Splish Splash: Modeling Diving

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In this study I modeled diving by dropping a metal plate into pool water. Not only did I measure the force that the water had on the plate at the time of impact, but I measured the surface tension for each of the three concentrations of chlorine. I found that with an increase of chlorine, the force the water had on the plate decreased. At 0.5 parts per million of chlorine the force was -34 ± 4 N and decreased to -30 ± 2 N with 3.0 ppm chlorine. I had similar results for the surface tension, with the surface tension decreasing from 93.47± 0.03 mN/m in 0.5 ppm to 63.42± 0.02 mN/m with the increased amount of 3.0 ppm chlorine in the water. The findings of this and similar future work could be used to improve injury understanding and treatment for divers around the world.

I. INTRODUCTION

I have been a springboard diver for approximately 10 years, including 4 years in NCAA Division III, and in that time I have experienced and seen many injuries due to diving. My personal injuries have included bruises, sprained wrists, back/ neck strain, lacerations, and a concussion. Although hitting the diving board is by far the most traumatic and feared by divers and spectators alike, I am particularly interested in injuries involving the diver's contact with the pool water. If done properly, as a diver enters the water, his or her hands (or feet, depending on the dive) absorb most of the initial impact force. The "new" technique of head-first entry, called the open-hand technique, has led to many more injuries to divers' upper extremities [1]. For this technique the diver flexes one wrist to 90° and places the other hand on top of it, interlacing thumbs, elbows are usually "locked" straight and shoulders are pushed up to minimize the space between the arms and the head. This technique allows the diver to enter the water with as little splash as possible. The "old" technique involved the diver making fists with both hands, sometimes grabbing one thumb with the other hand, and extending the elbows and arms like previously described. The most common diving injuries after injuries caused by contact with the diving board are wrist and elbow injuries [1]. A 1993 Paris hospital study showed 18 of 21 divers surveyed experienced pain in their hands upon impact with the water [1]. Overuse and/or repeated impact causes many long term injuries, like severe wrist sprain, fracture, or concussion. This year, three female divers from the College of Wooster's athletic conference had broken eardrums. By modeling the head-first-entry aspect of diving, I attempted to study the force experienced by a diver as a result of impact with water of varying chlorine levels.

I used two methods of experiment to investigate the effects of the levels of chlorine in the pool water on the force experienced by a diver. Each swimming pool has a different level of chlorine, and even the College of Wooster pool's chlorine levels change regularly, which is why I used the level of chlorine in pool water as the variable. First, I modeled the entry by dropping a metal plat into a bucket of the sample pool water. Then, I used an

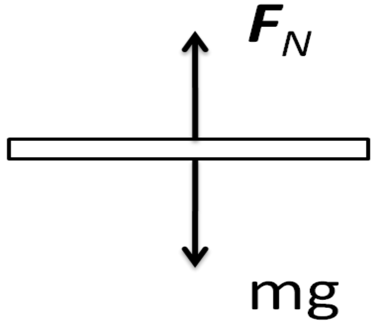

Figure 1. This is the free-body diagram of the plate, with F_N as the normal force from the water, and *mg* is the force due to gravity

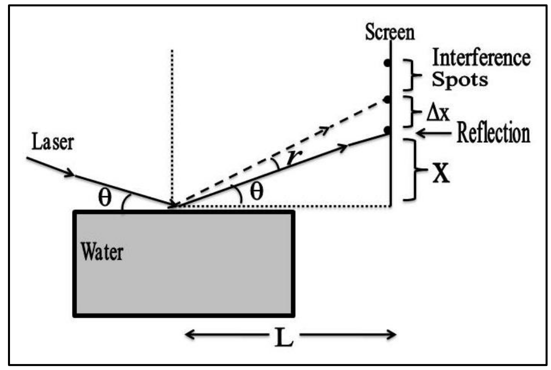

Figure 2. Diagram of the experiment with specific attention to the necessary measurements.

experiment from the regular Junior I.S. repertoire, measuring the surface tension of each of the pool water samples.

II. THEORY

Sir Isaac Newton described the motion of bodies in three observations, known today as Newton's Laws of Motion. The Second Law states that "the response of a body to a net force is an acceleration" [2], or more familiarly:

$$\vec{F}_{net} = m\vec{a} \, , \qquad (1)$$

where F_{net} is the sum of the forces acting on the body, m is the mass, and a is the acceleration. Acceleration can be represented as the time derivative of velocity, or the second time derivative of position. For this experiment, I used the former, so Equation 1 became

$$\vec{F}_{net} = m\frac{dv}{dt} \, . \qquad (2)$$

Figure 1 is the free-body diagram of the plate.

I chose not to describe the motion of the plate hitting the water as a collision because there is loss of energy to sound and the splashing water would be nearly impossible to measure with the equipment I had.

For the second aspect of my study, I used G. Weisbuch and F. Garbay's method to determine the surface tension of a liquid. In this method, surface waves are created using a function generator and a laser is reflected off the surface of the liquid at a very small angle. The reflection and interference pattern from the laser can be measured at known frequencies to determine the surface tension of the liquid. Specifically, varying the frequency of the speaker changes Δx. Figure 2 shows this set-up.

The dispersion relation for surface tension waves in this situation is

$$\omega^2 = \left(\frac{\sigma}{\rho}\right) q^3 \, , \qquad (3)$$

where ω is $2\pi f$, f is the frequency of the speaker in Hz, σ is the surface tension, ρ is the mass density of the liquid and q is the

a. b.

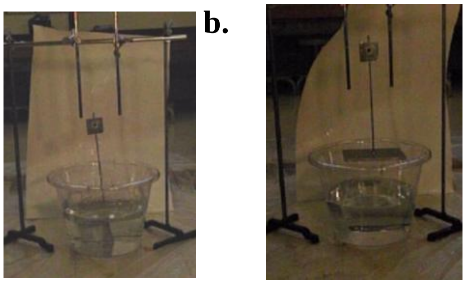

Figure 3. a.) A drop using 0.5 ppm chlorine water. b.) A drop using 3.0 ppm chlorine water.

wave vector [3]. The wave vector of cylindrical waves on the surface is described by this relationship, q,

$$q = \frac{2\pi}{\lambda}\sin\frac{r}{2}\left[\sin\left(\theta - \frac{r}{2}\right) + \sin\left(\theta + \frac{r}{2}\right)\right], \quad (4)$$

where λ is the wavelength of the laser, r is the angle between the reflected beam and the first intense dots, and θ is the angle of incidence of the laser (see Figure 2) [4]. As one can see from Figure 2,

$$\theta = \tan^{-1}\frac{x}{L} \quad (5)$$

and

$$r \cong \tan^{-1}\frac{\Delta x}{L}\,. \quad (6)$$

The small-angle approximation thus reduces Equation 4 to

$$q = \frac{2\pi r\theta}{\lambda}\,. \quad (7)$$

III. PROCEDURE

Drop Experiment

For the drop experiment, I dropped an aluminum plate with about the same surface area of my hands into a bucket of pool water. I took pool water samples from the College of Wooster's Swimming pool with the permission of head swim coach Rob Harrington. I used a total of three different concentrations of chlorine, 0.5 parts per million (ppm), 2.0 ppm, and 3.0 ppm. I gathered and stored the water in plastic tubs with lids. The aluminum plate and flag attachment I cut and assembled in the Physics workshop. The plate was guided into the bucket by two greased poles to minimize rotation of the plate as it fell.

For each drop of the plate I guided the plate up the guide poles, held the plate steady by the flag, and then released it when I thought it was level. I recorded each drop with a high speed camera at 1000 frames/ second. To analyze this data, I used iMovie and LoggerPro in combination. By uploading the high speed video into iMovie, I was able to crop the entire video clip down to the few seconds of each drop. LoggerPro is a program in which I could click on the black dot I marked on the flag attached to the plate, frame by frame, and it then calculates the position of the object in relation to time. I used the distance between the two guide-poles as my reference distance. Figure 3 shows the set up of the 0.5 ppm and 3.0 ppm runs, the set up for the 2.0 ppm was identical to these.

A source of error is the variability from drop to drop. I personally performed the drops of the plate into the sample water. I held the flag attached to the plate until I thought the plate was level and steady, and then I released the plate. Not all of the drops may have landed perfectly flat on the water, some may have had an edge enter the water first, which would have altered the change in velocity of the plate as it impacted the water. Thus I dropped the plate several times and picked the best three to analyze based on how flatly the plate hit the water.

Surface Tension Experiment

The surface tension experiment requires that a laser hit at the center of a circular water dish, filled perfectly to the brim, at an

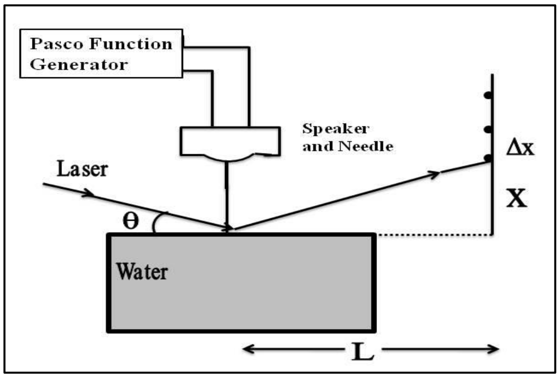

Figure 4. This is a diagram of the experimental set up.

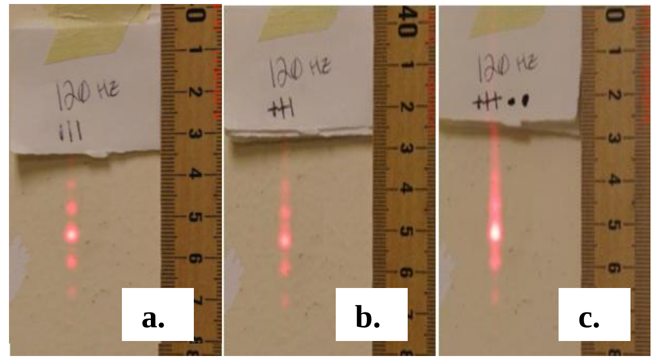

Figure 5. The reflection and interference spots at 120 Hz from chlorine water for a.) 0.5 ppm, b.) 2.0 ppm, c.) 3.0 ppm.

angle of less than 5 degrees. That beam of light is then reflected onto a flat surface so measurements may be taken of the reflection and interference points. To make cylindrical surface waves I positioned a needle, which was attached to the center of a speaker, such that it barely made contact with the surface of the water. The speaker was then connected to a Pasco wave generator, so I was able to adjust the frequency of the needle. Figure 4 is a diagram of this set up. In each set, I recorded the data by taking digital pictures of the reflection and interference points. I measured the Δx above and below the reflection point for each of 5 frequencies by drawing horizontal lines on the pictures that extended over the meter stick attached to the wall. Figure 5 shows the reflection and interference points for 120 Hz. I calculated the density of each water sample by massing 50 mL on an electric balance. I had to use such a small amount because of the limitations of the balance.

Due to other chemicals and substances in the pool water besides chlorine including calcium, sodium, human sweat, and general dirt among other things, uncertainty or errors may have been greater than anticipated. The pool chemical testing kit that I used only checked for chlorine, although other parts of the kit can check for calcium and alkalinity of the water. Also by greasing the guide poles and constantly washing the bucket, grease or soap may have been introduced into the sample water. Along those lines, I did not check the evaporation rate of the chlorine water, so I do not know if the water used for the surface tension tests had the same concentration of chlorine as it did when performed the drop tests. In the case of the 0.5 ppm water, it had sat, albeit covered, for almost two weeks in between the drop tests and the surface tension tests. These factors most likely had a negative effect of the results from the surface tension tests.

IV. RESULTS

LoggerPro automatically calculated the velocities of the falling plate, so in order to determine the acceleration of the plate; I had to take the difference of those velocities. I picked the points indicated by when the acceleration changed the most over one data point. On the graph of position, velocity, and acceleration, for each sample, like Figure 6, I picked the acceleration point which was greatest in the negative direction. Figure 6 shows a graph with the position, velocity, and acceleration from one sample

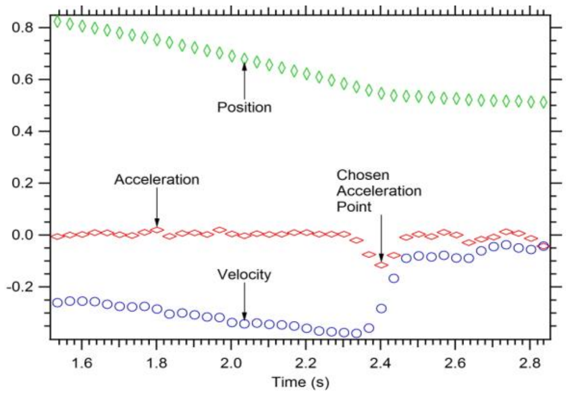

Figure 6. This IgorPro graph shows position, velocity, and acceleration with respect to time for each of the chlorine levels.

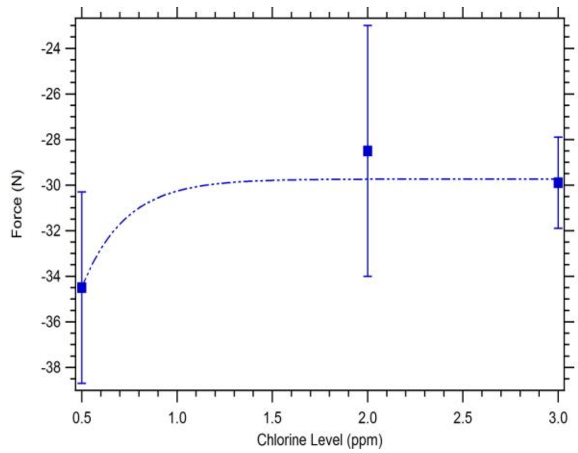

Figure 7. This IgorPro graph shows the data from Table 1 with an exponential fit line.

Table 1. This table gives my final results for the average force experienced by each plate on impact with the corresponding chlorine level.

Chlorine Level	Force
0.5 ppm	-34 ± 4 N
2.0 ppm	-29 ± 5 N
3.0 ppm	-30 ± 2 N

as well as the acceleration point chosen. Using the accelerations I chose I calculated the net forces using Equation 1, and the mass of the plate = 336.70 ± 0.02 g. The results are in Table 1 and Figure 7.

The results of this part of the experiment were what I had expected. As the level of chlorine in the water was increased the ability of the water to push back on the plate after contact was decreased. This means that diving into a pool with a higher level of chlorine would lower the risk of upper extremity injury.

I fit the data to an exponential curve because it would suggest that there is a certain point at which adding more chlorine would not be significantly beneficial, also, health concerns might hinder diving into pools with chlorine much higher than 3.0 ppm.

For the surface tension experiment, I averaged the Δx values for each frequency then used it in Equations 6 and 7 along with the calculated θ and $\lambda = 6.33\times10^{-7}$ m to calculate q. By rearranging Equation 3 as

$$\frac{q^3}{\omega^2} = b = \frac{\rho}{\sigma}, \qquad (8)$$

where b is the slope of the linear fit line of q^3 versus ω^2, when the y-intercept is held at 0, solving for the surface tension becomes clear; so I graphed q^3 versus ω^2. Figure 8 and Table 2 show the results of this part of the experiment.

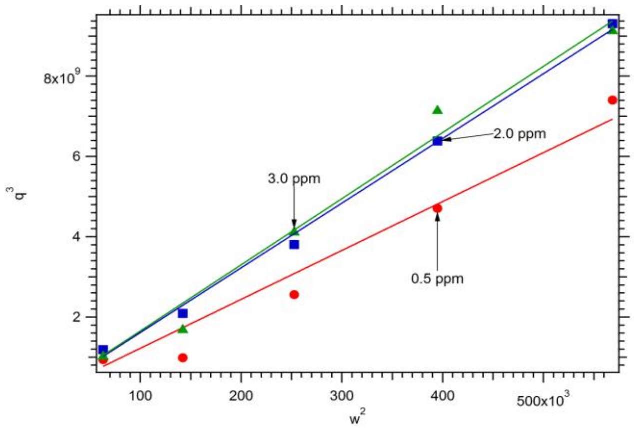

Figure 8. The slope of each of these linear fit lines is *b*, which I used to determine each water sample's surface tension.

Table 2. This table displays slopes from the graphs, the water densities, and the calculated surface tensions for each water sample.

Chlorine	Density (ρ)	q^3/ω^2 (*b*)	Surface Tension (σ)	mN/m
0.5 ppm	1139.8	12194	0.09347	93.47± 0.03
2.0 ppm	1129	16127	0.07001	70.01± 0.02
3.0 ppm	1045.8	16490	0.06342	63.42± 0.02

In a previous experiment, I calculated the surface tension of distilled water to be approximately 81.1 mN/m. This has 4% error from the accepted value of the surface tension of water at 20 ^{o}C, which is 72.8 mN/m [5]. The results of the 2.0 ppm and 3.0 ppm chlorine water samples are consistent with the results from the plate drop experiment with the surface tension, and thus the force of the water, decreasing with the increase of chlorine. The surface tension of the 0.5 ppm chlorine water was greater than both my experimental and the actual surface tension of distilled water. I do not have a hypothesis as to why this phenomenon occurred other than that the chlorine or other chemicals in the pool water sample somehow increased the covalent and hydrogen bonds amongst the molecules in the water.

V. CONCLUSIONS

At 0.5 parts per million of chlorine the force was -34 ± 4 N and decreased to -30 ± 2 N with 3.0 ppm chlorine, although at 2.0 ppm chlorine, the force was -29 ± 5 N. Within the error range, the value could fall between the other two. I had similar results for the surface tension, with the surface tension decreasing from 93.47 ± 0.03 mN/m in 0.5 ppm to 63.42 ± 0.02 mN/m with the increased amount of 3.0 ppm chlorine in the water, this time 2.0 ppm chlorine was between the 0.5 ppm chlorine and the 3.0 ppm chlorine at 70.01 ± 0.02 mN/m.

The varying results of the drop experiment and the surface tension experiment suggest that it was necessary to analyze a dive from different aspects in order to get a more comprehensive understanding of the situation of a head-first entry. Aside from the data at the lowest chlorine levels, it can be concluded that the higher the level of chlorine in pool water, the lesser the surface tension of the water. This provides a weaker force of impact, which may decrease the chance of injuries due to impacting the water.

Future work in this area is both feasible and applicable. To better model diving, one could vary the drop heights or make them more proportional to the actual diving heights of 1 m, 3 m, 5 m, 7.5 m, and 10 m. Also by varying the mass of the dropped object, the experiment could more closely resemble a human body. In other applications, the information from this and other like experiments could lead to better diving related injury remediation and/or prevention. Finally, maybe there is a way to develop a new technique of entry that would be less strenuous for divers.

Acknowledgments

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