Journal of Visualized Experiments

Impacts of Free-Falling Spheres onto a Deep Liquid Pool with Altered Fluid and Impactor Surface Conditions

--Manuscript Draft--

Article Type:	Invited Methods Article - JoVE Produced Video
Manuscript Number:	JoVE59300R1
Full Title:	Impacts of Free-Falling Spheres onto a Deep Liquid Pool with Altered Fluid and Impactor Surface Conditions
Keywords:	engineering, cavity formation, fluid dynamics, hydrophilic, hydrophobic, protocol, splashing, water entry, wetting, Worthington jet
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Additional Information:	
Question	**Response**
Please indicate whether this article will be Standard Access or Open Access.	Standard Access (US$2,400)
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TITLE:

Impacts of Free-falling Spheres on a Deep Liquid Pool with Altered Fluid and Impactor Surface Conditions

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SUMMARY:

This protocol demonstrates the basic experimental configuration for water entry experiments with free-falling spheres. Methods for the alteration of liquid surface with penetrable fabrics, the preparation of chemically non-wetting spheres, and steps for splash visualization and data extraction are discussed.

ABSTRACT:

Vertical impacts of spheres on clean water have been the subject of numerous water entry investigations characterizing cavity formation, splash crown ascension and Worthington jet stability. Here, we establish experimental protocols for examining splash dynamics when smooth free-falling spheres of varying wettability, mass, and diameter impact the free surface of a deep liquid pool modified by thin penetrable fabrics and liquid surfactants. Water entry investigations provide accessible, easily assembled and executed experiments for studying complex fluid mechanics. We present herein a tunable protocol for characterizing splash height, flow separation metrics, and impactor kinematics, and representative results which might be acquired if reproducing our approach. The methods are applicable when characteristic splash dimensions remain below approximately 0.5 m. However, this protocol may be adapted for greater impactor release heights and impact velocities, which augurs well for translating results to naval and industry applications.

INTRODUCTION:

The characterization of splash dynamics arising from vertical impacts of solid objects on a deep liquid pool[1] is applicable to military, naval and industrial applications such as ballistic missile water entry and sea surface landing[2-5]. The first studies of water entry were conducted well more than a century ago[6-7]. Here, we establish clear in-depth protocols and best practices for achieving consistent results for water entry investigations. To aid valid experimental design, a method is presented for the maintenance of sanitary conditions, alteration of interfacial conditions, control of dimensionless parameters, chemical modification of impactor surface, and visualization of splash kinematics.

Vertical impacts of free-falling hydrophilic spheres on the quiescent fluid show no sign of air-entrapment at low velocities[8]. We find that the placement of thin penetrable fabrics atop the fluid surface causes cavity formation due to forced flow separation[1]. A meager amount of fabric on the surface amplifies splashing across a range of moderate Weber numbers while sufficient layering attenuates splashing as spheres overcome drag at fluid entry[1]. In this article, we explain protocols suitable for establishing the effects of material strength on the water entry of hydrophilic spheres.

Cavity forming splashes from hydrophobic impactors show the ascension of a well-developed splash crown, followed by the protrusion of the primary jet high above the surface when compared to their water-liking counterparts[8]. Here, we present an approach for achieving water repellency through chemically modifying the surface of hydrophilic spheres.

With the advent of high-speed cameras, splash visualization and characterization have become more attainable. Even so, established standards in the field call for the use of a single camera orthogonal to the primary axis of travel. We show that the use of an additional high-speed camera for overhead views is necessary to adjudge spheres strike the intended location.

PROTOCOL:

1. Configuring the experiment for vertical impacts

1.1. Fill a transparent water tank of dimensions approximately 60 cm x 30 cm x 36 cm (length x weight x depth) with 32 L of water and mount a meter ruler ('visual scale') vertically inside the container such that the base sits atop the fluid, as seen in **Figure 1a**.

NOTE: Depth and width of the tank must be greater than 20 times the diameter of the largest spheres used in the experiment to ensure wall effects are negligible[9]. Greater entry speeds than those described here will require greater tank depth. The visual scale used to determine drop heights and calibration of tracking software is discussed in section 7.

1.2. Place an additional meter ruler under the water, which can act to magnify dimensions. This visual scale is used for calibrating tracking software for underwater measurements.

1.3. Construct a hinged platform ('release mechanism') that suspends spheres above the fluid and rotates downward, to achieve tangential acceleration greater than gravity at the impactor location when released, as seen in **Figure 1a**. Rapid rotation is achieved by connecting the hinged platform to the center of the supporting component using elastic bands. The result is an unsupported and non-rotating impactor.

NOTE: The platform is easily fabricated with 3D printer.

1.4. For impact trials, place thumb to base of hinged platform and rotate it 90° to a horizontal position for placement of spheres above the fluid.

NOTE: Retraction is triggered when thumb is released from base of the platform.

1.5. Affix the release mechanism to a retort stand, such that the device can be adjusted to various heights.

1.6. Place the retort stand next to the tank such that the release mechanism is within the same depth plane as the visual scale. Add a weight to the base of the retort stand as needed to prevent toppling.

1.7. Adjust the release mechanism to the maximum desired experimental drop height. This is necessary for optimal splash visualization as discussed in section 6 and ensures the splash characteristics of interest are always within the viewing frame of the camera.

1.8. Attach a multi-LED light to an articulating arm such that the light is mounted above the camera, looking down onto the splash zone. Ambient light alone is insufficient to illuminate the scene at the high frame rates needed to extract splash kinematics.

NOTE: One can never have too much light.

1.9. Place a black screen at the back of the water tank to aid splash and cavity visualization as seen in **Figure 2**.

1.10. Place a glass-protecting shock absorber, such as a closed-cell sponge, at the bottom of water tank and affix with weights to prevent resurfacing.

NOTE: The height of the fluid in the tank should be such that the sphere does not interact with shock absorber prior to air cavity pinch off[10].

2. Controlling dimensionless parameters

2.1. Conduct experiments with smooth spheres of various masses and diameters. For this, polyoxymethylene (e.g., Delrin) coin-making balls work particularly well and have no mold part line. Measure masses and diameters with an analytical balance and Vernier caliper respectively.

2.2. Conduct experiments over a range of heights *H* to generate impact velocities $U \approx \sqrt{2 \cdot g \cdot H}$ where $g = 9.81$ m/s^2 is the acceleration due to gravity. Measure height with the visual scale within the camera frame.

NOTE: Use the **Auto-Tracking** feature in the video analysis tool as discussed in section 7 to measure impact velocities.

2.3. Conduct experiments with fluid mixtures of water and suitable surfactants (e.g., glycerin or soap) to modify surface tension. Measure surface tension with a surface tensiometer.

2.4. Calculate Reynolds numbers $Re = \rho \cdot U \cdot D/\mu$ and Weber numbers $We = \rho \cdot U^2 \cdot D/\sigma$, where ρ is the density of the fluid, *D* is the sphere diameter, μ is the dynamic viscosity of the fluid and σ the surface tension of the fluid.

3. Maintaining sanitary experimental conditions

3.1. Conduct experiments while wearing industrial nitrile gloves and retrieve spheres from water tank with a sanitized scoop.

CAUTION: Skin naturally produces oils which can affect the wettability of impactors and taint fluid conditions.

3.2. Clean the spheres with 99% isopropyl alcohol and allow to dry for 1 min in between trials to preclude the influence of impurities.

3.3. If using fabrics that break apart during impact, replace the water in the tank after every trial if scraps cannot be manually collected.

3.4. At the end of experiment, empty the tank and leave it to dry.

3.5. Before an experiment, clean the tank with water to remove any impurities.

4. Layering the surface with penetrable fabrics

4.1. Separate the fabric into square or round plies in preparation for impact trials. Use a Vernier caliper to obtain compressed thickness of the fabric.

NOTE: Fabric thickness will change when wet.

4.2. Gently rest the dry fabric atop the surface of the liquid pool. Ensure that the plies do not begin descent before impactor release and replace fabrics immediately after collision.

4.3. Use a sanitized scoop to position the fabric below the hinged platform before releasing spheres.

4.4. (Optional) Conduct the following tests using a fabric sample for material characterization.

4.4.1. Perform **tensile testing** using a tensile tester to determine the elastic modulus of the sample.

4.4.2. Use a digital microscope to obtain a microscopic view of the fabric and determine **fiber length** using an imaging tool.

5. Preparing chemically hydrophobic spheres

5.1. Spray the hydrophobic base coat approximately 15–30 cm from the sphere surface. Avoid soaking the surface. Let it dry for 1–2 min before adding additional coatings. Apply two more base coats. Allow it to dry for 30 min before applying the top coat.

NOTE: The number of additional coats may vary based on recommendations from the product manufacturer.

5.2. Spray the hydrophobic top coat approximately 15–30 cm from the surface. Avoid soaking the surface. Let it dry for 1–2 min before adding additional coatings. Apply two or three more coatings of top coat. Allow to dry for 30 min for light use and 12 h for full use.

NOTE: The number of additional surface coats may vary based on recommendations from the product manufacturer.

5.3. After approximately 20 trials, the hydrophobic coating becomes compromised due to excessive handling. Remove coating with 99% isopropyl and repeat steps 5.1 and 5.2.

6. Synchronizing cameras for splash visualization

6.1. Place a high-speed camera with a suitable lens perpendicular to the impact axis and in-line with the surface of the fluid.

NOTE: A 55 mm prime lens provides a good starting point.

6.2. Where fabrics are to be used, add an additional high-speed camera to the experiment to provide a top-down view of the impacts, as seen in **Figure 1b**.

6.3. Synchronize multiple cameras to a computer using the following steps.

6.3.1. Connect both output terminals of the horizontal camera to both input terminals of the additional camera using BNC cables.

6.3.2. Connect the trigger switch to the horizontal camera only.

6.3.3. Plug Ethernet cables from both cameras into an off-network router connected to the computer.

NOTE: In the absence of a router, connect Ethernet cables of cameras to separate computers.

6.4. In the video acquisition software, configure the cameras with the following settings. Set frame rate to a minimum of 1000 fps, set screen resolution to the desired resolution. Set the shutter speed to 1 fps and set trigger mode to end.

6.5. From maximum release height, conduct a series of test trials to ensure that the Worthington jets are within the video frame.

6.6. Adjust the camera position and focus accordingly until the desired visualization quality is achieved.

6.7. After recording, extract kinematic and geometric measurements from videos using a suitable video analysis tool. Use **Tracker**, an open source analysis tool or any software of comparative capability.

7. Digitizing impact kinematics with tracker software

7.1. Select **calibration stick** from the Tracker toolbox and match it to the visual scale (**Figure 2a**), making the stick as long as possible.

7.2. Click **calibration stick** and set the scaling value to the length of the visual scale spanned by the stick. That is, if the calibration stick spans 1 cm on visual scale, set scaling value to 1.

NOTE: This ensures measurements taken from software are in the order of centimeters.

7.3. Toggle video playback by clicking **start** and **stop** and set video to the desired frame.

7.4. Select **measuring stick** from the Tracker toolbox and extract splash crown height κ, cavity width β, cavity depth λ, and Worthington jet height h, as seen in **Figure 2b**,**c**.

NOTE: The measuring stick is adjustable at both ends and can be used simultaneously with other toolbox selections.

7.5. Select **protractor** from the Tracker toolbox and measure the separation angle θ of fluid with respect to the impactor, as seen in **Figure 2b**. The protractor is adjustable at both ends and can be used simultaneously with other toolbox selections.

7.6. Select the **Auto-Tracking** feature in the software to record temporal position and velocity data. When tracking is interrupted due to lack of clarity in the video, use manual tracking until clarity is obtained and auto-tracking is resumed.

REPRESENTATIVE RESULTS:

This established protocols allow for the observance of the Worthington jets arising from vertical impacts over a range of Weber numbers We as seen in **Figure 2c**. These results are published in Watson et al.[1], which can be referenced for the exact experimental conditions used to produce the data presented herein. We focus on the narrow elongated film of fluid protruding above the free liquid surface. In **Figure 3** we show a meager amount of fabric amplifies splashing while sufficient layering attenuates splash back. Results are non-dimensionalized using the sphere diameter D as seen in **Figure 3b**.

We show the relation between non-dimensionalized cavity properties such as cavity depth λ^*, splash crown height κ^*, cavity width β^* and Weber number We in **Figure 4a**–**d**. Results are captured with a single frontal high-speed camera in a well-lit environment. A representative camera view is seen in **Figure 2b**. Across the range of experimental We in **Figure 4**, dimensions of cavities created by a sphere impacting a single layer of fabric show little variation.

We consider the trajectory of spheres after impact with the interfacial surface and track temporal position data until cavity pinch off occurs as seen in **Figure 5a**. We then smooth the data with a Savitzky-Golay filter[11] to remove the effects of experimental noise prior to numerical differentiation. The resulting velocity curves in **Figure 5b** are again smoothed prior to numerical differentiation for obtaining du/dt necessary for force analysis.

FIGURE AND TABLE LEGENDS:

Figure 1. Schematic of the experimental setup. (**a**) High-speed cameras capture frontal and overhead views with diffuse lighting positioned above the frontal camera. The trigger switch is optional, given the availability of manual controls in video recording software on the computer. (**b**) Photo sequence of hydrophilic sphere impact on a thin penetrable fabric atop the fluid, filmed using the overhead camera. A black dot is used to ensure no rotation present during free fall.

Figure 2. Splash visualization for hydrophobic sphere impact on an unaltered surface. The photo sequence shows (**a**) water entry, (**b**) splash crown ascension and air-entrapment, (**c**) Worthington jet formation and, (**d**) jet breakup for a representative splash. Sphere has impact velocity of $U =$ 3.5 m/s. A meter stick is used to calibrate measurements within the video analysis tool, used to measure splash crown height κ, cavity width β, cavity depth λ, separation angle θ and Worthington jet height h.

Figure 3. Splash heights across Weber number (We). (**a**) Worthington jet height h_{max} vs. We, with h_{max}/D vs. We shown in (**b**). Number preceding "Ply" denotes the layers of fabric.

Figure 4. Variation of cavity dimensions across Weber numbers. Relation between We and the (**a**) separation angle Θ, (**b**) cavity depth λ, (**c**) splash crown height κ, and (**d**) cavity width β. Properties are non-dimensionalized in terms of sphere diameter, D. Error bars denote standard deviation for the average of five trials at each point. Figure is modified from Watson et al.[1].

Figure 5. Representative kinematics of sphere during underwater descent. Temporal tracks of (**a**) vertical position y and (**b**) velocity u for impacting spheres with 0- to 4- layers of fabric atop the water. Trajectories are non-dimensionalized in terms of the sphere diameter, D and impact velocity U respectively.

DISCUSSION:

This protocol describes the experimental design and best practices for investigations of free-falling spheres onto a deep liquid pool. We begin by highlighting steps necessary for configuring the experiment for vertical impacts. It is important to create an ideal splash environment with the use of a sufficiently large splash zone such that wall effects are negligible[9], and a suitable visual scale for extracting kinematics[12-21]. While shock absorbers can be improvised from excess lab materials, they must be sanitized before the experiment with water and a suitable dirt removing agent. Failure to clean the shock absorber and the tank can lead to the introduction of impurities during an experiment and alter splash characteristics. In the literature, there exists a lack of detail regarding maintenance of experimental cleanliness and as such, this article presents guidelines for obtaining consistent results from water entry trials.

The techniques described above are subject to tuning as seen in previous studies. The spring-actuated release mechanism employed by the authors can be substituted with electromagnets[15] when using ferrous spheres. The ease of use of the method is improved when high-speed cameras are set to automatically trigger after spheres fall through photocells[12] or infrared triggers[22,23], but these add complexity. Impactor surface treatments to control wettability can also be done by using more rigorous approaches as seen in Duez et al.[8]. For example, spheres grafted with octyltriethoxysilane, rinsed with isopropyl and heated in an oven at 90 °C achieve super-hydrophobicity[8]. The protocol can be further tuned for improved cavity visualization by replacing the black screen (shown in **Figure 1a**) with backlighting, which makes cavity features more pronounced[3].

Care should be taken when considering temporal kinematics for theoretical investigations. Temporal position tracks present less distortion than for velocity tracks but require smoothing prior to numerical differentiation[1,3,15]. The Savitzky-Golay filter performs a polynomial regression on a range of equally spaced values to determine the smoothed value for each point and can more faithfully maintain a track's salient features[11]. For tracking sphere position, a second-degree polynomial within the Savitzky-Golay filter preserves the track's salient features while removing experimental noise. Finally, researchers have choice of the moving average span of the filter, which should be as small as possible while still achieving the desired level of smoothing.

The established protocol is not restricted to the list of materials presented here and can be undertaken on a larger scale to generate greater impact velocities and increased range of dimensionless parameters which augurs well for translating results to naval and industry applications.

ACKNOWLEDGMENTS:

The authors would like to acknowledge the College of Engineering and Computer Sciences (CECS) at the University of Central Florida for funding this project, Joshua Bom and Chris Souchik for splash imagery and Nicholas Smith for valuable feedback.

DISCLOSURES:

The authors have nothing to disclose.

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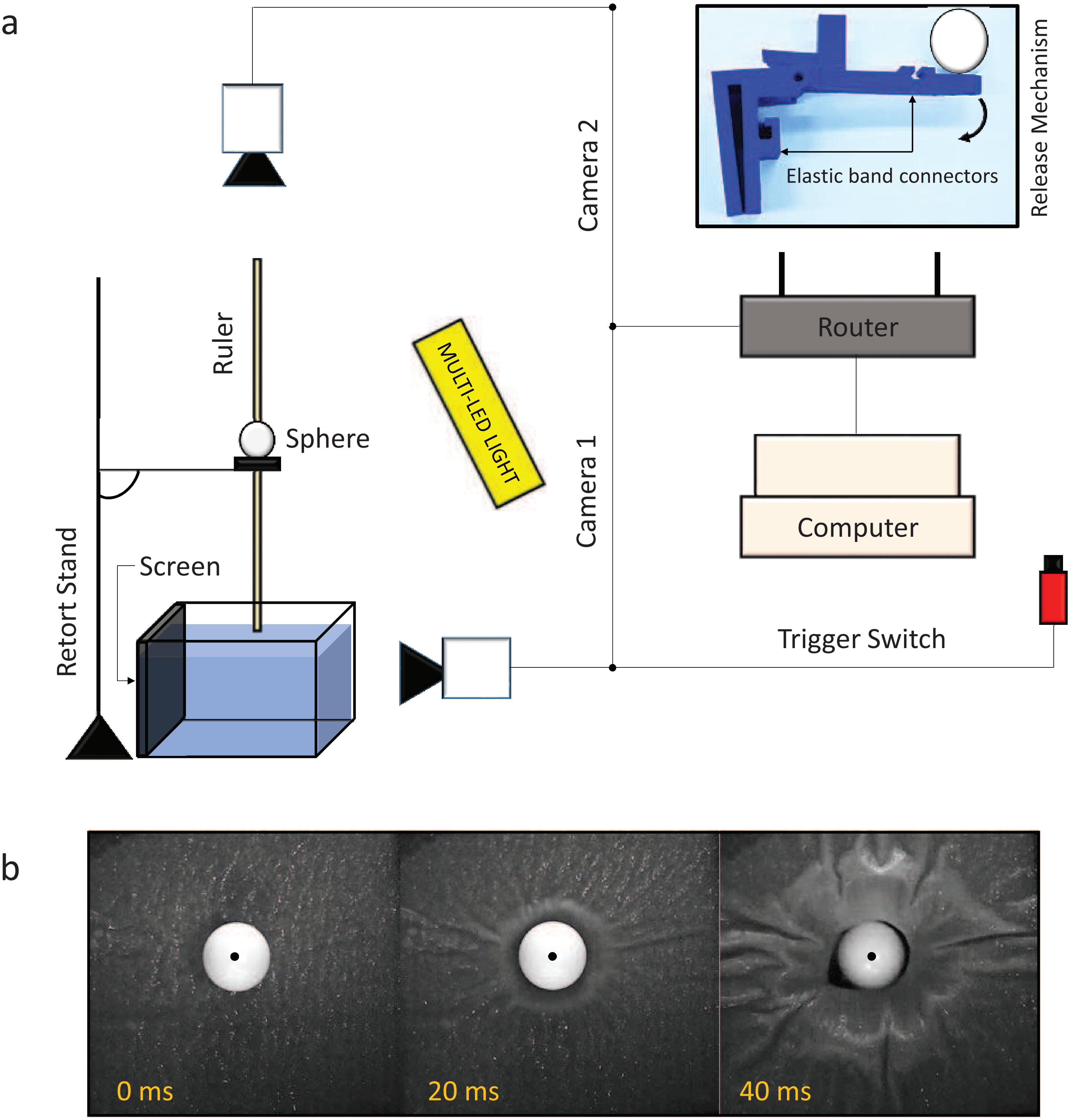
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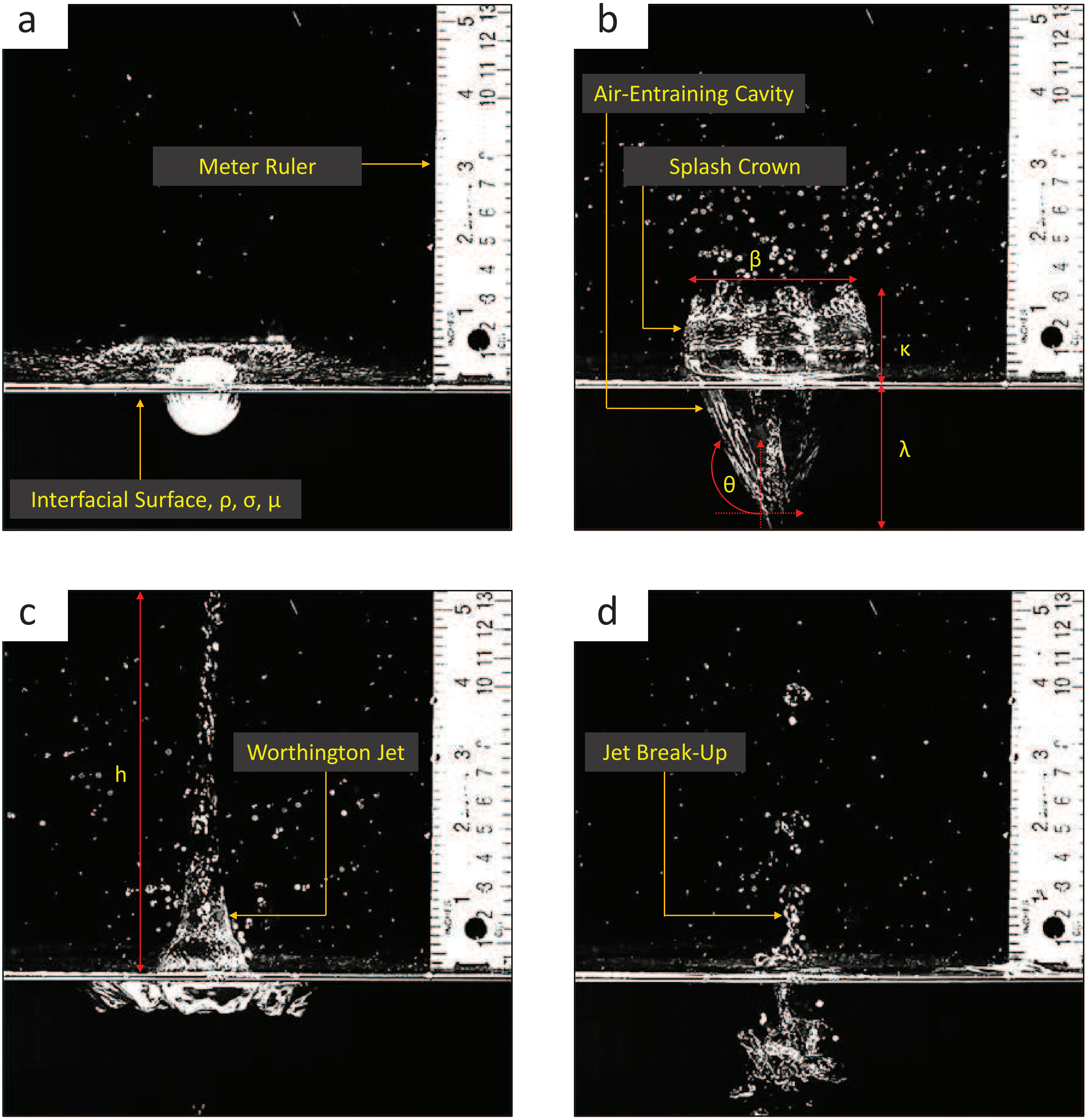
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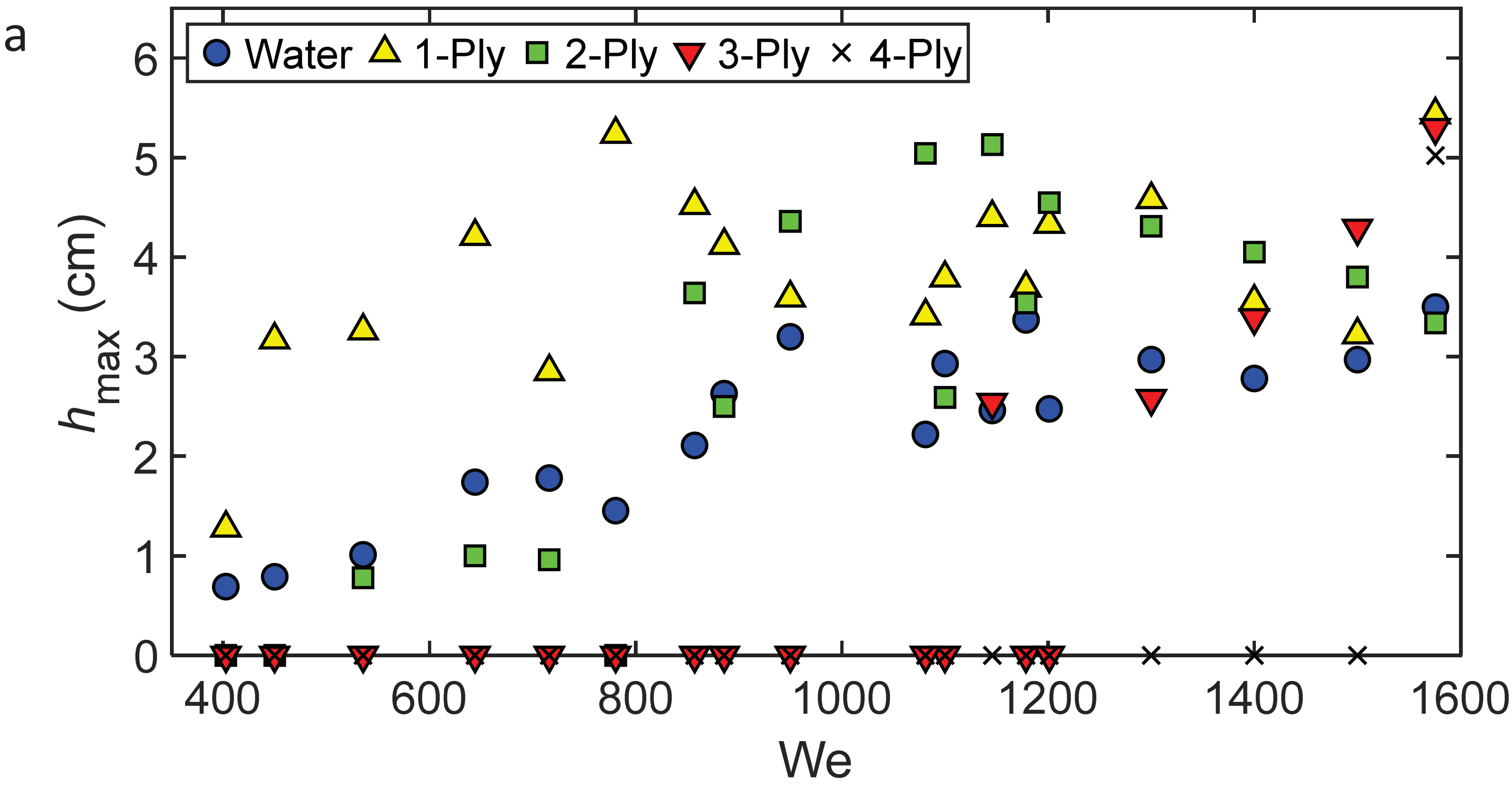
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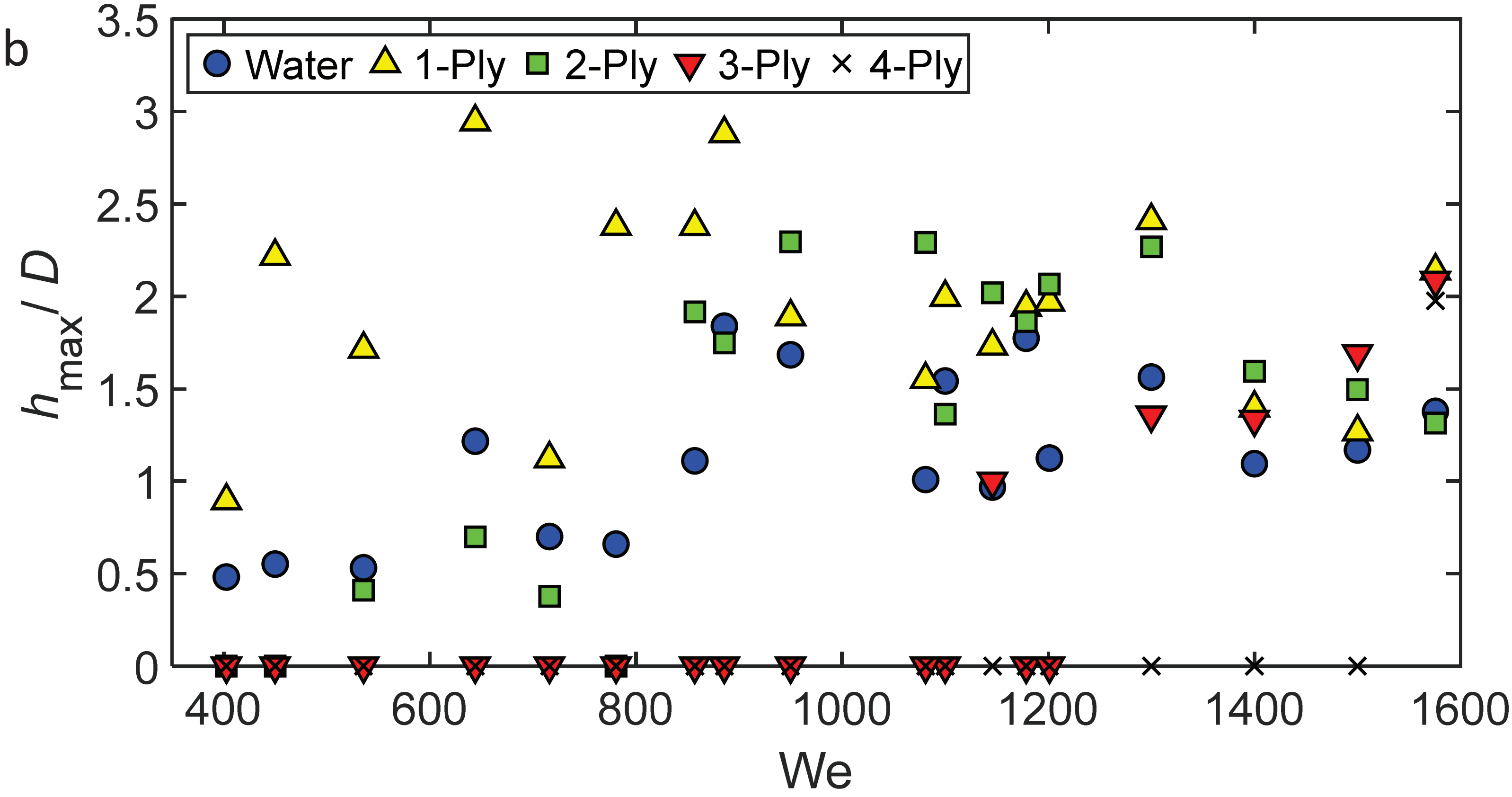
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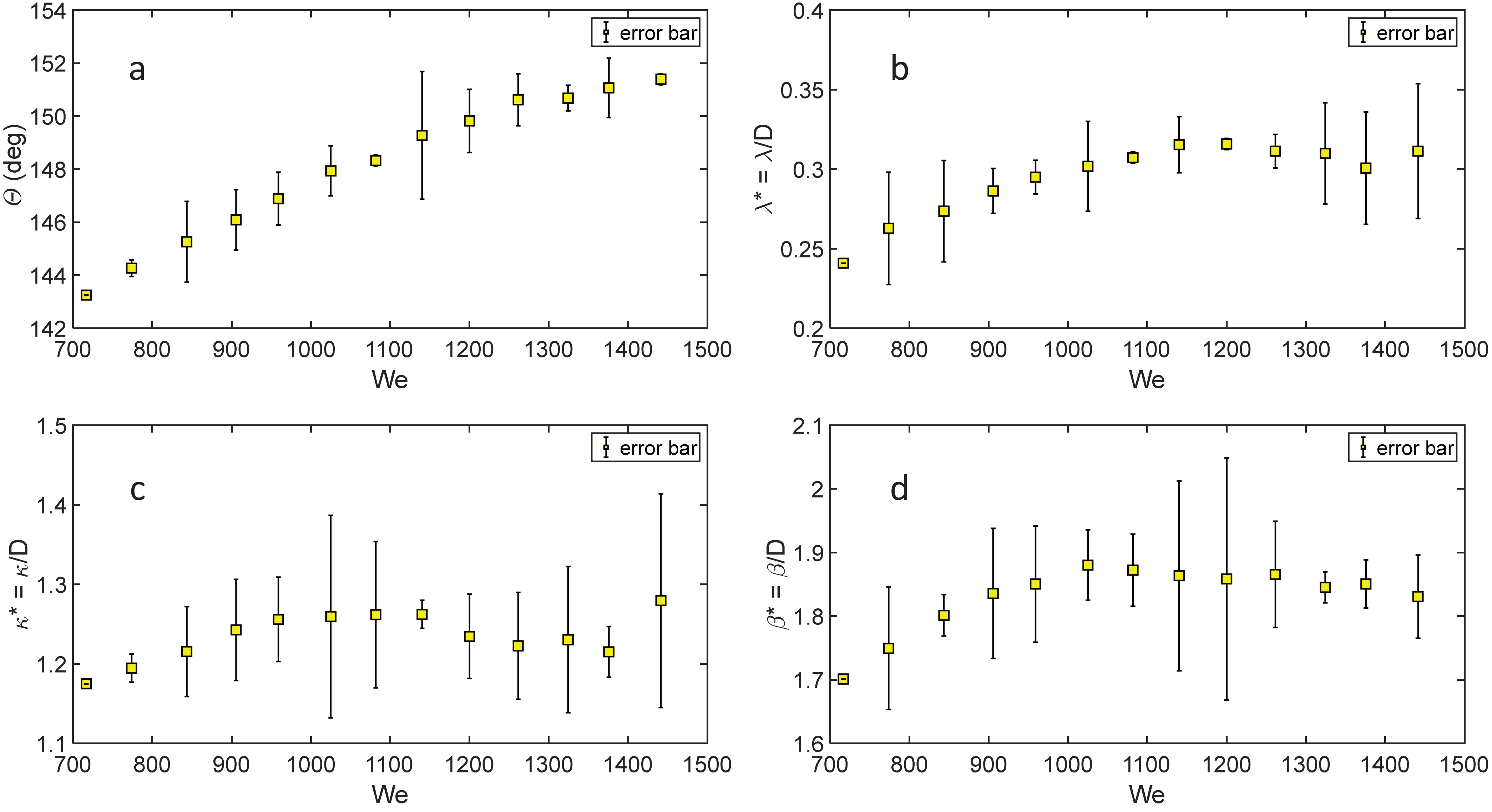
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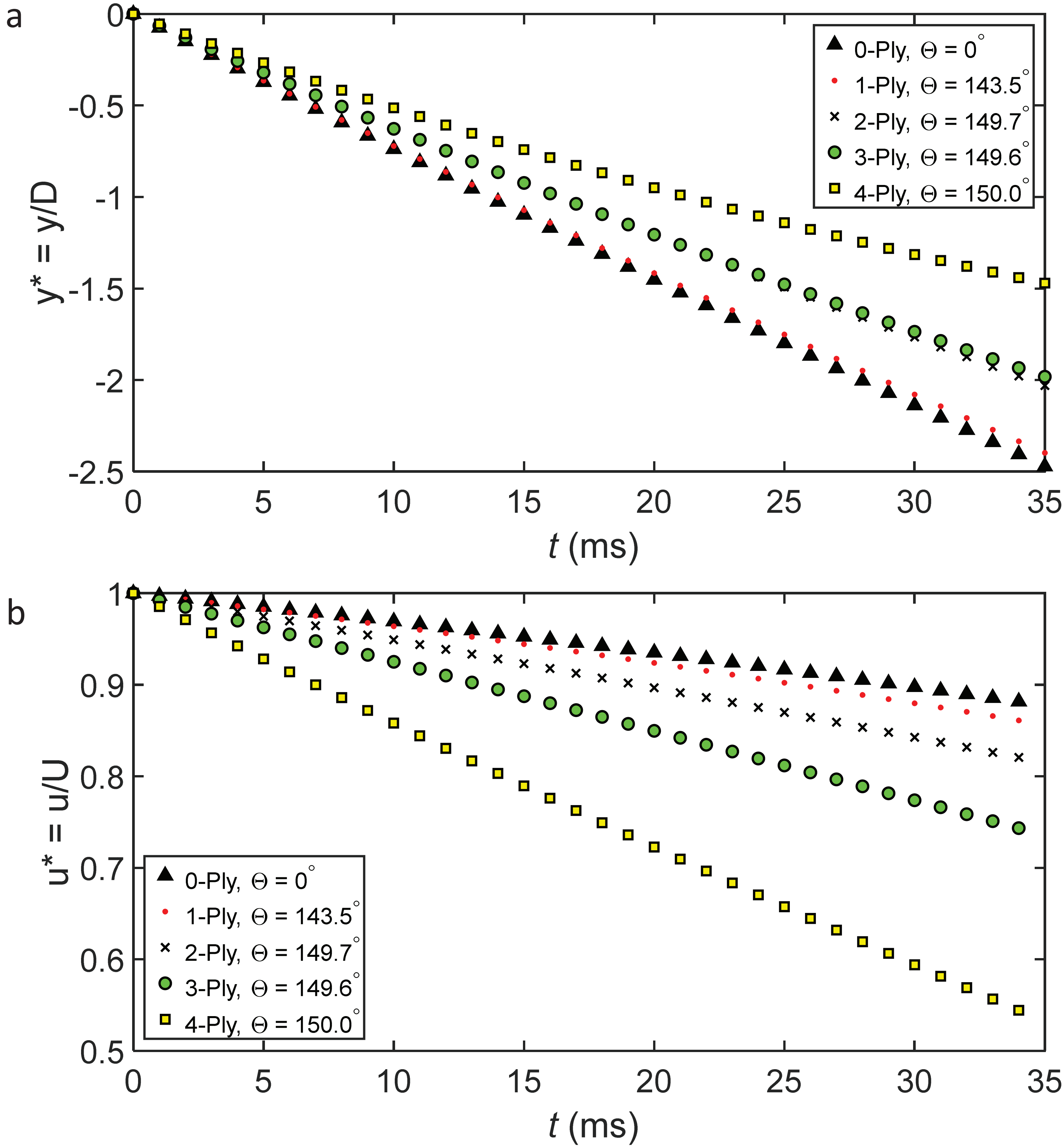
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Name of Material/ Equipment	Company	Catalog Number	Comments/Description
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Alcohol	Swan	M314	99% Isopropyl
BNC Cables	Thorlabs	2249-C-24	
Caliper	Anytime Tools	203185	Dial
Camera	Photron	Mini AX-100	16GB Ram
Computer	Dell	Windows 7 Pro	
Fabric	Georgia Pacific	19378	Toilet Paper
Fabric	Kleenex	10036000478478	Tissue
Laser Cutter	Glowforge	Basic	
Lights	GS Vitec	LT-V9-15	Multi-LED
Microscope	Keyence	VHX-900F	Digital
Retort Stand	VWR	VWRF08530.083	
Router	ASUS	RT-N12	Off Network
Ruler	Westcott	10432	Meter Ruler
Software	Open-Source	Tracker	Video Analysis
Software	Photron	Fastcam Viewer	Video Recording
Sphere	Amazon	8DELSET	Delrin
Spray	Rust-Oleum	274232	Water Repelling
Surfactant	Dawn	37000973782	Liquid Soap
Surfactant	USP Kosher	5 Gallons	Glycerin
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University of Central Florida

College of Engineering and Computer Science
Department of Mechanical and Aerospace Engineering

Dear Dr. Jialan Zhang,
c\o Dr. Alisha DSouza,

Thank you very much for the constructive reviews of our manuscript “Impacts of free-falling spheres onto a deep liquid pool with altered fluid and impactor surface conditions.” In keeping with the recommendations of the reviewers, we make corrections to the manuscript and hereby submit our revisions for further scrutiny. We believe the new manuscript is improved in readability and offers more clarity as compared to the previous version.

As detailed in the attached point-by-point list of responses, we have attempted to implement most of the suggestions.

We hope that this explanation and our attempts to translate same into the revised manuscript adequately address your concerns. We look forward to any further additions and corrections to our manuscript.

Yours sincerely,

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Editorial Comments to Author

Changes to be made by the author(s) regarding the manuscript:

Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.
We proofread manuscript for spelling and grammatical errors.

Abstract (150-300 words): Please expand it to provide an overview of the advantages, limitations and applications of the protocol.
We adjusted the abstract which now reads:

"Vertical impacts of spheres on clean water have been the subject of numerous water entry investigations characterizing cavity formation, splash crown ascension and Worthington jet stability. Here, we establish experimental protocols for examining splash dynamics when smooth free-falling spheres of varying wettability, mass, and diameter impact the free surface of a deep liquid pool modified by thin penetrable fabrics and liquid surfactants. Water entry investigations provide accessible, easily assembled and executed experiments for studying complex fluid mechanics. We present herein a tunable protocol for characterizing splash height, flow separation metrics, and impactor kinematics, and representative results which might be acquired if reproducing our approach. The methods are applicable when characteristic splash dimensions remain below approximately 0.5 m. However, this protocol may be adapted for greater impactor release heights and impact velocities, which augurs well for translating results to naval and industry applications."

Please renumber the references in the text; currently the reference number starts from 2.
We rechecked and renumbered references in the text.

7.1-7.4: Software steps must be more explicitly explained ('click', 'select', etc.). Please add more specific details (e.g. button clicks for software actions, numerical values for settings, etc.).
We adjust the steps with further details and incorporated button clicks where applicable.

Representative Results: Please remove the subheadings.
All subheadings removed.

Figure 3: Please define error bars in the figure legend.

We now define error bars in all figure legends and add a sentence to the caption stating what they represent.

Table of Materials: Please sort the items in alphabetical order according to the name of material/equipment.

Items checked and sorted in alphabetical order according to the name of the material/equipment.

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Reviewer #1 Comments to Editor and Author

This manuscript presents a standardized protocol for observing splash dynamics of a rigid sphere impacting onto a deep pool of fluid. It provides detailed guidelines for the releasing mechanism of the rigid sphere, the pool of fluid, fabrication of the rigid sphere, surface modification of the sphere, and analysis of the splash and its relevant parameters. Splash dynamics is a widely studied field and this appears to be the first paper to explicitly describe a standardized protocol for studying splashes of rigid spheres. This paper would be of particular interest for engineers.

Major Concerns

I have no major concerns.

Minor Concerns

The parameters presented in Fig. 3 should be presented in the main text for clarity. Currently, they are only in the figure captions.

We adjusted the corresponding text in "Digitizing Impact Kinematics with Tracker Software". The sentence now reads:

"A measuring stick is used to extract splash crown height κ, cavity width β, cavity depth λ, and Worthington jet height h, as seen in Figures 2b – c."

What do the error bars in Fig. 3 represent? This should be stated in the caption.

We believe the referee was referring to Figure 4. Therefore, we inserted the following sentence into the caption:

"Error bars denote standard deviation for the average of five trials at each point."

Reviewer #2 Comments to Editor and Author

This manuscript describes an experimental apparatus and procedure for dropping spheres into a liquid basin while controlling for and measuring a variety of variables relating to the cavity dynamics, splash crown dynamics and sphere trajectory. The authors detail relevant information from previous studies and provide experimental results for a series of operating conditions.

Major Concerns

In general, there are some useful details provided in the paper, however it would benefit from great organization and clarity.

In the Introduction section paper 2 is the first one referenced (line 47). Paper 1 should be the first one discussed and referenced in the text.
We thank the reviewer for this observation. We rechecked and renumbered references in the text.

The authors suggest that there is a lack of procedural consistency in published works which could be problematic. What information are the authors using to arrive at this suggestion? It is unclear that there have been issues or inconsistencies in the published data or other problems that have resulted from this.
We agree with the recommendation and seek to soften our stance. The sentence now reads:

"Here, we establish clear in-depth protocols and best practices for achieving consistent results from water entry investigations."

Much more detail is desired on the drop mechanism in order for a reader to replicate the method developed. In what direction does it retract, how is it made/mounted, how is it triggered, etc.?
We include an image of the release mechanism in Figure 1a to improve clarity for readers. Steps 1.3. and 1.4. were also adjusted and now reads:

"Construct a hinged platform ('release mechanism') that suspends spheres above fluid and rotates downward, to achieve tangential acceleration greater than gravity at the impactor location when released, as seen in Figure 1a. Rapid rotation is achieved by connecting the hinged platform to the center of the supporting component using elastic bands. The result is an unsupported and non-rotating impactor. Note: Platform is easily fabricated with 3D printer."

"For impact trials, place thumb to base of platform and rotate 90° to a horizontal position for placement of spheres above fluid. Note: Retraction is triggered when thumb is released from base of platform."

Line 113, the authors state the impact velocity is found from an equation that assumes negligible drag. This clearly has limitations and uncertainty. Why is it not recommended to use the software to determine the velocity at impact? Would that not be a "best practice" as opposed to assuming drag doesn't slow the sphere down?

We thank the reviewer for this observation. We address our oversight by modifying the protocol which now reads:

"Conduct experiments over a range of heights H to generate impact velocities $U \approx \sqrt{2gH}$ where $g = 9.81$ m/s^2 is the acceleration due to gravity. Measure height with visual scale within the camera frame. Note: Use **Auto-Tracking** feature in video analysis tool as discussed in Section 7, to measure impact velocities."

The authors recommend some measurements (mass and diameter) but not others (viscosity, density). As the paper seems aimed at the sphere dropping/impacting variables it is recommended that more attention is given to those details. Measuring fluid properties and diameters should be within the realm of all experimentalists and therefore unnecessary to include here.

We agree that measurements such as mass and diameter are trivial, but allow such discussion to remain in the manuscript to satisfy the requirements of the journal. We include discussion of other splash measurements such as jet height, cavity depth and width, separation angle and location, and sphere depth. Additional metrics not included, such as lamella breakup measurements would be very specific to other studies and are therefore not included here. We welcome greater clarification from the reviewer should our manuscript warrant further adjustment.

Why are pre-test trials with a hydrophilic sphere recommended (line 134)? How should hydrophilicity be determined? What is the critical velocity that is referred to here? More likely it is an impact Weber or Froude number that also depends on contact angle between the liquid and solid surface.

We thank the reviewer for this suggestion. We reviewed the step and decided that it is in fact extraneous to the protocol.

Line 181 - what is meant by "verify impact eccentricity" and why is this considered a critical step in synchronizing cameras for splash visualization?

We use the term to suggest that the use of an additional camera allows determination of impact location of the free-falling sphere. However, given that this suggestion is already made in the introduction, we remove the particular phrase from the protocol to prevent redundancy.

It should be noted somewhere in the paper that a separate ruler is needed for above the water and below the water. The water can act to magnify dimensions which would either need to be quantified or shown to be non-existent.

We thank the reviewer for this suggestion. We added the following step (1.2.) which reads: “Place additional meter ruler under water, which can act to magnify dimensions. This visual scale is used for calibrating tracking software for underwater measurements.”

Line 222 - are the author suggesting that a protractor be held up against the computer screen or something else? More clarification is needed.

We thank the reviewer for this comment and provide clarity by modifying the sentence which now reads:

“Select protractor from toolbox and measure separation angle θ of fluid with respect to the impactor as seen in Figure 2b.”

Section 8 - Calculating Drag at Fluid Entry - seems extraneous to the objective of the paper. It is recommended that this be removed, or much more information be provided so that the reader can understand how this is relevant to the running of sphere impact trials.

We conclude that this section is in fact extraneous to the scope of the paper and agree with the reviewer’s suggestion to have it removed.

The authors provide results that one might get if reproducing their approach, which is fine. However, the reader would need to know the exact experimental condition for every one of the presented data points if they truly wanted to replicate the authors' data. This information is not provided. So the data shown in Figures 2-4 would not be useful, as presented, for comparison purposes. A table could be provided that includes all of the relevant detail needed (drop height, impact velocity, diameter, static contact angle, mass, etc.). Or, if the authors included the data for some other reason this should be clarified and made clear as to how it fits with the main objective of the work. The results are interesting in their own right, but it seems they have already been published and the conclusions drawn from them would not exactly be relevant to the JoVE work.

We include representative results in keeping with the requirements of the journal, and refer the reviewer to another published example: https://www.jove.com/video/58045/controllable-nucleation-cavitation-from-plasmonic-gold-nanoparticles

In any case, the reviewer makes a valid argument. Therefore, we have amended the first paragraph of Representative Results to read:

"Our established protocols allow for the observance of the Worthington jets arising from vertical impacts over a range of Weber numbers We as seen in **Figure 2c**. These results are published in Watson *et al.* (2018)[1], which can be referenced for exact experimental conditions used to produce the data presented herein. We focus on the narrow elongated film of fluid protruding above the free liquid surface. In **Figure 3** we show a meager amount of fabric amplifies splashing while sufficient layering attenuates splash back. Results are non-dimensionalized using the sphere diameter D as seen in **Figure 3b**."

It was good to include a mention of the filtering used for determining trajectory and velocity. This section would benefit from some more detail on the mechanics of this operation.

We have bolstered our paragraph on the Savitzky-Golay filter in the Discussion. The related paragraph now reads:

"Care should be taken when considering temporal kinematics for theoretical investigations. Temporal position tracks present less distortion than for velocity tracks but require smoothing prior to numerical differentiation[1,3,15]. The Savitzky-Golay filter performs a polynomial regression on a range of equally spaced values to determine the smoothed value for each point and can more faithfully maintain a track's salient features[11]. For tracking sphere position, a second-degree polynomial inside the Savitzky-Golay filter preserves the track's salient features while removing experimental noise. Finally, researchers have choice of the moving average span of the filter, which should be as small as possible while still achieving the desired level of smoothing."

Minor Concerns

Line 98 states that light is parallel to the camera. In Figure 1 it appears to be angled relative to both cameras. Please clarify.

This sentence now reads:

"Attach a multi-LED light to magic arm such that the light is mounted above the camera, looking down onto the splash zone."

Lines 164-170 suggest 2 base coats and 2 top coats. Would this not really be 3 base coats and 1 top coat?

The manufacturer for the spray used in our experiment suggests 3 base coats and 3 – 4 top coats for optimal use. We insert the following note into the protocol:

“Note: Number of additional surface coats may vary based on recommendations of product manufacturer.”

The authors might want to consider backlighting for cavity visualization, or at least commenting on this as it seems to be the norm in the published research.

We thank the reviewer for this suggestion and added the following sentence to paragraph 2 of the Discussion which reads:

“The protocol can be further tuned for improved cavity visualization by replacing the black screen in Figure 1a with backlighting, which makes cavity features more pronounced.”

Why is much of the text highlighted in yellow?

We highlight several text in yellow in keeping with the request of the journal’s “**Instruction for Authors**” which reads:

“For a Protocol section that exceeds 3 pages, highlight in yellow up to 2.75 pages (no less than 1 page) of protocol text (including headers and spacing) to be featured in the video. Our scriptwriters will derive the video script directly from the highlighted text.”

Please define Weber number explicitly.

We define the Weber number in “Controlling dimensionless parameters”.

In Figure 2c height is indicated as "h" while in Figure 3 "H" is used. Please be consistent.

“H” has been replaced with “h” in Figure 3 and the text rechecked for consistency.

Please show specific measurements of h, lambda, beta, theta, and kappa on the digital images and define them in the text. Figure 2 alludes to them but seeing the actual lines that indicate their measurement removes confusion.

We adjusted the corresponding text in “Digitizing Impact Kinematics with Tracker Software”. The sentence now reads:

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“A measuring stick is used to extract splash crown height κ, cavity width β, cavity depth λ, and Worthington jet height h, as seen in Figures 2b – c.”