wingfield (1998). The finding of deeper starts from the poolside than from the intermediate starting block was novel and demonstrates once more that head depth is influenced by multiple variables and starting height above the water surface is just one of these variables. Any explanation of these findings is limited to speculation on our part due to the lack of 'air flight' data. Additional research is recommended on how the trajectory through the air, angle of entry, and underwater trajectory influence head depth and velocity following competitive swim starts from various starting heights.

Our research on the effect of starting block height on maximum head depth during the swim start highlighted the conundrum with the standing NFHS and USA Swimming rules at the time. If it was unsafe for swimmers to start from a 0.46 m starting block into water less than 1.22 m, then, from the perspective of maximum head depth and head velocity, our data indicated that it was also unsafe for swimmers

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Table 4 Maximum Depth of the Center of the Head (MHD) and Velocity at Maximum Head Depth (VEL) for Different Starting Heights Above the Water Surface

Authors	Participants	Age (yr)	Pool Depth (m)	Block Height (m)	MHD (m)		VEL ($m \cdot s^{-1}$)	
					Mean	Max.	Mean	Max.
Welch and Owens (1986)*	30 collegiate swimmers	Not provided	3.81	0.38	0.61	x	x	x
				0.76	0.68	x	x	x
Gehlsen and Wingfield (1998)#	20 collegiate swimmers	Not provided	4.0	0.46	~0.95	x	~2.90	x
				0.56	~0.80	x	~2.91	x
				0.66	~0.90	x	~2.92	x
				0.76	~0.95	x	~2.93	x
Cornett et al. (2011c)^	11 collegiate swimmer	20.1 ± 1.2	3.66	0.21	0.93 ± 0.16	1.25	2.88 ± 0.52	3.52
				0.46	0.83 ± 0.18	1.19	2.43 ± 0.42	3.02
				0.76	1.00 ± 0.21	1.32	2.97 ± 0.45	3.79

Note. Mean values for MHD and VEL are mean ± *SD*.

* Did not report whether MHD was different for the different starting heights. # Reported a significant main effect for block height but did not report the results of pairwise comparisons. ^ MHD and VEL were significantly greater for the 0.76 m and 0.21 m starting heights than for the 0.46 m starting height ($p < .05$), but not different from each other.

to perform starts from the poolside into water less than 1.22 m deep. Ultimately, the NFHS and USA Swimming changed their rules to reflect these research findings such that swimmers are no longer permitted to execute a racing start from the poolside or any height starting block into water depths of less than 1.22 m (NFHS, 2012; USA Swimming, 2004). As to whether the 1.22 m water depth is sufficient to allow swimmers of all ages and experience levels to safely execute racing starts from any starting block requires considerable additional analysis.

Project #5: The Teaching of Competitive Swim Starts

The majority of the start safety literature seemed to be focused on how swimmer characteristics (e.g., age and experience level) and aspects of the aquatic environment (e.g., pool water depth and block height) affected racing start 'outcomes,' such as the maximum depths attained and the velocity at those depths. This research has been performed using a quasi-experimental approach, whereby swimmers of different ages and/or experience levels were simply observed executing starts, and utilizing an experimental paradigm, whereby swimmers execute multiple starts under different conditions. It needs to be stated that swimmers ultimately determine the depths they attain during a racing start based upon their experience, practice, and of course, the instruction they receive from their coaches. Up to now, very little attention has been paid to the latter element, the role coaching/instruction plays in the outcomes of the execution of the racing start.

Blitvich et al. (1999) performed the first in a series of studies that investigated whether an intervention program could help swimmers to decrease dive depth and how well these instructed skills were retained. Ninety-five first-year university students participated in the initial phase of their study. Survey responses indicated that, on average, the study participants had taken less than 30 swim lessons "taught by a qualified person." Although each student performed four different types of dives into a 2.0 m water depth (deck dive, block dive, running dive, and treading water dive, i.e., a head-first dive followed by treading water), for this discussion we will focus on the block dive as it is the most pertinent to our discussion of swim start safety. The mean value for maximum head depth following a block dive was 0.64 m and the deepest start observed was 1.48 m deep. The participants who expressed a "low diving skill level" were asked to participate in a follow up study. Those who agreed to participate underwent an intervention program specifically aimed at improving their diving skills. The program consisted of seven 10-minute sessions "which emphasized locking thumbs and holding arms extended beyond the head, and steering and gliding skills" (Blitvich, McElroy, & Blanksby, 2000b, p. 120). At the end of the training sessions, the participants were asked to execute another block dive and, as was done before the participants performed their first block dive, the researchers instructed the students to "perform a shallow dive and swim to the other end of the pool." After the training program, the students executed significantly shallower starts (0.52 m) than before the sessions (0.76 m; Blitvich et al., 2000b). Thus, it seemed the diving skills intervention program helped the lower-skilled study participants to perform shallower dives. Though there was no "uninstructed" control group in the study design, the evidence provided indicated that instruction, even relatively minimal in duration, could effectively influence dive outcomes.

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Blitvich, McElroy, Blanksby, and Parker (2003) were interested in whether or not the participants retained their acquired diving skills. The 34 students who participated in the diving skills training program described above were invited to participate in a follow-up study eight months later and 22 of them agreed to take part in the study. The participants simply reported to the pool and executed the same dives that they performed in the previous study by Blitvich et al. (2000b). The authors reported maximum head depth was significantly shallower eight months after the training program (0.55 m) than it was before the training program (0.73 m). From this, it appeared that if the appropriate skills are developed through effective instruction they can be sustained over time minimizing the risk of injury as a result of a head-first dive from a starting block. The evidence here suggested that instruction was important and that these skills were learned and could be refined.

The fact that diving skill intervention programs can be used to help unskilled individuals decrease maximum head depth for block dives suggested to us that proper training practices are important and a means by which the safety of swimmers executing competitive swim starts can be ensured. We recognize that it is an assumption on our part that these findings might apply to young competitive swimmers. Nevertheless, given the importance of instruction (and coaching) on racing start outcomes, we thought it important to better understand what the coaches' perceptions about the start were and the skills they focused on as a means to teach it. At the time (2002–2005) neither USA Swimming nor the American Red Cross (ARC) had a coaching certification process that offered any formal discussion or required any training on the topic of racing starts.

With the cooperation of the American Swim Coach Association and USA Swimming, a survey was developed specifically to address issues pertaining to "racing start instruction" (Cornett, White, Wright, & Stager, 2012b). The survey was administered via an e-mail link sent to all registered USA Swimming coaches. The final survey elicited 471 usable responses from coaches ranging in experience level from very little professional experience to coaches with more than 25 years of experience. When coaches were asked if a progression was used when teaching starts, 4.6% reported using a written checklist, 89.8% a mental one, and 5.5% none at all. Of those who used a progression to teach racing starts, 78.3% used a personally designed progression while the remaining 21.7% used information provided by a professional organization. The findings from this survey led us to conclude that teaching the racing start largely has been an informal process and the lack of an authoritative resource used in teaching racing starts to novice swimmers warranted further investigation with regard to the safety of the athletes learning this skill. Following discussion with the ARC and USA Swimming concerning the results of the survey, the ARC developed the *Safety Training for Swim Coaches* manual and USA Swimming incorporated the manual into their curriculum for training their coaches.

The ARC's *Safety Training for Swim Coaches* manual describes a progression for the teaching of head-first entries (American Red Cross [ARC], 2013). This progression ends with a "shallow-angle dive" from the side of the pool, not a racing start. Thus, during their training, swim coaches are not provided with an actual progression for teaching the competitive swim start. When coaches were asked about the steps used to teach the racing start, they described fundamental skills they felt important: "start from the side in deep water," "completing a shallow start from the side," "jump from the block," and "standing dive off a block in deep water." Some of these identified skills could help to bridge the gap between the last step in the ARC's head-first entry progression (i.e., the "shallow-angle dive" from the poolside) and an actual racing start from a starting block. The development of such a racing start progression would be an important step in formalizing the teaching of this complex skill.

Importantly, from this survey and from the experimental data we, and others, obtained, the ability of swimmers to control the dive trajectory was recognized as critical to safe outcomes (Blitvich et al., 2000a; Cornett et al., 2011b; Cornett et al., 2012a; White et al., 2011). USA Swimming thus devised a 'swimmer certification' process whereby all swimmers must be observed executing racing starts and approved by a certified coach before being permitted to start in water less than 1.84 m (6 ft; USA Swimming, 2013). Again, there was recognition that, although experienced athletes may make "automatic" adjustments to start depth in response factors, such as water depth, this movement is complex and learned. As such, it requires instruction, practice, and the recognition by athletes and coaches that, if executed too deeply, the outcome can be catastrophic.

Upon completion of the initial five planned projects, we reflected on the NFHS rule change that originally led us into this line of inquiry. The NFHS presumed that their mandate would (1) reduce the number of pool bottom collisions occurring when swimmers execute racing starts and (2) act to lessen the severity of injuries when such collisions do occur. We realized that our work (and that of others) had contributed to a better understanding of the factors involved in determining whether collisions may occur. Little had been done to further the understanding of the severity of such injuries or truly quantify the potential for injury. The available research pertained to the various characteristics of the athletes which may place them at risk (e.g., age, experience, control), the role of skill level and the teaching of skills in preventing injuries, and the variables related to the aquatic environment that might increase or decrease the probability of contact with the pool bottom (e.g., water depth, block height). Very little research was available that would allow estimation of the severity of injury should contact occur. Because of this, we decided that we needed to perform one additional study on competitive swim start safety.

Project #6: Vertical Head Velocity During Worst-Case Scenario Swim Starts

The catastrophic consequences of a head-first impact with the pool bottom are primarily caused by the momentum generated by the combination of velocity (at impact) and the mass of the swimmer (momentum = mass × velocity). The majority of head velocity values presented in the start safety literature has been measured at maximum head depth, meaning velocity values obtained when the vertical velocity component is zero. This is somewhat problematic for estimating the injury severity should a pool bottom collision occur because the potential impact velocity is not precisely known unless certain assumptions are validated. The vertical head velocity during trajectories with significant vertical components is a much better estimate for this purpose and more closely replicates a head-first entry start. And, if vertical head velocities at relevant water depths were available, it would provide a convenient method for evaluating current and future minimum

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water depth requirements for executing racing starts. For instance, we would be able to determine the vertical head velocity at a head depth of 1.22 m which would then allow estimation of the potential impact consequences at this water depth. We could also assess other water depths (such as 2.0 m which was recently considered by the Centers for Disease Control and Prevention [CDC] as a suggested minimum depth for the installation of starting blocks; CDC, 2012) in a similar manner as well. With this hypothesis having been stated, we should point out that the swimmer's mass plays an important role such that doubling the mass at the same velocity doubles the momentum. It is the magnitude of these inertial forces that causes the catastrophic injuries that are observed when impacts occur. We will discuss this in greater detail later in this section.

Albrand and Walter (1975) conducted the first investigation we could locate in the literature to estimate vertical velocity at various water depths. They had two "expert divers" dive into a diving well from different heights and platform types: poolside, 1-m and 5-m platform, and 1-m and 3-m springboard. The poolside and 1-m platform were the most relevant diving conditions to our interest in competitive swim start safety, so we focused on the findings specifically related to these two conditions. Albrand and Walter measured the underwater vertical position of the athletes every 0.04 s until downward movement ceased. Using their data for position and time, we estimated the vertical velocity at different water depths. In particular, we were able to determine the head velocity at 1.22 m, the current minimum allowable water depth by USA Swimming and the NFHS, and 2.0 m, the proposed minimum water depth by the CDC. By so doing, we estimated the divers were traveling 4.1 and 5.6 $m \cdot s^{-1}$ at a depth of 1.22 m when diving from the poolside and 1-m platform, respectively. At a depth of 2.0 m, the divers were moving vertically at 3.7 and 4.9 $m \cdot s^{-1}$, again, from the poolside and 1-m platform, respectively. As the study was purely descriptive, Albrand and Walter did not provide any basis for putting these velocities into context. Thus, the level of risk to the athlete if a pool bottom collision were to occur was not expressed. In addition, the small sample size ($n = 2$) and limited description of subject characteristics made it difficult to generalize from this study.

We were only able to locate one additional study in the literature presenting vertical head velocity values at various water depths: Blanksby et al. (1996). The purpose of their study was to assess the head depths and vertical velocities attained after entry for the different developmental progression stages used to teach children how to dive: (1) the 'sit dive,' (2) the 'double kneel dive,' (3) the 'single kneel dive,' (4) the 'crouch dive,' (5) the 'one foot forward standing dive,' (6) the 'standing dive,' (7) the 'standing block jump,' and (8) the 'block dive.' The final stage, the block dive, is the most relevant stage to our discussion of competitive swim start safety. They reported that 42%, 27%, and 3.5% of children, who "were able to perform a standing dive from the starting block but were not highly skilled," reached depths greater than 1.0 m (3.3 ft), 1.2 m (3.94 ft), and 1.52 m (5.0 ft), respectively, when performing block dives into a water depth of 1.8 m.

The authors also assessed the vertical head velocities at water depths of 1.0, 1.2, and 1.52 m and then, perhaps most importantly, compared the velocities with critical threshold velocities for injury from the literature. They used the critical threshold velocities described by Stone (1981) who found that the momentum created from a pool bottom impact at 0.6 $m \cdot s^{-1}$ was sufficient to dislocate the adult cervical spine and at 1.2 m·s^{-1} was enough to crush the cervical spine. When Blanksby et al. compared measured vertical head velocities from block dives to the critical velocity thresholds, they found that 30.8%, 11.5%, and 3.8% of the children were traveling fast enough at depths of 1.0, 1.2, and 1.52 m, respectively, to dislocate the adult cervical spine. And, 19.2%, 3.8%, and 0% of swimmers were traveling fast enough at depths of 1.0, 1.2, and 1.52 m, respectively, to crush the cervical spine. In their conclusions, Blanksby et al. recommended 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.

As indicated earlier, the importance of the study conducted by Blanksby et al. (1996) was that it took the additional step to compare vertical head velocities with critical threshold values for head and neck injury from the literature. The comparisons were obviously imperfect as the values for thresholds were for adults rather than children. Nevertheless, by doing so, Blanksby et al. were able to assess the potential for catastrophic head and neck injury during dives from a starting block. The participants in their study were young (mean age was 6.9 yrs) beginning swimmers learning to perform *dives* from a starting block, not racing starts. Previously, we indicated that body mass was a direct and critical product creating the development of momentum and thus larger, more massive swimmers would generate more momentum and thus greater reaction forces upon impact. Our earlier research also suggested larger, more massive swimmers travel faster compounding their greater momentum. In any event, we felt it would be valuable to extend the results of Blanksby et al. to older, more experienced swimmers executing actual racing starts.

We designed a study that combined elements of the studies by Albrand and Walter (1975) and Blanksby et al. (1996). We were trying to learn about the *potential* for catastrophic injury during racing starts so we felt it was necessary to mimic the worst possible situation (Stager, Cornett, & Naganobori, 2013). In our view, this was a situation in which the swimmer dove directly toward the pool bottom from a standard 0.76 m (30 in) starting block in a streamlined body position. This trajectory would result in the greatest velocities at any given depth with minimal resistive forces acting upon the body. We considered these starts to represent 'worst-case' dives because the swimmers were asked to modify their typical start trajectory by traveling directly toward the pool bottom in a diving well and touching it if possible. We then measured vertical head velocity at predetermined water depths. Our results indicated that vertical head velocity was 3.2 m·s^{-1} at a depth of 1.22 m and decreased to 2.01 m·s^{-1} at a depth of 2.0 m. As hypothesized, vertical head velocity was significantly correlated with mass (and height) at each water depth ($p < .05$) suggesting that body size is a contributing parameter that needs to be considered as particularly relevant from the perspective of start safety.

We also compared our vertical head velocity values to the critical threshold values for head and neck injury suggested by Viano and Parenteau (2008) and those described earlier by Stone (1981). Studying head impacts using cadavers, Viano and Parenteau (2008) suggested that for inverted drops on a rigid surface, similar to what might occur in a diving accident, there is a 15% risk of catastrophic head and neck injury at a speed of 1.9 m·s^{-1} and a 50% risk at 3.4 m·s^{-1}. Based on these comparisons, it appears the potential for injury during worst-case starts exists at all depths analyzed (from 1.0 m to 2.5 m; Table 5). The conclusion from this assess-

Table 5 Percentage of Starts with Vertical Head Velocities Greater Than Critical Velocity Injury Thresholds at Various Water Depths

Depth (m)	> 0.6 $m \cdot s^{-1}$	> 1.2 $m \cdot s^{-1}$	> 1.9 $m \cdot s^{-1}$	> 3.4 $m \cdot s^{-1}$
1.00	100	100	100	73
1.25	100	100	91	45
1.50	100	95	86	18
1.75	100	95	68	0
2.00	100	91	59	0
2.25	95	86	45	0
2.50	95	73	36	0

Note. The momentum created from a pool bottom impact at 0.6 $m \cdot s^{-1}$ was sufficient to dislocate the adult cervical spine and at 1.2 $m \cdot s^{-1}$ was enough to crush the cervical spine (Stone, 1981). In addition, 1.9 and 3.4 $m \cdot s^{-1}$ represent 15% and 50% risk of catastrophic head and neck injury should an impact occur (Viano & Parenteau, 2008).

ment is that, while water depth is obviously important, it does not appear to be a viable solution as a means to *eliminate* catastrophic injuries except where starting blocks can be located in water exceeding 2.5 m. This is particularly problematic for those pools already in existence that do not have deep water into which races can be started. Within the range of typical depths for new multiuse aquatic facilities, the focus will have to be on *minimizing the risk* of an impact occurring rather than attempting to *eliminate the possibility* of a swimmer contacting the pool bottom, unless starting blocks can be located adjacent to water that exceeds 2.5 m.

Other Factors Affecting Racing Start Outcomes

The projects described above detail the logic flow and thought processes we used to develop and test the hypotheses that we felt needed to be addressed regarding swim start safety at the time of the NFHS rule change. While conducting these projects and reviewing the existing literature before the projects, we gathered additional information pertaining to competitive swim starts that was tangential to our primary research questions. Because of the additional insight this information provided, we briefly describe a few of these topics below.

Start and Entry Types

Over the last several decades there has been an ‘evolution’ in start mechanics. Three main start types have been described and analyzed in the literature: the conventional (or arm swing) start, the grab start, and the track start (Counsilman et al., 1988). For the conventional start, the feet are at the front of the block with a slight forward bend at the waist and the arms either hanging down at the sides or in the straight back position. At the start signal, the swimmer swings the arms in a counterclockwise circular manner (from the perspective of the right hand of the swimmer) or in a straight forward manner in preparation for take-off and entry (Maglischo, 2003).

For the grab start, like the conventional start, the swimmer's feet are placed at the front of the block. The hand position is different though; the swimmer grabs the front edge of the block either inside or outside the feet (Maglischo, 2003). On the start signal, the swimmer pulls down and forward on the block in preparation for take-off. The third start type, the track start, is different from the grab start only in that the feet are staggered. One foot is placed at the front edge of the starting block but the other one is placed toward the back edge (Maglischo, 2003).

The conventional start was the predominant start type in the 1960s and into the 1970s, before being phased out in favor of the grab start. Eventually, the track start began to gain in popularity to the point where it is the most common start type today. Of the nearly 700 swim starts we filmed in actual swimming competitions, 93.6% of them were track starts and the remaining 6.4% were grab starts (Cornett et al., 2010, 2011a).

Most of the studies that have compared racing start parameters for different start types have been primarily concerned with performance, not safety. In the one study that was concerned with safety, Counsilman et al. (1988) compared maximum start depth for the grab start and track start. They found that "the depth was almost identical" for both start types for males and females. When we analyzed 471 swim starts during a competition in a 1.22 m water depth (Cornett et al., 2010), our focus was not on the effect of start type on swim start variables but we did identify the start type used for each start. As a result, we were able to return to our data and compare maximum head depth for the grab and track starts. When we did this, we found the difference between the means was not statistically significant ($p > .05$). Thus, based on these two analyses, it does not appear that start type impacts maximum depth during the competitive swim start, but the situation is different for entry type.

Two types of entry are discussed in the literature: the flat entry and the pike entry. Counsilman et al. (1988) described the flat entry as when "the hands enter the water first with the rest of the body entering the water slightly in back of this point" (p. 2). For the pike start, on the other hand, "the swimmer was instructed to leap upward and to pike at the hips when he attained maximum height" and "the effect would be to incline his body steeply toward the water at an angle of about 45°" (p. 2). The result is that the water entry angle is much steeper for the pike start than for the flat start. Although it is not clear how steep the entry angle has to be in order for the start to qualify as a pike start, several studies expressed concern with the safety of the pike entry due to the steep entry angle. These concerns appear to be justified as three separate studies found the pike entry to result in significantly deeper starts than other starts with the more traditional entry angles (Welch & Owens, 1986; Counsilman et al., 1988; Gehlsen & Wingfield, 1998). It is likely due to the depths associated with the pike entry that Counsilman et al. called this a "potentially dangerous technique" and Welch and Owen recommended that coaches teaching "new or unfamiliar methods," such as the pike entry, do so in water at least 1.83 m deep.

While we did not test any hypotheses regarding maximum head depth and velocity for the different entry types, we identify this as a potential area for future research. It is common practice for coaches to have swimmers dive over and past Styrofoam tubes (or 'noodles'). Presumably, this practice is used in an effort to teach swimmers to push with the legs as they take-off from the starting block. In observing this practice, we have commonly seen swimmers entering the water at

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a steep angle, similar to what occurs for pike entries. As a result, these trials may result in significantly increased maximum head depth. Thus, we recommend future research to be directed at the execution of this particular skill with and without the Styrofoam tube, or 'noodle,' obstacle.

Competitive Strokes

Our primary concern when analyzing starts during actual swimming competitions was to describe the depths and velocities attained. We were certain, however, to record the competitive stroke that was performed when the swimmer surfaced for each start. The majority of the work on competitive swim start safety had the swimmers executing the front crawl (or freestyle) when surfacing. Because we recorded the competitive stroke performed upon surfacing, we were able to determine the effect of stroke on maximum head depth and head velocity at that depth. We found that maximum head depth was significantly greater when swimming breaststroke on the first length of the race (0.64 m) than when swimming butterfly (0.57 m) or freestyle (0.53 m; Cornett et al., 2010). Further, the starts were significantly deeper when performing butterfly than freestyle (Cornett et al., 2010). This may seem like an odd finding in that the swimmer does not begin swimming the stroke until after maximum head depth is reached. But, it makes sense when considering what the swimmers are doing underwater prior to surfacing for each stroke. During the breaststroke, the swimmer typically executes the underwater pullout in which he or she does a complete arm and leg cycle underwater before surfacing. During the butterfly, it is common for the swimmer to execute multiple dolphin kicks underwater before surfacing. It seems that swimmers may go deeper during breaststroke and butterfly starts so that they have additional time underwater to complete the underwater pullout or the dolphin kicks. In terms of relative risk for the different strokes, then, from the perspective of head depth *only*, the greatest risk is presented by breaststroke events and the least risk by freestyle events.

Although our priority throughout this project has been to evaluate safety concerns for competitive swim starts in which swimmers perform a forward dive from the starting block, we did record and analyze backstroke starts during the competition in 1.22 m (Cornett et al., 2011d). There was a significant main effect for age group for maximum head depth during the backstroke start. Swimmers in the eight years and younger age group performed starts that were significantly shallower (0.17 m) than all other age groups (9–10, 0.30 m; 11–12, 0.36 m; 13–14, 0.43 m; and 15 years and over, 0.57 m). In addition, swimmers in the 9–10 age group executed starts that were significantly shallower than the swimmers in the 13–14 and 15 years and older groups and swimmers in the 11–12 age group performed shallower starts than the swimmers in the 15 years and older age group.

When comparing maximum head depth for backstroke starts with those of the other competitive strokes, we found that maximum head depth was significantly shallower for backstroke starts than starts for the other competitive strokes for the four youngest age groups. We did not find a significant difference in maximum head depth when comparing backstroke starts with both freestyle and butterfly starts for the oldest age group. Thus, when considering the relative risk of racing starts for the four competitive strokes on the basis of head depth only, backstroke starts seem to be less risky than freestyle, butterfly, and breaststroke starts for the youngest four age groups. For older swimmers, however, there appears to be similar risk for backstroke, butterfly, and freestyle starts.

Age, Height, Mass, and Experience

Finally, from the perspective of stratifying risk, we felt it important to explore how the swimmer's characteristics (e.g., age, height, mass, experience) influence swim start parameters. These variables are such that they are often highly correlated, and thus, it is difficult to determine whether a specific variable is having an independent effect on start depth and head velocity or if the variables are having an effect collectively. We have repeatedly shown that older, taller, more massive, more experienced swimmers execute starts with greater maximum head depth and velocity at maximum head depth (Cornett et al., 2010, 2011a, 2012a; White et al., 2011), but it is currently unclear as to which variable has the greatest influence.

In our earliest work on start safety (Cornett et al., 2010, 2011a), we found that swimmer age had a significant effect on maximum head depth and velocity at that depth. The youngest swimmers, those eight years and younger, performed starts that were significantly shallower than the other four age groups (9–10 year olds, 11–12 year olds, 13–14 year olds, and 15 years and older; Table 1; Cornett et al., 2010). In addition, the second oldest group, 13–14 year olds, executed starts that were significantly deeper than the three youngest age groups. Further, head velocity at maximum head depth increased with age as well; all pairwise age group comparisons for head velocity were statistically significant with the exception of the 8 years and younger and 9–10 groups and the 13–14 and 15 years and older groups (Cornett et al., 2010). We had similar findings when analyzing the maximum head depth and head velocity at maximum head depth when comparing starts of swimmers at a competition in a water depth of 2.29 m (Table 1). The 15 years and older group performed starts that were deeper and faster than those of the 10 years and younger group (Cornett et al., 2011a).

The extent to which other subject characteristics, such as height, body mass, and swimming experience affected maximum head depth and head velocity at maximum head depth is unknown. Limitations imposed by the institutional review board (minors without parental consent in the public domain) prevented us from knowing the identity of the swimmers or measuring particular participant characteristics when we filmed these starts at actual swimming competitions. For this reason, we were unable to further assess the impact of height, body mass, and swimming experience on competitive swim start parameters.

Simply moving from the 'field' to a more controlled environment does not necessarily solve the problem of identifying the impact of individual participant characteristics on racing start parameters. In a more controlled setting, we can certainly measure participant characteristics but challenges remain due to the strong correlations between age, height, mass, and swimming experience. We could have gained a better idea about the effect of one participant characteristic (e.g., height) on swim start parameters if we matched subjects on the others (i.e., age, body mass, and swimming experience) while letting the one characteristic vary, but a limited number of participants prevented us from successfully completing this experimental design. It would be valuable for future research to isolate the effects of the individual swimmer characteristics on racing start outcomes or use a larger sample with multiple regression analyses.

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Concluding Remarks

Within the last decade or so, there have been a number of important contributions to the discussion pertaining to safety during competitive racing starts. For all intents and purposes, the findings suggest that there is a continued need to analyze and review data before establishing comprehensive minimum water depth mandates for executing competitive racing starts. There is still insufficient data to make compelling arguments for or against existing and/or proposed depth mandates and recommendations.

There are, however, two separate desirable outcomes of these water depth mandates: (1) having enough water depth to eliminate the chance of a swimmer hitting the bottom and (2) lowering the chances of a swimmer being injured should contact with the bottom occur. Research findings pertaining to vertical head velocities during 'worst-case scenario' starts suggested the second outcome seems to be the more achievable and certainly more realistic, especially when dealing with existing and multiuse facilities. With this in mind, we draw several conclusions.

The swimmers at the greatest risk of experiencing a catastrophic injury during the execution of a competitive swim start are physically mature swimmers with limited practice and start experience. We make this conclusion based on two major findings. First, older, taller, and more massive swimmers have been repeatedly observed performing starts with greater maximum head depth and head velocity (Cornett et al., 2010, 2011a). At the same time, swimmers lacking in competitive experience have been shown to be more inconsistent in terms of controlling or modifying start depth (White et al., 2011; Cornett et al., 2012a). This combination of deep, fast starts and a lack of control can have catastrophic consequences. Surprisingly, the younger, novice swimmers, in general, seem to be at lower risk in this regard. The young, novice swimmers as a group simply do not tend to attain head depths and velocities great enough to place them at the same level of risk as equally inexperienced but physically mature swimmers. This is certainly not to say, however, that they are risk-free.

We conclude, similar to previous authors on this topic, that the empirical evidence suggests that the current minimum depth of 1.22 m needs further careful consideration. It appears that there is very little margin for error at this depth, particularly for older, physically mature swimmers due to the depths and velocities they can achieve. A significant number of swimmers closely approached the pool bottom at this depth (Cornett et al., 2010) such that the potential for contact appears unacceptably high. Unfortunately, similar data from competitions held in 1.52 m (5 ft) are not yet available making firm recommendations on "how deep is deep enough" to be difficult.

It is certainly possible to require deeper minimum pool water depths than what are called for by current regulations. Doing so would likely help to reduce the risk of injury due to pool bottom collisions during the swim start. The studies presented in this review lead directly to this conclusion. While the risk can be minimized, marginally increasing the minimum allowable depth is unlikely to eliminate it. Our study of 'worst-case scenario' swim starts demonstrated that the potential for catastrophic head and neck injury existed at water depths as deep as 2.5 m (Stager et al., 2013). Thus, reducing the risk associated with competitive racing starts may be less a matter of *eliminating the possibility of contact* and more about improving *coach and swimmer training and education*. The recommendation, however, would be to pursue both strategies: increased minimum water depth *and* enhanced coach and swimmer safety training.

Furthermore, there may be unintended consequences associated with attempting to ensure that all pools are deep enough to eliminate contact altogether. Deeper pools are more expensive to build and maintain in addition to being less accommodating to multiple uses such as recreation and teaching. And, from our facility surveys, requiring pools to be 1.52 m (5 ft) or deeper at the starting end for the execution of racing starts could invalidate roughly 25% of available competitive facilities (Drew et al., 2002). Future multiuse pool design should be encouraged to include one section of the pool (typically one end) shallow enough for learners and recreational swimmers to be able to stand, and one end with sufficient depth to minimize the risk of spinal cord injury if used for starts (in competition, or for learning, practice, or recreational lap swimming).

Even if minimum water depth is increased, measuring the effectiveness of these changes will be extremely challenging because it remains difficult to count events that do not happen. Catastrophic spinal cord injuries happen infrequently in competitive swimming. When they do occur, it is tragic and enduring to the athlete, families, and teams involved. But accidents that do not happen cannot be counted and thus the reward for making changes to water depth mandates will be difficult to identify and document as compared with the tangible costs associated with building deeper starting ends for pools.

As a result of some of these recent research findings, instruction and teaching of safe practices has already become more formalized. More still can be done. There is a need to design, validate, and universally adopt an effective and appropriate racing start instructional progression. This requires additional study to review the fundamental skills required and establish the order in which these skill should be taught. Currently, no such teaching progression *developed through empirical* research exists.

It must be recognized that racing starts are complex, learned neuromotor skills. As such, coaches share in the responsibility (with swimmers) to recognize that racing starts are learned and executed safely. Perhaps there needs to be a greater recognition that this ‘partnership’ exists literally and figuratively. While ultimately swimmers ‘choose’ their dive depth, this is based upon their body size, collective experience, available practice, instruction received from their coaches, and even selective attention while performing start entries. The evidence provided suggested that ‘instruction’ can be effective and the learned skills from this instruction can be retained. Thus, rather than only building deeper pools, it would seem to be similarly appropriate to increase the time spent on validating learning progressions as well as teaching and refining the neuromotor skills needed to safely execute this complex movement.

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