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RESEARCH

Vertical Head Velocity During Worst-Case Scenario Swim Starts

Joel M. Stager, Andrew C. Cornett, and Hiroki Naganobori

The potential for injury exists during the execution of a competitive swim start if an athlete contacts the pool bottom. The aim of the study was to provide vertical head velocities (VHV) at predetermined water depths when competitive swimmers perform worst-case scenario swim starts. A total of 22 swimmers performed starts from a standard starting block into a diving well with a water depth of 3.66 m. The starts were considered worst-case scenarios because the swimmers were asked to modify their typical start trajectory by traveling directly toward the pool bottom. VHV was 3.67 ± 0.66 m·s^{-1} at a water depth of 1.0 m and decreased to 1.67 ± 0.62 m·s^{-1} at a depth of 2.50 m. VHV was correlated ($p < .05$) with height and mass at the seven different depths evaluated. The potential for injury during worst-case starts existed at all depths measured. In terms of risk management for injury potential, there seems to be modest additional benefit to increasing entry water depth from 1.75 m to 2.50 m as more than one third of swimmers would still have a 15% risk of catastrophic neck injury should an impact occur at 1.75 m water depth.

Keywords: water safety; diving, injury; competitive swimming

In 1989, the U.S. Consumer Product Safety Commission reported that "approximately 700 spinal cord diving injuries are estimated to occur in the U.S. annually as a result of recreational diving into residential pools, public pools, and other bodies of water" and the "cost of these [diving] injuries could total $1.4–$3.5 billion" (Gabrielsen, McElhaney, & O'Brien, 2001; p. 1–2). Subsequently, Day, Stolz, Mehan, Smith, and McKenzie (2008) projected that from 1990–2006, 111,000 patients under 20 years of age received medical treatment for diving-related incidents with an estimated 38% involving the head and neck. While the majority of the reported diving injuries resulted in "treat and release" scenarios, there were some classified as permanent and "catastrophic" (Day et al., 2008). These catastrophic cases often involved collisions with the pool bottom during a head-first dive causing hyperflexion, vertical compression, or hyperextension of the cervical vertebrae and resulting in para- or quadriplegia (Albrand & Walter, 1975). Due to the frequency of diving-related injuries, their potentially catastrophic nature, and

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the long-term cost of medical treatment for these injuries, additional information pertinent to this topic appears warranted.

The majority of the knowledge on diving injuries is derived from retrospective research that attempts to identify the characteristics of individuals and situations most commonly associated with severe diving injuries (Aito, D'Andrea, & Werhagen, 2005; Day et al., 2008; DeVivo & Sekar, 1997; Schmitt & Gerner, 2001). From this research, we know that a typical case of spinal cord injury (SCI) from head-first diving into swimming pools involved an unmarried male in his twenties diving into water less than 1.22 m deep from a height less than 1 m above the water surface (Day et al., 2008; DeVivo & Sekar, 1997). A typical SCI event occurred in a swimming pool without adequate lighting, visible depth indicators, or a lifeguard on duty (DeVivo & Sekar, 1997). Additional research has helped to identify factors affecting the risk and severity of injury when a diver comes into contact with the pool bottom: the diver's momentum, a product of body mass and velocity; the diver's physical traits; the orientation of the head, neck, and torso at impact; and the anatomical location of impact and nature of the interface (Viano & Parenteau, 2008). These research findings lead logically to strategies for lessening the incidence rates and severity of diving injuries. Some of the proposed strategies are behavioral and structural approaches and are obvious: limiting access to unsupervised facilities, adding visible depth indicators, and improved lighting around and in pools. Other strategies, however, focus more on the underlying physics of the impacts: softening pool bottoms, increasing pool depth, and decreasing diving board/platform height. Increasing pool water depth is perhaps the most commonly discussed approach for decreasing diving injury frequency. Its effectiveness though, as well as the effectiveness of the other measures, remains uncertain due to a general lack of data.

Competitive racing starts represent a subset of all types of head-first entries (and thus injuries) that occur each year. While it is difficult to estimate the exact number, it is likely that more than 10 million racing starts are performed annually by the nearly half million competitive swimmers in the United States. The various U.S. governing bodies in the sport of swimming (USA Swimming [USAS]; National Federation of State High School Associations [NFHS]; National Collegiate Athletic Association [NCAA]) require a minimum water depth of 1.22 m for the execution of racing starts (USA Swimming, 2012; NFHS, 2012; NCAA, 2011), presumably as an adequate approach of protecting athletes from pool bottom collisions. To underline the importance of this issue, the Center for Disease Control and Prevention (CDC) currently is constructing a comprehensive Model Aquatic Health Code: A National Model Swimming Pool and Spa Code (MAHC), part of which may dictate a federal minimum pool water depth for the installation of competitive starting blocks (CDC, 2013). In our opinion, it is unclear what minimum water depth is most appropriate due to a lack of empirical data. To our knowledge, neither the current enforced water depth regulations nor the standards being proposed by the CDCs MAHC are based on quantitative analyses of competitive swimmers executing racing starts.

The purpose of the current study was to provide empirically-derived data on fundamental parameters known to affect the severity of injuries should a worst-case impact with the pool bottom occur during a specific type of head-first dive (i.e., the competitive swim start). Specifically, we evaluated vertical head velocities at various water depths when swimmers dove toward the pool bottom in a diving well, hypothesizing that these vertical head velocities would decrease as a function of water depth. In addition, we examined the relationship between these velocities and measures of body size expecting that height and mass would be positively correlated with vertical head velocity at the different water depths. Then, by comparing the velocities with established critical thresholds consistent with catastrophic head and neck injuries within the literature, conclusions are drawn concerning the question, how deep is deep enough?

Method

Participants

Indiana University's Human Subjects Committee approved the project before the initiation of the study, and written informed consent was obtained from each participant and a parent or guardian if the swimmer was a minor. The participants were all members of a USA Swimming registered competitive swim club. The swimmers' age, height, mass, and competitive swimming experience were recorded before data collection. Because a focus of the study was to determine which factors, if any, were related to vertical head velocity at certain water depths, a wide range for height, mass, and competitive swimming experience was considered desirable. As such, swimmers of varying size and experience were recruited for the study.

A total of 22 competitive swimmers (4 females and 18 males) participated in this study. Because statistical analyses revealed that the females and males were not significantly different with respect to vertical head velocity, all further analyses were conducted with the sexes pooled. The means and standard deviations for age, height, mass, and competitive swimming experience were 17.1 ± 4.4 years, 168.6 ± 12.5 cm, 65.6 ± 16.3 kg, and 6.5 ± 4.9 years, respectively. Swimmers' skill levels ranged from novice to a USA Swimming World Championship Trials qualifier.

Procedures

The testing took place in a swimming venue that consisted of a six-lane competition pool (22.86 m × 13.70 m) and a separate diving well (12.83 m × 10.96 m) at a time when there were no other activities taking place in the facility. A starting block with a standard platform height of 0.76 m above the water surface was custom-designed and built for this project (Adolph Kiefer and Associates, Zion, IL). The starting platform was inclined at an angle of 10° from horizontal and had a surface area of 0.39 m^2. The starting block was mounted on a steel platform that made it possible to move it to different locations on the pool deck. Data collection was conducted in the diving well and the starting block appropriately placed so that the water depth was 3.66 m at the location the swimmers entered the water.

As a means of studying the worst-case scenario, the swimmers were asked to dive directly toward the pool bottom. This was done because the shortest distance between the water surface and pool bottom is the path perpendicular to the water surface. This trajectory will result in the greatest velocities at any given depth (assuming all other variables are equal) as this minimizes the resistive forces acting upon the body. All participants performed five trials from the starting block, with each trial consisting of a "typical" competitive racing start modified only by the swimmer diving directly toward the pool bottom and touching it if possible. Participants were directed to maintain a streamlined position once in the water without any assisting kicks or arm pulls as they descended toward the pool bottom. To mimic a typical competitive situation, participants were instructed to "step onto the block," "take your mark," and start on the audio signal from a commercial starting system (Daktronics, Omnisport HS 100, Brookings, SD).

Video Recording

The underwater portion of the swim start was filmed using a Canon GL2 digital video camcorder (Canon Inc., Tokyo, Japan) enclosed in a sealed housing unit (Ikelite Underwater Systems, Indianapolis, IN) and mounted on a tripod (Hercules model, Quick-Set Inc., Northbrook, IL) on the bottom of the diving well. The camera was aligned perpendicular to the direction of the dive and a Canon WD-58 wide-angle adapter (Canon Inc., Tokyo, Japan) was used to ensure that the field of view included the subjects' underwater motions from entry until after the deepest point of the dive. 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 input directly to a laptop computer. The video signal was captured using SIMI Motion software (zFlo Inc., Quincy, MA).

Calibration

The dive area in front of the block was calibrated using the 2D direct linear transformation 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), with an approximately 0.05 m diameter, were located at regular intervals around it.

During the calibration process, additional cues were included in the same image as the calibration frame and used as reference points. The starting wall was used to establish references for vertical and horizontal coordinates. In addition, a floating PVC pipe frame, with three marker balls above the surface and below the surface, was used as a reference for the water surface. These reference points 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 the y-axis pointed vertically.

Video Analysis

Following the calibration of the dive area, the competitive dives were recorded and analyzed using SIMI Motion. In each dive, the external auditory meatus, an anatomical landmark for the center of the subject's head, was manually digitized from the frame in which first movement was detected until the swimmer reached the pool bottom. For the trials in which the swimmer did not reach the pool bottom, the head was digitized until downward movement subsided. The (x, y) position was calculated using SIMI Motion and the coordinate system transformation described above.

Data Analysis

The position and velocity in the x- and y-direction were available for each trial from the swimmer's first movement on the starting platform until the point after water entry in which downward velocity ceased. Of particular interest was the downward velocity at head depths of 1.00 m, 1.25 m, 1.50 m, 1.75 m, 2.00 m, 2.25 m, and 2.50 m because the current minimum water depth of USA Swimming and the proposed minimum water depth by the CDC both fall within this range of depths.

Since the participants executed five trials, there were five vertical velocity values available for each swimmer at each of the depths listed above. Because the purpose of the study was to describe vertical head velocity during worst-case scenario starts, the greatest velocity for each swimmer at each depth was used for all descriptive and inferential statistical procedures.

The mean, standard deviation, minimum, and maximum values were determined for vertical head velocity at each of the water depths of interest and the time elapsed from water entry to each depth. Pearson product-moment correlation coefficients were calculated to determine the relationship between vertical head velocity at each depth and height, mass, and competitive swimming experience. For all analyses reported, an alpha level of 0.05 was used to determine statistical significance.

Results

The mean, standard deviation, minimum, and maximum values for vertical head velocity at the predetermined water depths and the time to reach those water depths following water entry are shown in Table 1. The Pearson product-moment correlation coefficients and p-values for the relationship between vertical head velocity and height, mass, and competitive swimming experience for the different water depths are displayed in Table 2.

Discussion

Whether a pool bottom collision occurs during a competitive swim start is primarily dependent on a diver's trajectory whereas the severity of the injury from such a collision is influenced to a great extent by the velocity at impact. The majority of research on swim start safety focuses on swimmer trajectory during the start, in particular the deepest point in the trajectory, or maximum depth. We chose to control trajectory in this study by having all swimmers dive toward the pool bottom so that we could examine the potential impact velocity at certain water depths if a swimmer were to collide with the pool bottom at that depth. In doing so, we were able to get an idea of the injury potential for a range of water depths, which includes the current minimum water depth enforced by USA Swimming (1.22 m) as well as the proposed minimum depth by the CDCs MAHC (2.0 m).

Table 1 Mean, Standard Deviation, Minimum, and Maximum Values for Vertical Head Velocity and Time to Reach That Water Depth After Water Entry at Different Water Depths (N = 22)

	Vertical Head Velocity ($m \cdot s^{-1}$)			Time (s)		
Water Depth (m)	Mean (*SD*)	Minimum	Maximum	Mean (*SD*)	Minimum	Maximum
1.00	3.67 (0.66)	2.20	4.62	0.23 (0.03)	0.19	0.30
1.25	3.14 (0.73)	1.70	4.17	0.31 (0.05)	0.25	0.42
1.50	2.65 (0.69)	1.18	3.62	0.41 (0.08)	0.32	0.60
1.75	2.26 (0.65)	1.02	3.32	0.52 (0.12)	0.38	0.83
2.00	2.01 (0.63)	0.71	3.05	0.65 (0.17)	0.47	1.12
2.25	1.85 (0.61)	0.49	2.99	0.80 (0.24)	0.56	1.54
2.50	1.67 (0.62)	0.55	2.89	0.99 (0.36)	0.65	2.25

Table 2 The Pearson Correlation Coefficients and p-Values for the Relationships Between Vertical Head Velocity ($m \cdot s^{-1}$) and Mass, Height, and Competitive Experience at Different Water Depths (N = 22)

	Mass (kg)		Height (cm)		Experience (yrs)	
Water Depth (m)	r	p	r	p	r	p
1.00	0.52	0.013	0.69	<0.001	0.50	0.018
1.25	0.59	0.004	0.70	<0.001	0.52	0.013
1.50	0.61	0.003	0.66	0.001	0.52	0.012
1.75	0.57	0.005	0.62	0.002	0.47	0.026
2.00	0.52	0.012	0.61	0.003	0.35	0.106
2.25	0.49	0.020	0.56	0.007	0.35	0.115
2.50	0.50	0.017	0.55	0.008	0.35	0.106

Vertical Head Velocity

For descriptive purposes, vertical velocity during the swim start can be described as follows: Once leaving the starting block and while in the air, a swimmer very quickly begins accelerating toward the water surface and pool bottom. By the time the swimmer's head enters the water, downward velocity is, according to our data, on average, 4.41 $m \cdot s^{-1}$ (ranging from 3.56 to 5.29 $m \cdot s^{-1}$ for all subjects). When the swimmer's head reaches a water depth of 0.25 m, the downward, positive acceleration ceases for most swimmers although a few of the taller swimmers continued to exhibit small, downward, positive accelerations at this depth. At a water depth of 0.5 m, all of the swimmers were negatively accelerating toward the pool bottom with the negative acceleration peaking between 0.5 and 0.75 m. The average vertical head velocity decreased 16.8% (4.41–3.67 $m \cdot s^{-1}$) from the time the swimmers entered the water until they reached a water depth of 1.0 m and 62.1% (4.41–1.67 $m \cdot s^{-1}$) from water entry to a water depth of 2.50 m. While not obvious from the group mean data, the rate at which the swimmers slowed varied considerably. Vertical head velocity decreased by as much as 88.2% (4.68–0.55 $m \cdot s^{-1}$) from water entry to a water depth of 2.50 m for one swimmer and as little as 34.2% (4.39–2.89 $m \cdot s^{-1}$) for another. From the perspective of safety, it is clear that a swimmer capable of traveling downward at nearly 3.0 $m \cdot s^{-1}$ at a water depth of 2.50 m is at greater risk of catastrophic head and neck injury should an impact occur than a swimmer traveling at 0.5 $m \cdot s^{-1}$. Additional information is needed, however, to accurately assess the magnitude of this risk.

The pertinent questions concerning the magnitude of risk from pool bottom collisions are (1) at which depth are the swimmers' speeds fast enough to do permanent catastrophic damage and (2) at which speeds are they too slow to cause an injury? Based upon head impacts using cadavers, Viano and Parenteau (2008) developed critical velocity thresholds for catastrophic head and neck injury in an analysis of existent research. They 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 $m \cdot s^{-1}$ and a 50% risk at 3.4 $m \cdot s^{-1}$ (Viano & Parenteau, 2008). By comparing these critical thresholds with the vertical head velocities we calculated, we can estimate the risk of head and neck injury should a pool bottom collision occur at certain water depths (Table 3). This comparison indicates that nearly one fifth of swimmers in our sample are traveling fast enough at a head depth of 1.50 m to be at a 50% risk of catastrophic head and neck injury should an impact occur. In addition, during these worst-case swim starts, over one third of the swimmers still had a 15% risk of head and neck injury should an impact occur at the greatest water depth assessed, 2.50 m. Thus, while increasing water depth may help to decrease the frequency of injury rates and lessen severity, it does not eliminate the injury potential within the range of depths we measured. Even at depths as great as 2.50 m, there were still swimmers traveling fast enough during worst-case starts to suffer catastrophic injury should an impact occur.

Table 3 Percentage of Starts With Vertical Head Velocities Greater Than 1.9 and 3.4 $m \cdot s^{-1}$ at Various Water Depths (*N* = 22)

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

Note: 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).

At this point, it is relevant to acknowledge that these percentages reflect, in part, the swimmers selected to take part in the investigation. As we will discuss later, specific characteristics of the subject pool strongly influence the velocities observed. For example, it is likely that had we selected only experienced, physically mature swimmers for the study, the proportion of swimmers classified as being at risk for catastrophic injury using these thresholds would be much higher.

Factors Associated With Vertical Head Velocity

Based solely on vertical head velocity, some swimmers seem to be at greater risk of catastrophic head and neck injury from pool bottom collisions than others. The tallest swimmers had the greatest vertical velocities at the different water depths, and thus the greatest potential for injury should an impact occur. The significant positive correlation between height and vertical head velocity was expected, especially at the shallower depths (Table 2). The taller swimmers have centers of mass that are higher above the water surface than the shorter swimmers. As a result, all else being equal, the center of mass has a longer time to accelerate before water entry when taller swimmers jump off the starting blocks than shorter swimmers. Likewise, the significant positive correlation between mass and vertical head velocity was hypothesized because, again, all else being equal, greater resistive forces are necessary to slow bodies with greater mass.

The statistical relationship between height and vertical head velocity is confounded by the significant correlations among height, mass, and competitive experience. The relationship between mass and vertical head velocity is confounded in a similar manner. In an effort to gain clarity on this issue, partial correlations were conducted such that (1) the relationship between height and vertical head velocity could be examined while controlling for the effects of mass and competitive experience and (2) the relationship between mass and vertical head velocity could be examined while controlling for the effects of height and competitive experience. The analyses revealed a significant relationship between height and vertical head velocity when controlling for mass and competitive experience at a depth of 1.0 m ($r = .55$, $p = .013$) and 1.25 m ($r = .46$, $p = .041$). Thus, at the shallowest depths measured, vertical head velocity and height are significantly related to each other even after we account for body mass.

We also predicted a significant correlation between vertical head velocity at the different water depths and the number of years participants had been swimming competitively (Table 2). While the relationship between these two variables was in fact significant, it is difficult to interpret the importance of this finding. Competitive experience was originally recorded because we thought it would provide a rough measure of a swimmer's skill to 'streamline' and thus minimize resistive forces once in the water. The problem was that we measured competitive swimming experience, not the ability to minimize resistive forces per se. We did this because we expected that as swimmers accumulated practice experience, they would also improve their streamlining technique, and thus their skill to minimize resistive forces. Admittedly, the extent to which this is the case is unknown; additional research is needed before exact conclusions concerning the nature of the relationship between vertical head velocity and competitive swimming experience can be drawn.

We can use the significant positive correlations between vertical head velocity and height and mass to further stratify the risk of catastrophic injury during a

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competitive swim start. Examining these relationships in conjunction with critical velocity thresholds developed by Viano and Parenteau (2008) clearly demonstrates the greater relative risk of the taller, more massive swimmers (Figure 1). Of the 12 swimmers in this study above the average height of all participants, eight had vertical head velocities in excess of 3.40 $m \cdot s^{-1}$ at a water depth of 1.22 m. On the other hand, 2 of the 10 swimmers who were below the average height exceeded the same threshold at the same depth. Similarly, the most massive swimmers were at the greatest relative risk of injury from pool bottom collisions. In fact, of the 12 swimmers in this study above the average mass of all participants, seven had vertical head velocities in excess of 3.40 $m \cdot s^{-1}$ at a water depth of 1.22 m whereas 3 of the 10 swimmers who were below the average mass exceeded the same threshold at this depth.

Ironically, the pervasive concern over swim start safety is focused on the youngest, least experienced swimmers. The present data illustrates that the taller, more massive swimmers are *potentially* at greater risk due to their greater velocities sustained at different water depths. This conclusion, however, is based solely upon vertical head velocity and does not consider the depths typically attained by swimmers during starts nor the skill of swimmers to modify and/or control dive depth.

Maximum Head Depth During Competitive Swim Starts

Previously, we performed an analysis of 471 racing starts during an actual swimming competition (Cornett, White, Wright, Willmott, & Stager, 2010). We selected the meet for data collection because the water depth at the starting end was 1.22 m, the minimum depth permitted by USA Swimming for competitive swim starts. We found that the older, and presumably taller and more massive, swimmers performed significantly deeper starts than the younger swimmers (Cornett et al., 2010). In addition, during this meet, we observed 14 starts (about 3%) that resulted in the swimmer contacting the pool bottom with one or more body parts (Cornett et al., 2010). It is noteworthy that of these contact cases none of the swimmers impacted the pool bottom with their head and none were in the youngest age group.

We have conducted additional research in deeper water that has produced similar conclusions. We analyzed 211 racing starts taking place in swimming competitions with a water depth of 2.29 m at the starting end (Cornett, White, Wright, Willmott, & Stager, 2011). Maximum head depths during competition in a depth of 2.29 m were deeper than those reported for starts executed during competition in a water depth of 1.22 m (Cornett et al., 2011). Once again, however, older swimmers (15 years and older) performed significantly deeper racing starts than younger swimmers (10 years and younger). As important as this, perhaps, is our observation that over 2% of the starts filmed in 2.29 m water depth had maximum head depths in excess of 1.22 m (Cornett et al., 2011).

Based on vertical head *velocity* during worst-case scenario swim starts, the current study has demonstrated that the potential for catastrophic head and neck injury exists at water depths as great as 2.50 m. Considering only maximum head *depth* from previous studies, the risk of injury is greater in the older, taller, more massive swimmers. So, considering both depth and velocity, it seems that all swimmers are at risk for catastrophic head and neck injury when executing swim starts in a 1.22 m

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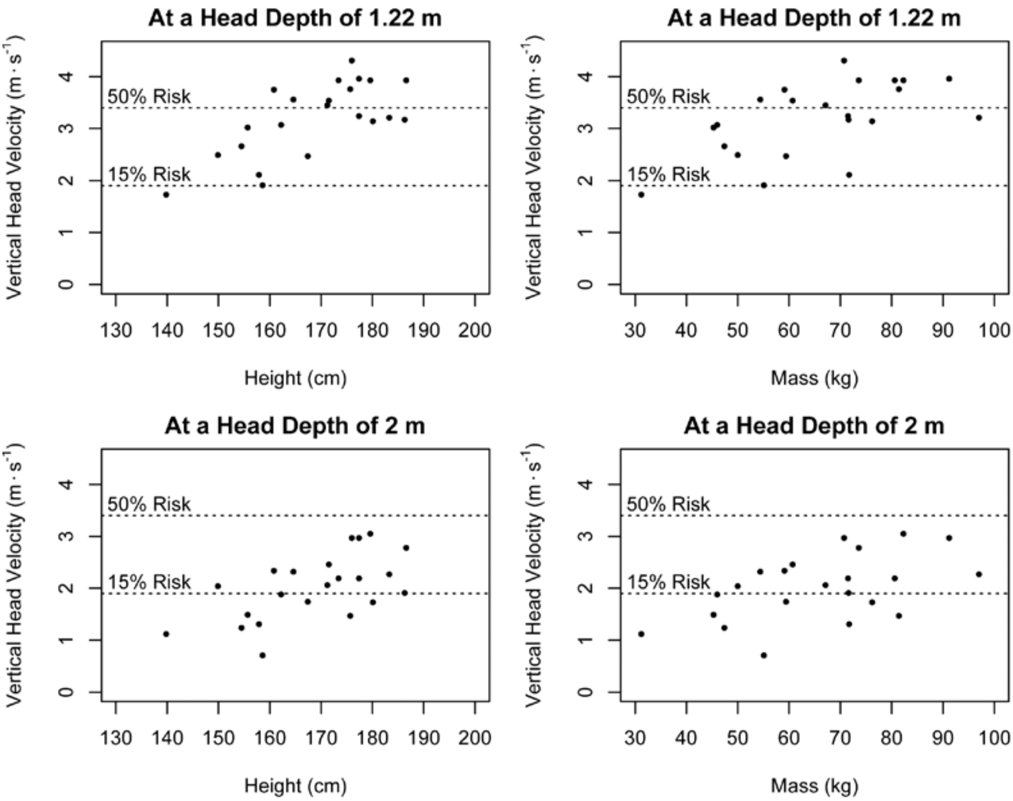

Figure 1 — Vertical head velocity (m•s^{-1}) as a function of height (cm) at a water depth of 1.22 m (upper left), mass (kg) at a water depth of 1.22 m (upper right), height (cm) at a water depth of 2.0 m (lower left), and mass (kg) at a water depth of 2.0 m (lower right). Water depths of 1.22 and 2.0 m were used because they are the current minimum water depth enforced by USA Swimming and the proposed minimum water depth by the Center for Disease Control and Prevention, respectively. The dotted lines on the graphs correspond to vertical head speeds of 1.9 and 3.4 m•s^{-1} and represent 15% and 50% risks of catastrophic head and neck injury, respectively, should a hard-surface impact occur (Viano & Parenteau, 2008).

water depth and that risk is greater for taller, more massive swimmers. Before establishing any comprehensive water depth regulations based on these findings, however, there is one further issue that must be discussed.

Time to Reach Different Water Depths After Water Entry

The amount of time it takes a swimmer to reach a certain water depth after water entry is an important variable from the perspective of start safety. The longer it takes a swimmer to reach the pool bottom after water entry, the available time the swimmer has to alter his trajectory so as to avoid contacting the pool bottom.

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Albrand and Walter (1975) previously investigated the vertical head velocity when two expert divers dove into a diving well from different heights and found that the divers reached depths of 2–3 m in less than a half second. They suggested that minimum water depth restrictions be based on the depths reached a half a second after water entry because "the average person has a reaction time of 0.25 to 0.50 seconds" (Albrand & Walter, 1975). The swimmers we filmed were shown to reach depths up to 1.5 m in less than half a second during simulated worst-case swim starts. Thus, using Albrand and Walter's logic, these water depths should be considered unsafe for the execution of competitive racing starts because swimmers do not appear to have enough time available to react and/or to adjust their trajectory should there be a need to do so.

The skill to coordinate, control, and modify starting depth is an important safety consideration. Individuals with greater control over their trajectory and/or skill to modify their trajectory once leaving the starting block are at less of a risk of contacting the pool bottom than those swimmers with less control of starting depth and/or less skill to modify start depth in response to certain factors. When asked to do so, experienced competitive swimmers have been shown to more consistently adjust their typical starting depth than inexperienced competitive swimmers (White, Cornett, Wright, Willmott, & Stager, 2011). From the perspective of depth modification, it was the inexperienced competitive swimmers, who also happened to be shorter and less massive than the experienced swimmers, who were at a greater risk of injury due to pool bottom collisions during execution of the competitive swim start.

In summary, "how deep is deep enough?" is a difficult question to address and to some extent the answer is dependent upon an affiliated question, "deep enough for what?" If the intention of the governing bodies is to eliminate any chance of catastrophic injury, one legislative outcome might be necessary, but if the goal is to minimize the risk to some reasonable and acceptable level, an entirely different rule might be required. As noted earlier, USA Swimming requires a minimum water depth of 1.22 m for the execution of swim starts and the Center for Disease Control and Prevention (CDC) currently is composing a comprehensive Model Aquatic Health Code which may dictate a federal minimum pool water depth of 2.0 m for the installation of competitive starting blocks. In our opinion, these and any future mandates should be based upon empirical data. The data presented here suggest that within the feasible range of minimum water depths the possibility of catastrophic head and neck injury cannot be eliminated; it can only be minimized. Even at depths as great as 2.50 m, there are still swimmers traveling fast enough during worst-case starts to suffer substantial injury should an impact occur.

If we are only able to minimize the risk of catastrophic injury during execution of the competitive swim start, it is important that we identify the swimmers at the greatest risk of injury due to pool bottom collisions. From the perspective of vertical head velocity, taller, more massive swimmers are at a greater risk of injury because they are moving faster toward the pool bottom at the different water depths. Previous research regarding maximum head depth also suggested that the taller, more massive swimmers have a greater risk of catastrophic head and neck injury from pool bottom collisions than shorter, less massive swimmers because they typically perform starts that are deeper (Cornett et al., 2010 and 2011; White et al., 2011). Maximum head depth and vertical velocity are not the only factors that need to be considered though. The skill to control and/or modify depth and the available time required to do so must be considered because these are important factors in avoiding pool bottom collisions as well. The least experienced competitive swimmers were not able to modify start depth with the same consistency as the more experienced ones (White et al., 2011). Thus, these inexperienced swimmers seem to be at a greater risk of injury based on inconsistently modifying start depth.

Conclusions

When weighing all the information, we conclude that the swimmers at the greatest risk of injury from a pool bottom collision are the inexperienced full-grown, or nearly full-grown, competitive swimmers such as one might find on a junior varsity swim team. These swimmers often lack the skill to control or modify starting depth but have heights and masses associated with deep starts and vertical head velocities frequently exceeding thresholds established as capable of resulting in serious head and neck injury. This combination of factors can have catastrophic consequences.

The potential for injury during worst-case scenario starts existed at all depths measured. In regards to reducing this injury potential, there seems to be only modest additional benefit to increasing water depth from 1.75 to 2.50 m as more than one third of the starts analyzed still had at least a 15% risk of catastrophic head and neck injury should an impact occur. Further study and consideration should be given to the parameters reviewed here for dives executed into these water depths. In addition, increased efforts should be spent on ensuring that all swimmers, especially physically mature, but inexperienced individuals who are tall and have a large body mass, are carefully instructed and able to control swim start depth before performing starts in shallower water.

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