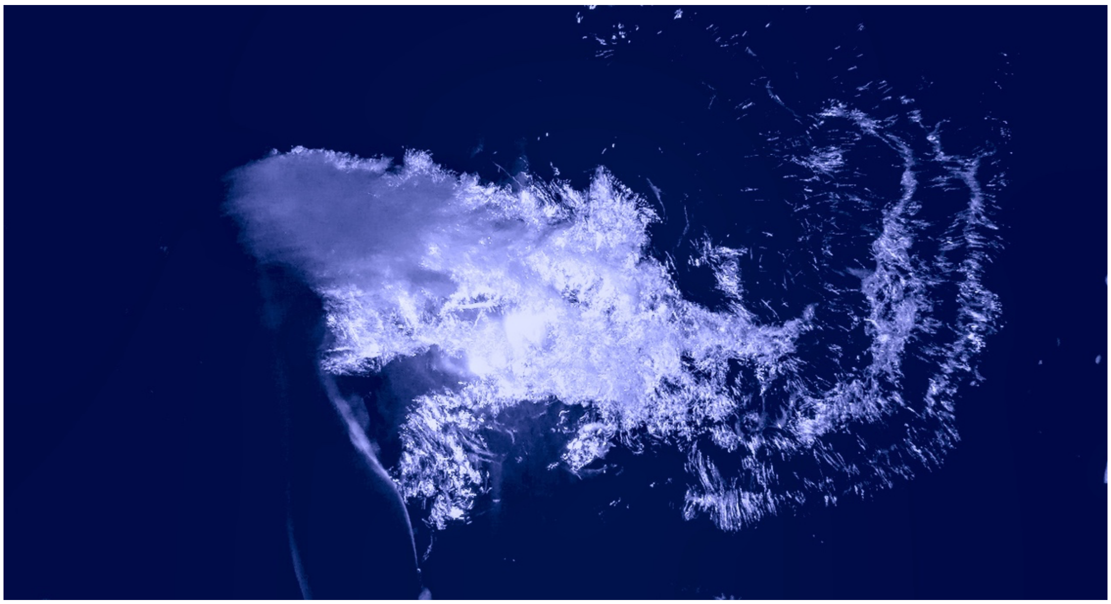
KICKING BUBBLES (VIDEO)



TEAM SECOND, FALL 2023

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ACKNOWLEDGEMENTS
Jill Murphey

Music Credits

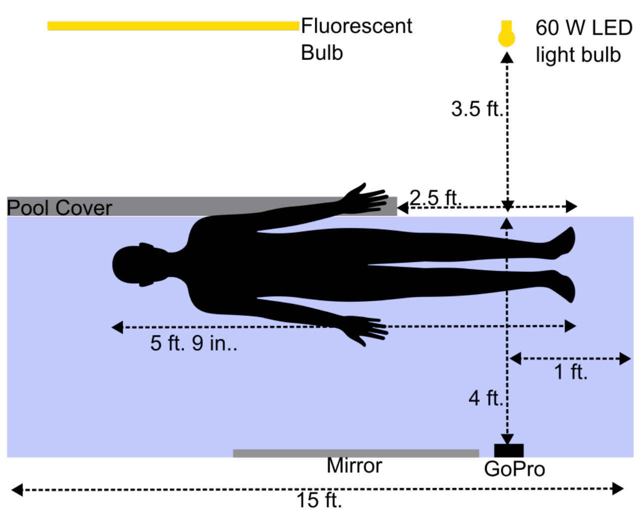
Swans in Flight by Asher Fulero

(YouTube Audio Library)

INTRODUCTION

For the Team Second assignment for the Fall 2023 iteration of MCEN 5151 – Flow Visualization at the University of Colorado Boulder, I filmed a video of a swimmer kicking in a pool of water. My *artistic objective* was to create a striking video or image of the flow induced during swimming. As a child, I was taught that you swim fastest when you do not fight the water to move through it. Through this video, I hoped to show the symbiotic cooperation between the swimmer and the water. As a scientist, I find the fluid-structure interaction of swimming fascinating. Through this kicking video, I hoped to capture the vortices shed as a swimmer kicks to propel through the water.

This video was partially inspired by an early 2000s anecdote that was common within the swimming community. Olympic Gold Medalist, Misty Hyman, who pioneered the underwater kicking technique adopted by almost all elite swimmers today, was said to have filmed herself dolphin or "butterfly" kicking with an ink-filled tube that dispensed ink into the flow of her kick (DeSimone, 1997). According to this anecdote, she was able to generate extremely large vortices as she kicked (DeSimone, 1997). As ink, other dyes, and other common particles for seeding flow are banned from most public swimming pools, I wanted to try to visualize the vortices produced by kicking through some other means.



SETUP

To film this video, I placed a GoPro HERO11 Black camera on the floor of a 4 ft. deep swimming flume. This flume is housed at my mother's house. A swimming flume (often called an "endless pool") is like a swimming treadmill. When the propulsive jets of this flume are off, the flume is just a small, rectangular swimming pool. I opted to use the flume rather than a public swimming pool so that I could control the background of the photo and types of lighting I could use illuminate the flow. The room in which the flume is housed includes a large fluorescent light hovering over a portion of the flume. However, that fluorescent light flickers frequently and is off-centered with the flume, making an awkward backdrop for an image. The room also a 60 Watt LED light fixture hovering over one end of the flume, approximately centered over the swimming flume. After much trial and error (8+ hours of filming), I found that kicking underneath this LED light produced compelling images that highlighted the flow most clearly. To block the flickering of the fluorescent light, I positioned the pool cover – an opaque, insulated layer used to retain heat – over most of the pool. The pool cover prevented most of the fluorescent light from reaching the lens of the GoPro. The pool cover also offered a solid surface I could hang onto while trying to kick without moving myself forward. I positioned my torso underneath the pool cover[*]. While this was not the most convenient position to kick, this was the only area above the flume with a mostly neutral background.

This video depicts a swimmer dolphin kicking on her side. Dolphin kick is traditionally used as a part of the butterfly stroke or immediately after a freestyler, butterflyer, or backstroker pushes off a wall. The dolphin kick involves moving both legs simultaneously back and forth, emulating the motion of a dolphin's tail fluke. Swimmers often kick while facing down or to one side (Alves et al., 2006). This motion propels the swimmer forward. In this video, I perform a dolphin kick while positioned on my side (my left side for the first portion of the video and my right side for the second portion). Before and after each trial, I tried to allow for any waves or bubbles to dissipate as I wished to capture the initial perturbation of the water. With prolonged kicking, too many bubbles and turbulence obscured the striking S-shaped wake that I saw in images with less initial disturbance.

PHYSICS

The physics of swimming is rather complex (Arellano et al., 2006; Hay & Thayer, 1989; Sanders et al., 1995; Wei et al., 2014), which is why I opted to show only a portion of a swimming stroke in this video. By focusing on kicking – dolphin kicking in particular – I hoped to illustrate the fluid-structure interaction between a swimmer's legs and feet and the surrounding water.

In this video, we see entrained bubbles form as my legs kick across the frame (Von Loebbecke et al., 2009). These bubbles form as I drag my upper leg across the surface of the water, pulling air into the flow. The bubbles outline vortices shed from my feet. These vortices are similar to those shown by Von Loebbecke et al. in 2009 (and reproduced below in Figure 1). The shed vortices and entrained bubbles leave behind a striking S-shaped wake.

As I kick, bubbles form as a result of hydrodynamic cavitation (Blake et al., 2015; "Cavitation," 2023). Hydrodynamic cavitation occurs when there is a local decrease in pressure below the saturated vapor pressure of the liquid. This local decrease is then followed by recovery of pressure to above the vapor pressure ("Cavitation," 2023). The result of these rapidly changing pressures is bubble formation, bubble implosion, and liquid vaporization. As I kick in this video, the interface between my feet and the water for a boundary layer. Since my feet move rapidly through the water, my feet force the fluid immediately around my feet to move at a similar velocity. We know from the Bernoulli equation that an increase in velocity causes a decrease in pressure.

[*] There was a small airgap between the pool cover and the surface of the water, where I could breathe. My mother, Jill Murphey, also supervised my filming and served as a life-guard in case I got trapped under the pool cover.

Therefore, my kicking causes a local decrease in pressure in the fluid immediately around my feet. In this case, my feet move at such a velocity to cause the pressure of the fluid to dip below the saturated vapor pressure of the water. To determine whether cavitation appears in this video, we can use the cavitation number. The cavitation number is defined as $Ca = \frac{p - p_v}{\frac{1}{2}\rho v^2}$, where p is the local pressure, p_v is the vapor pressure, v is the characteristic velocity, and ρ is the density. However, given the setup in this video, it is rather challenging to quantify the local pressure in this video without local pressure gauges (e.g., on my foot).

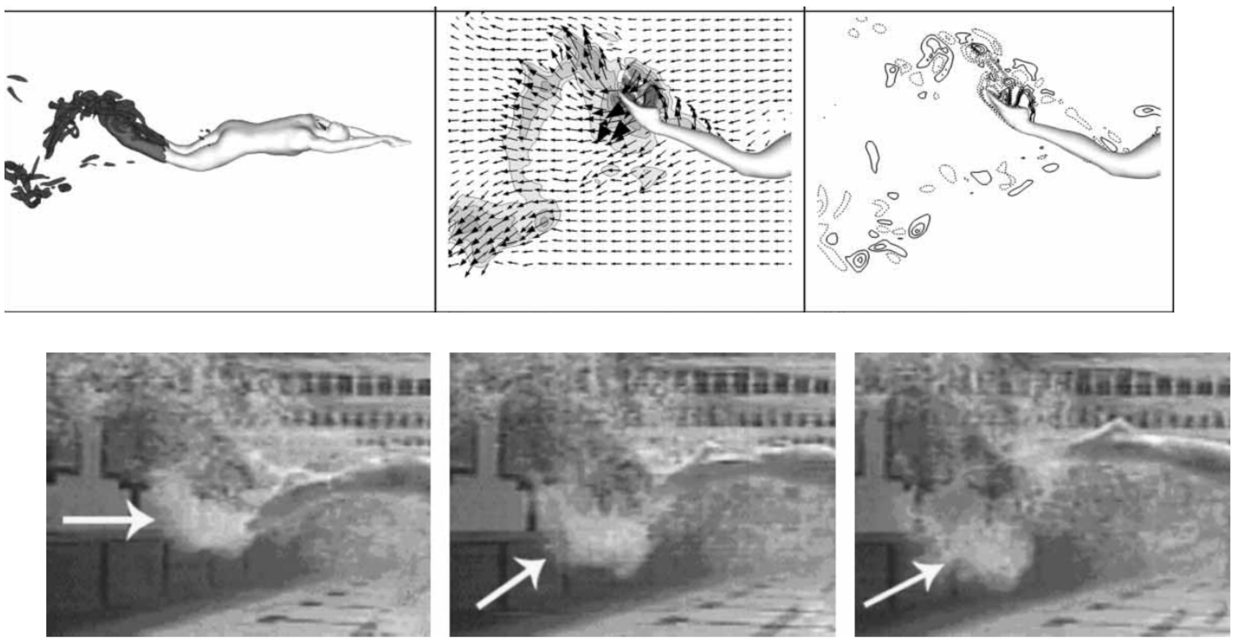


FIGURE 1: COMPUTATIONAL FLUID DYNAMICS SIMULATION OF VORTEX SHEDDING (TOP PANEL) AND STILL IMAGES OF A SWIMMER DOLPHIN KICKING (BOTTOM PANEL). THE ARROWS POINT TO VORTICES SHED FROM THE SWIMMER'S FOOT OUTLINED BY ENTRAINED BUBBLES (VON LOEBBECKE ET AL., 2009)

Swimmers care most about the propulsive impact of movement through the water. To understand the propulsive power and efficiency of kicks, we look to the Strouhal number, which describes oscillating flows, typically driven by the propulsive oscillation of a structure (e.g., a tail or a swimmer's legs) ("Strouhal Number," 2023). In animal locomotion, the Strouhal number is given as $St = \frac{fA}{U}$, where f is the oscillation frequency of the swimmer's legs, U is the velocity of the swimmer through the water, and A is the peak to peak amplitude of the kick ("Strouhal Number," 2023). Since I limited forward motion in this video by holding onto the pool cover, I have opted to use an approximation of my velocity based on a cross-pool kicking trial conducted the same day as this experiment. During the same filming session, I attempted to keep the frequency of my kick and amplitude constant while traversing the length of the swim flume (~12 ft.) using dolphin kick only. My mother timed this trial, recording a time of 2.3 seconds. This equates to a kicking velocity of 12 ft/2.3s = 5.2 ft/s or 62.4 in/s.

I calculate the frequency of my kick oscillation f from the raw video. I complete two cycles of my kick in 4.6 seconds during the continuous kicking video, yielding an average frequency of 0.43 Hz. Using the same video, I tracked my leg movement frame by frame to estimate the peak kick amplitude from the forward most point to the rearmost point. The white wall visible at the top of the video frames is 37 inches long. I used this white wall as a reference distance to help quantify the kick amplitude[†]. My feet appear to travel from a point approximately aligned with the leftmost edge of the white wall up to edge of the silver handle on the other side of the wall – a distance of approximately 32 inches. Therefore, my kick has an amplitude of approximately 32 inches in this video.

$$St = \frac{fA}{U} = \frac{(0.43 \text{ Hz} * 32 \text{ in})}{62.4 \text{ in/s}} = 2.2 \text{ x } 10^{-1}$$

This Strouhal number is an order of magnitude smaller than reported in the literature (Alves et al., 2006; von Loebbecke et al., 2009). For a sub-elite female swimmer, we should expect to see a Strouhal number of 1.05. Alves et al. suggest that lateral kicking (as we see in this video) coincides with lower mean body velocities and lower frequency kicking, yielding a higher Strouhal number. However, the difference between my Strouhal number and the literature could arise because I intentionally slowing my kick frequency to accentuate the flow around my feet and limit perturbations that may have obfuscated the vortices around my feet. This slow kick frequency (much slower than I would normally perform while swimming) may have artificially decreased the Strouhal number.

From this information, we can also estimate the Reynolds number for the kick to determine whether turbulence plays a role. The Reynolds number for a swimming body in a fluid is defined by $\text{Re} = \frac{2\text{rV}\rho}{\mu}$, where r is the hydraulic radius (r = $2A/P$, where A is the cross-sectional area, and P is the wetted perimeter), V is the flow velocity, ρ is the fluid density (1.225 kg/m^3), and μ is the fluid viscosity (1.05 × 10^{-3} Pa-s) (Merck, 2017). The hydraulic radius of my leg is rather challenging to estimate. To gain a first-order approximation of the hydraulic radius, I can approximate my leg and foot as a cylinder of a diameter corresponding to average diameter for the entire leg. I estimate that the average diameter is approximately the diameter of my calf[‡]. The circumference of my calf is ~15.7 inches, giving a radius of ~2.5 inches ($\text{r} = \text{C} / (2 * \pi)$). With this radius, we can calculate the cross-sectional area of my leg ($2.5^2 * \pi$ = 19.6 in^2). The wetted perimeter of the cylinder is $\text{P} = 2\pi\text{r} = 2\pi(2.5 \text{ in}) = 15.7\text{in}$, which gives a hydraulic radius r = $2A/P = 1.6 \text{ in} = 0.04 \text{ m}$.

$$\text{Re} = \frac{2\text{rV}\rho}{\mu} = \frac{2*1.6 \text{ in}*62.4 \text{ in/s}*1.225 \text{ kg/m}^3}{1.05 \text{ x } 10^{-3} \text{ Pa} - \text{s}} = \frac{2*0.04\text{m}*1.6\text{m/s}*1.225 \text{ kg/m}^3}{1.05 \text{ x } 10^{-3} \text{ Pa} - \text{s}} = 150$$

Given this relatively low Reynolds number (Re = 150), this kicking video may illustrate low Reynolds number turbulence. Similar low Reynolds numbers and turbulence have been recorded during animal locomotion in the literature (Liu, 2005)

[†] I could have done this using pixel distances as well.
[‡] This is a very rough approximation.

Flow Visualization

The flow visualization technique in this video is a seeded boundary technique. The "particles" that seed the boundary in this video are the entrained bubbles. LED backlighting illuminates these bubbles and the turbulence produced as I kick. A mirror, placed on the bottle of the swimming flume helps reflect some of the light upward to further highlight the bubbles. To some extent, the lighting also illuminates some of the surface waves generated from the kicking.

Photography

To capture this video, I used a GoPro HERO11 Black recording 120 frames per second at 4k resolution with a "wide angle lens." As described above, I placed the GoPro on the bottom of the swimming flume, directly underneath the LED bulb. I also captured still images using a burst mode that recorded 30 frames over 3 seconds. This mode generated the thumbnails for my image. For this burst mode, the camera automatically used an aperture of f/2.5, an exposure of 1/24, and an ISO of 1484. I was unable to modify these settings, which was unfortunately. Clearly, I required a much faster shutter speed than 1/24.

While my camera could record 240 fps, it could only do so at a reduced resolution (30p). To optimize the balance between frame rate and image resolution, I opted for the 4k 120 fps video option. At 120 fps, between, my foot moves 0.52 inches. In class, we learned this is not quite the temporal resolution we would need to prevent motion blur in this image. With that logic, 240 fps also would have been insufficient. However, I do not believe the motion blur in this video is all that distracting (it was in the still images I captured). Given the limitations of the GoPro, I believe this compromise was justified to get better spatial resolution that illustrates the scales the entrained bubbles and magnitude of the kick and vortices.

Table 1: Camera and Video Settings

Camera	GoPro HERO11 Black
Lens	Wide Angle Lens
Light Source	60 Watt LED Light bulb
Image	
Focal Length	2.7 mm (15mm FF equivalent)
ISO Speed Rating	ISO 1484
Aperture	Auto - unknown
F number	f/2.5
Exposure	1/24
RAW Image Size	5568 x 4872
Edited Image Size	4416 x 2389
Edited Resolution	72 pixels/inch
Camera Mode	Burst – 30 frames over 1 second
Video	
Playback speed	Varied – between 0.25x up to 1x
Lens	Wide Angle Lens
Camera Modes	4k, 120 fps
Edited Video Resolution	4k, 60 fps

Post-Processing

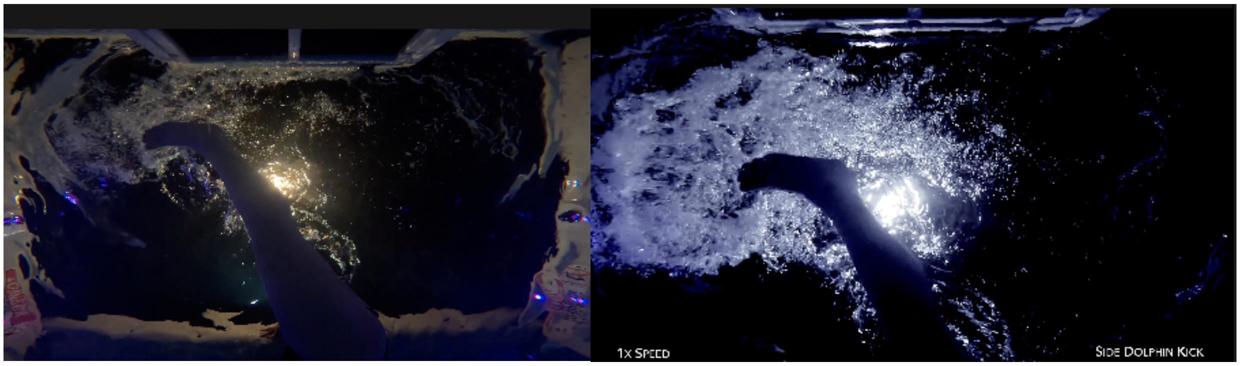


Figure 2: Unedited (left) and Edited (Right) Frames from the Kicking Video

To edit this video, I used a free trial of Final Cut Pro. Upon importing this video into Final Cut Pro, I cropped out the side walls and pool cover that were visible in the frame. I found these elements unnecessary to visualize the flow. I also applied an image filter to decrease some of the yellowish light from the LED bulb. Final Cut Pro has built in filters to assist with editing. I opted for the "Moonlight" filter, which increased the contrast, modified the hue of the shadows, midtones and highlights; decreased the saturation of the shadows and midtones; and increased the exposure of the midtones and highlights. Images of the color, saturation, and exposure curves are in the Appendix of this document. I also added music by Asher Fulero (free and non-copyrighted on Youtube Audio Library) to highlight the beauty of the frames. To accentuate the vortex shedding off my feet when my feet complete the final forward kick in the video, I aligned the final chord of the music "Swans in Flight" with the final flick of my toes in the final frames of the video.

Conclusion

This video depicts the vortices shed from the fluid-structure interaction between the swimmer's legs and the surrounding water during a dolphin kick. I find the frames of this video mesmerizing. As a lifelong swimmer, I have found many images of swimming to be either purely academic or geared toward captivating a swimming fanbase (i.e., those interested mostly in the sport of swimming instead of the science). As such, those images focus mostly on the dynamics of the swimmer themselves. Rarely do these images incorporate an artistic representation of the *flow*. I believe the video discussed in this report incorporates artistic elements that augment the illustration of the physics in a striking and dramatic way.

Acknowledgements

I thank my mother, Jill Murphey, for her assistance in filming this video. She helped me experiment with lighting and lifeguarded me as we conducted many trials.

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APPENDIX

EDITED TONE CURVES

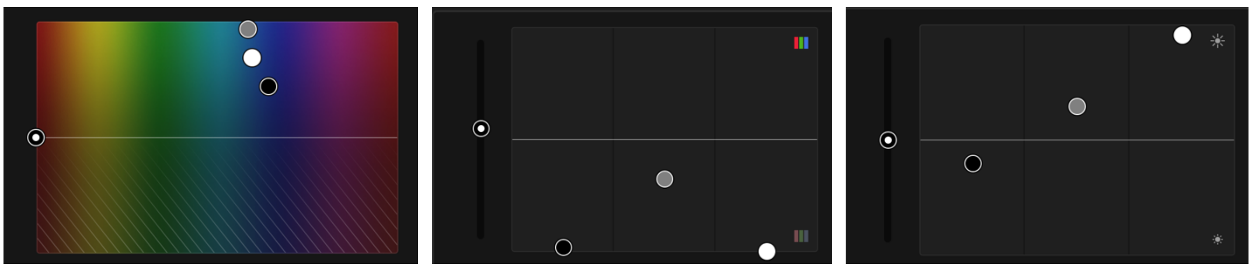
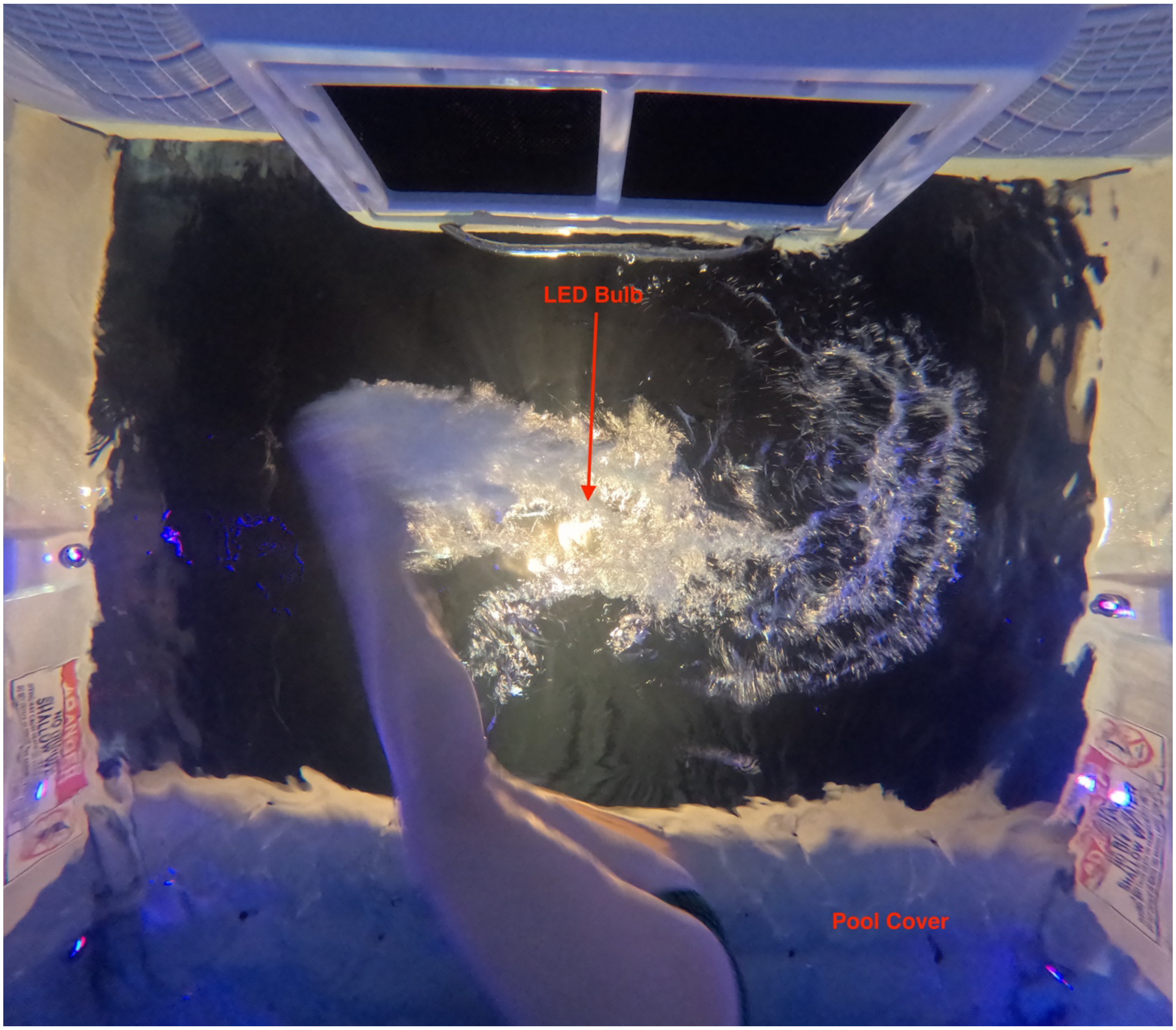
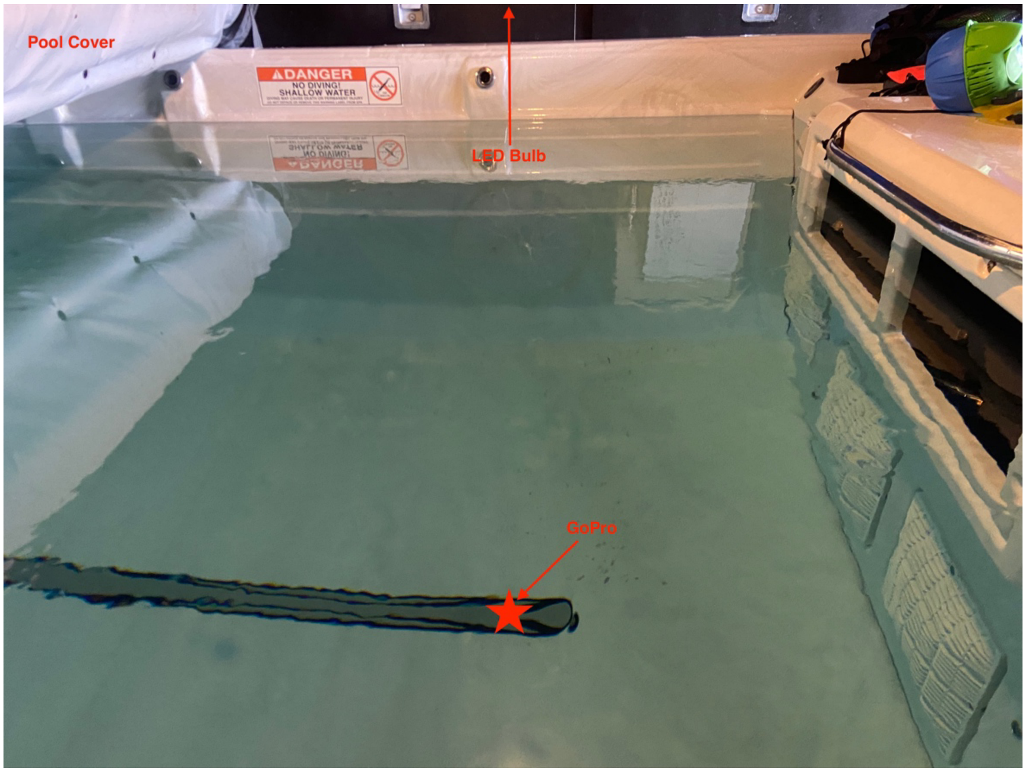


FIGURE 3: COLOR (LEFT), SATURATION (MIDDLE), AND EXPOSURE (RIGHT) SETTINGS FOR THE EDITED VIDEO.

More Setup Images




Pool Cover
ΔDANGER
NO DIVING!
SHALLOW WATER
LED Bulb
GoPro