# How Tongue Size and Roughness Affect Lapping

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## Abstract
The biomechanics of domestic cat lapping (Felis catus) and domestic dog lapping (Canis familiaris) is currently under debate. Lapping mechanics in vertebrates with incomplete cheeks (cheeks that cannot form suction for oral liquid ingestion, often carnivorous vertebrates[1, 9]), such as cats and dogs, is a balance of inertia and the force of gravity likely optimized for ingestion and physical necessities. Physiology dictates vertebrate mass, which dictates vertebrate tongue size, which dictates lapping mechanics to achieve optimum liquid ingestion; with either a touch lapping, scooping, or a hybrid lapping method. The physics of this optimized system then determines how high a column of liquid can be raised before it collapses due to gravity, and therefore, lapping frequency. Through tongue roughness model variation experiments it was found that pore-scale geometrical roughness does not appear to affect lapping or liquid uptake. Through tongue size model variation experiments it was found that there is a critical tongue radius in the range of 25 mm to 35 mm above which touch lapping is no longer an efficient way to uptake liquid. Vertebrates with incomplete cheeks may use a touch lapping method to ingest water if their tongue radius is less than this critical radius and use an alternative ingestion method if their tongue radius is larger.

## Background
The biomechanics behind domestic cat lapping (Felis catus) and domestic dog lapping (Canis familiaris) is a topic of recent debate. Reis et al.[1] as well as Crompton and Musinsky[2] successfully outlined the mechanics behind this phenomenon for cat and dog lapping, respectively. Both authors demonstrated how cats and dogs ingest water through lapping by using the dorsal side of their curled tongue to uptake a liquid column from a liquid basin and then quickly close their mouth around the column before it is pulled apart by gravity. It was found that cats more often touch their tongue to the liquid surface than penetrate the liquid. This permits cats to lap more precisely than canines.[1] Dogs, on the other hand, almost always penetrate the liquid surface and scoop some of the liquid in a spoon shaped pocket on the ventral side of their tongue. This captured liquid exits the “spoon pocket” before the dog closes its mouth around the rising column. Some of the liquid exiting the spoon pocket adds to the column while the rest falls back into the basin or onto the floor.[2] Reis et al. describes how the uptake column is governed by a balance between inertia and the force of gravity. After the tongue touches and adheres to the liquid, inertia, or the upward momentum of the liquid, drives the column upward while gravity pulls it back down. It was determined that cats lap at an optimum frequency to capture the most liquid per lap, $3.5 \pm 0.4$ Hz.[1] It was also noticed that within

the feline family this frequency scales to the mass of the animal, such that

$$F \sim M^{-1/6}, \qquad (1)$$

where F is frequency and M is the mass of the feline.[1] This power scaling relationship is often seen in nature and in many cases correlates to the mass of the animal. Examples include metabolic rate and mass in mammals (Metabolic Rate $\propto$ Mass$^{3/4}$),[3] wet dog shake frequency and dog radius (Shake Frequency ~ Radius$^{-3/4}$),[4] and the transition from a walk to a trot to a gallop and mass in terrestrial locomotion animals (Stride Frequency = 4.5·Mass$^{-0.14\ (\approx -1/7)}$).[5]

Reis et al. observed that only the smooth tip of the cat tongue, which is free of filiform papillae and fungiform papillae,[6] touch the liquid during lapping. From video imaging of tigers (30 fs$^{-1}$ and 250 fs$^{-1}$) and still photo imaging it appears that rough sections of the tongue can come into contact with the liquid surface when larger felines lap, as seen in Figure 1.

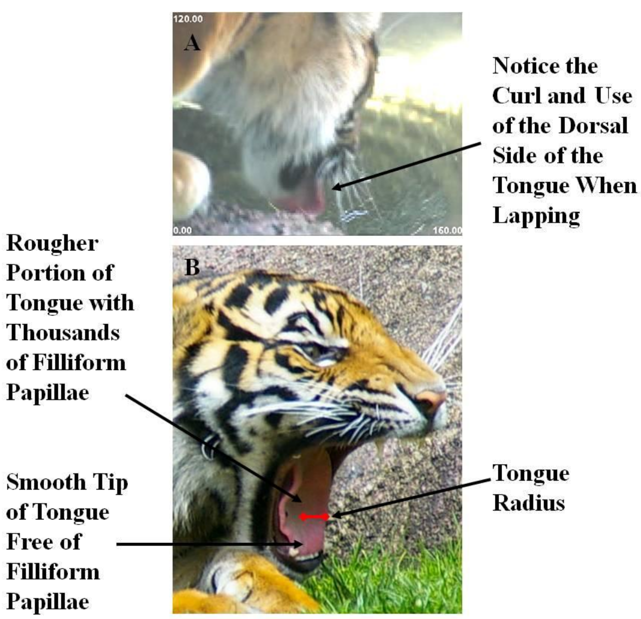


Figure 1: Top (A): 18 month old male Sumatran tiger lapping at the Point Defiance Zoo and Aquarium in Tacoma, WA;[7] Bottom (B): Sumatran tiger yawning at the Point Defiance Zoo and Aquarium in Tacoma, WA.

Neither Reis et al. nor Crompton and Musinsky explored tongue roughness as a factor for liquid adhesion during lapping or how tongue size impacts lapping for tongue radii larger than 12.7 mm. The focus of this study was to experimentally determine how geometrical surface roughness (to simulate tongue roughness) and tongue size each affect the lapping mechanism for vertebrates with incomplete cheeks. Two experiments were conducted: tongue roughness variation and tongue size variation.

## Materials and Methods

The effects of surface roughness were investigated using experimental tongue roughness models. Uniform tongue roughness models were created using pvc-pipe coupling sections (17 mm radius) with one end covered in sandpaper and a hydrophobic coating applied to the sides of each model (rain-x). Eight tongue models were created with a different grade of Norton 3X Sandpaper affixed to the base of each model, with sandpaper grades ranging from 60 to 400 grit. (Grade is the text standard of the numeric grit size, while grit is the numeric standard for abrasive grains measured in openings per linear inch. The higher the grit/grade the finer the grains and the smoother the surface.[11]) The Norton 3X Sandpaper was assumed to have a chemically homogeneous surface that affected fluid in the same way throughout the range of roughness samples used. In addition, this roughness range covered a wide array of geometrical roughnesses within pore scale geometry and each grade used was found to be hydrophilic, to better model a real tongue.

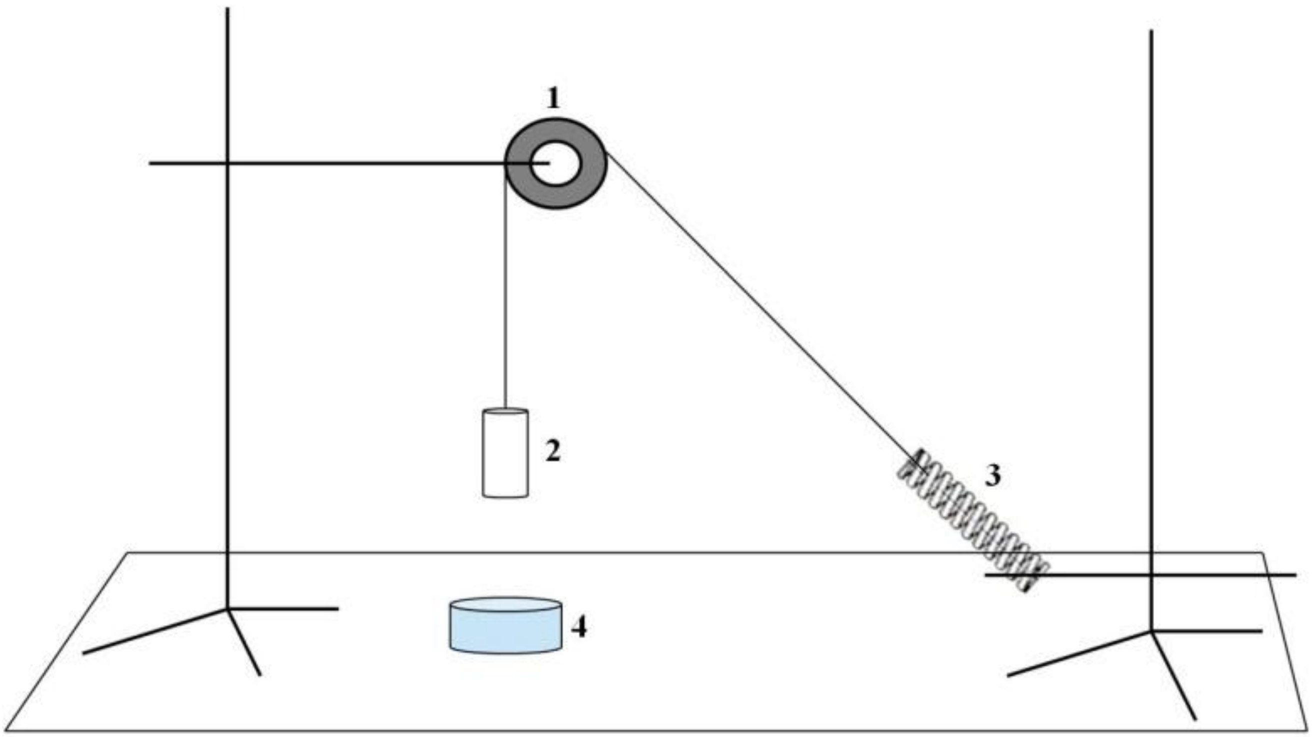


Figure 2: Spring-Pulley System: 1) frictionless pulley, 2) tongue model, 3) spring, and 4) water basin.

The tongue roughness models were then attached to a spring-pulley system, as seen in Figure 2, by hanging the tongue model with a rubber stopper placed into the open end of the pvc-pipe opposite the sandpaper covering. This spring-pulley system allowed the tongue models to oscillate vertically when released and come into contact with a water surface (an 80 ml pitre dish filled with room temperature tap water) during the minimum point of the oscillation. This motion mimicked the tongue touching and leaving the water during lapping. Similar to a feline tongue, the tongue models created a rising water column when leaving the water surface. Tongue model ascent height was not restricted.

A Fastec Inline high speed camera recording at 250 $fs^{-1}$ was placed approximately 1.8 meters from the spring-pulley system and used to record the tongue model release, column uptake, and oscillations. Each model was rotated every three trials to prevent the sandpaper from absorbing water. In this way, 12 total trials were conducted for each sandpaper grade.

The high speed videos captured by the camera were then analyzed using MaxTraq video tracking software. From this analysis the tongue model height at column pinch off, water column height at column pinch off (which is the moment the water column breaks away from the tongue model), droplet height at column pinch off, and frequency were recorded. Figure 3 illustrates these measurements using the MaxTraq software.

To examine the effects of tongue size, radius was varied between tongue models. The tongue size models created for this experiment varied from 14.35 mm to 57.33 mm in radius. Each model had 400 grade Norton 3X Sandpaper as a base covering. 400 grade sandpaper was used since it was the smoothest grade available

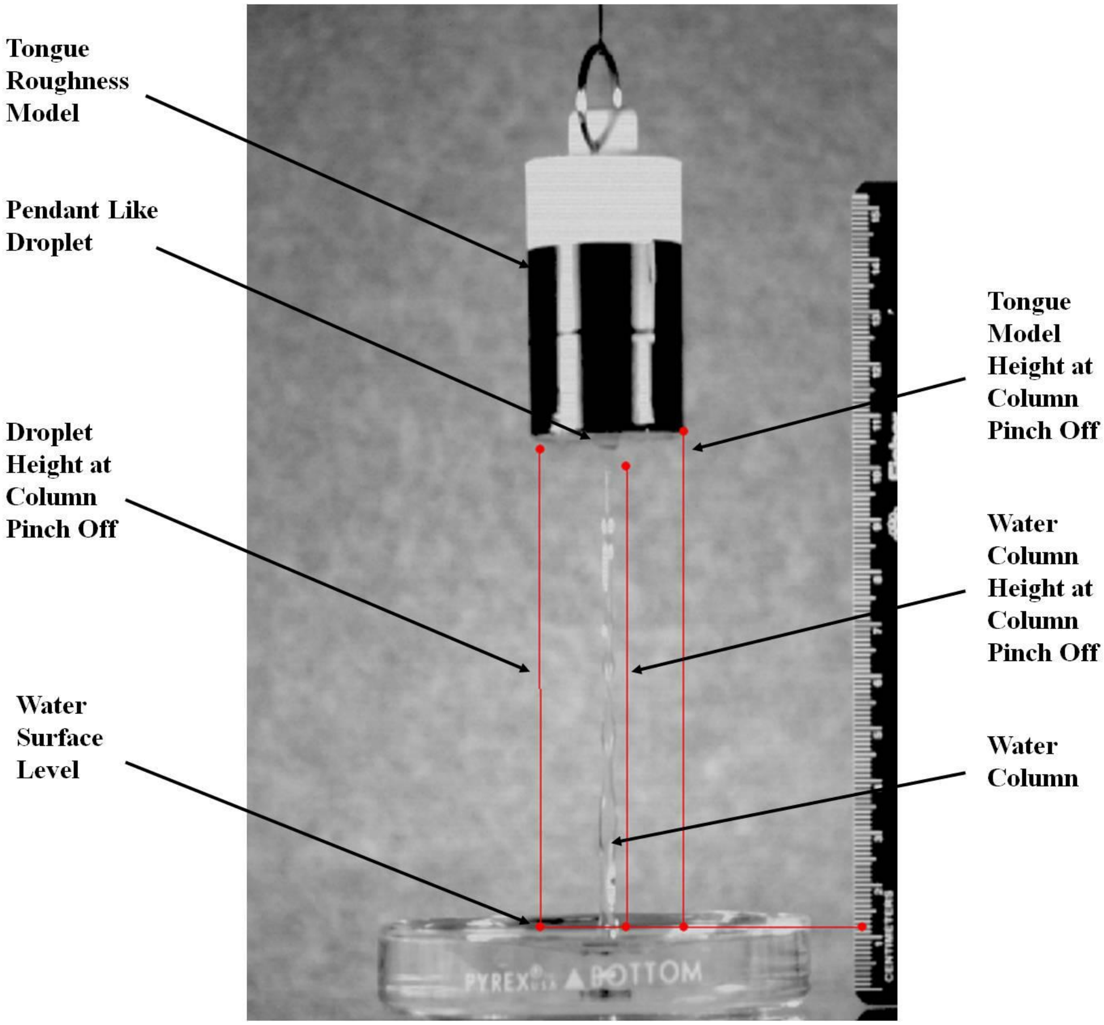


Figure 3: Video analysis image at the moment of column pinch off using MaxTraq software. The tongue model height at column pinch off, water column height at column pinch off, droplet height at column pinch off, and frequency were recorded.

and thus the closest to mimicking a smooth tongue. The tongue size models were created in the same method as the tongue roughness models. The tongue size study trials and analysis were conducted in the same fashion as the tongue roughness study, conducting 6 total trials for each radius size. Minor differences included a larger water basin filled with 2000 ml of room temperature tap water and a unique method to attach the tongue size models to the spring-pulley system. To attach the tongue size models four small holes were drilled in the pvc-piping and a string-washer adjustable hanging system was used.

A spring with spring constant 3.56 $Nm^{-1}$ was used for the roughness study whereas a spring with spring constant 9.33 $Nm^{-1}$ was used for the size study. By using these springs and making all tongue models the same, the tongue roughness models were constrained to the frequencies of 1.43 ± 0.03 Hz and the tongue size models were constrained to the frequencies of approximately 1.35 ± 0.30 Hz.

**Observations and Results**

There were three significant visual observations made during the two experimental processes. First, throughout the tongue roughness investigation it was observed that tongue models with smoother sandpaper appeared to be less "wettable." These models also appeared to have a larger pendant like droplet, as described by Reis et al.,[1] remaining on the sandpaper after the column pinched off. That is, there was a smaller droplet (less water) remaining on the rougher surfaces after column pinch off.

Second, during the tongue size study, the two largest tongue models less frequently penetrated the water surface. A "plop" sound was often heard during these trials as the tongue model came into contact with the water surface, perhaps caused by air trappage.

Third, during the size study, it was also noticed that the larger tongue models had difficulty drawing up a water column. Often during these trials the sides of the rising column would immediately rush in from all directions and cross in the middle, quickly making the column unstable. This is seen in Figure 4, where still video frames illustrate the uptake column difference between the large and small tongue radii.

Though it was observed that smoother surfaces tended to have a larger droplet attached to the tongue model after column pinch off, the tongue roughness model height at pinch off for varying roughnesses was approximately 10.82 ± 2.80 cm from the surface of the water, for all roughness trials. This is seen in Figure 5.

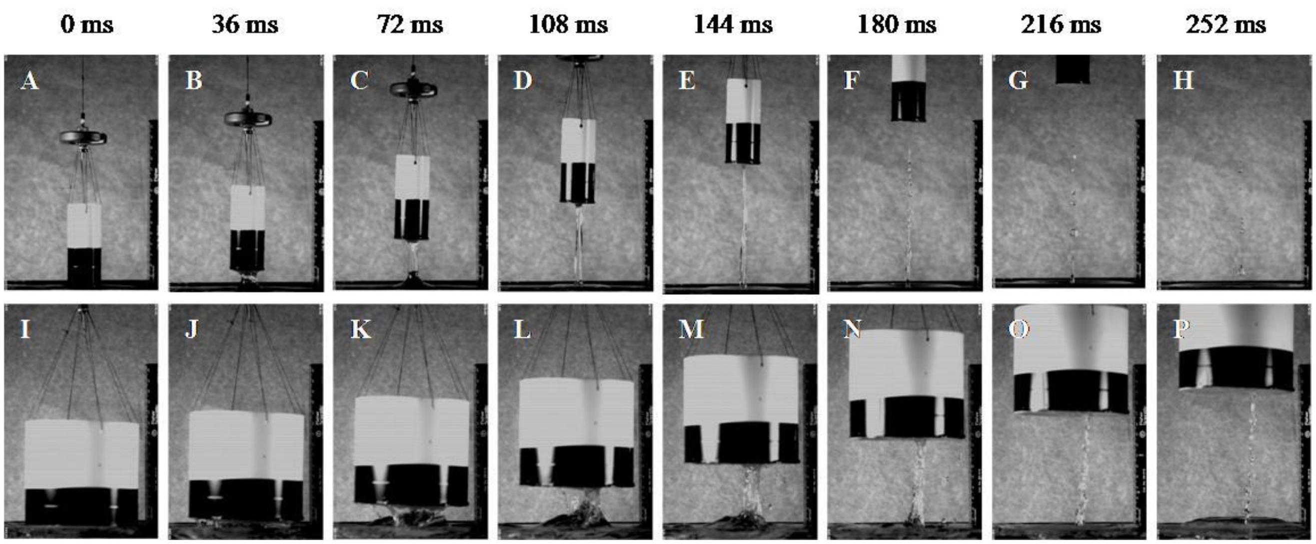


Figure 4: Series of Video Frames: Frames A through H demonstrate the more stable column uptake of smaller tongue radii while frames I through P demonstrate the unstable column uptake of larger tongue radii. These frames are in sequence with time zero beginning in the left hand frame, when each dropper is leaving the water surface, and increasing by increments of 36 ms. The 17.33 mm radius tongue size model on the upper journal has a column pinch off between frames E and F and frequency 1.3 Hz while the 57.33 mm radius tongue size model on the lower journal has a column pinch off in frame P and frequency 1.49 Hz.

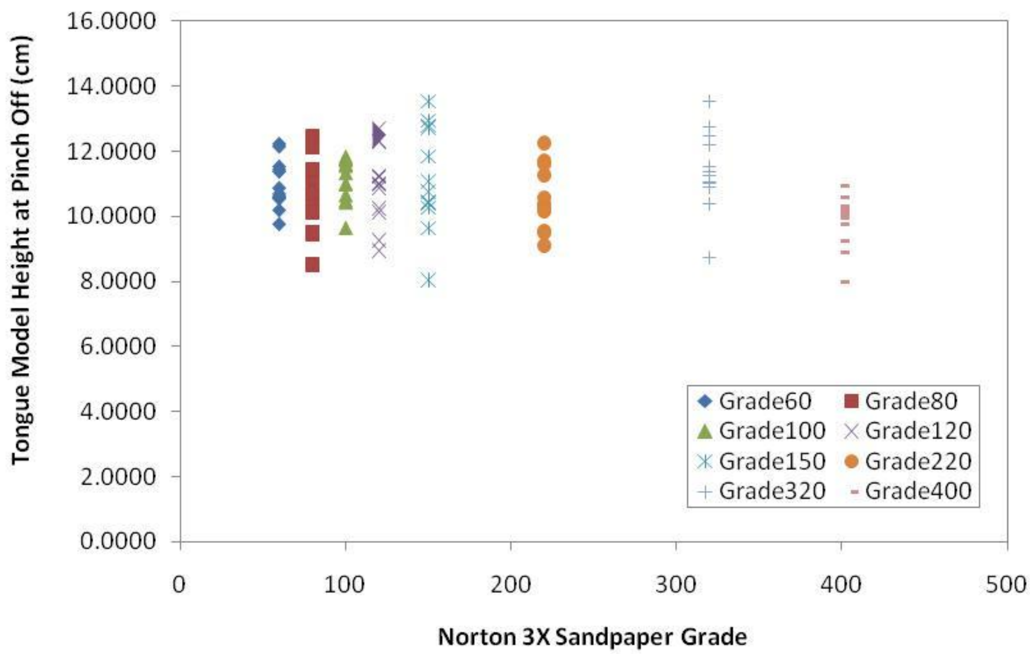


Figure 5: Roughness Variability Data: A small height range dispersion (± 2.80 cm) is seen in all sandpaper grades for the tongue roughness model height at column pinch off.

In addition, for size variation experiments, an increasing trend and decreasing trend were noticed with a critical tongue radius dividing them. This is highlighted by the superimposed parallelograms in Figures 6 and 7.

Furthermore, by investigating lapping frequency for vertebrates outside of the feline family through experimental recordings and You Tube videos, it was found that lapping frequency decreased as animal mass increased.

**Discussion**

The data analyzed from these studies provides two major insights into the lapping mechanism. First, the tongue roughness model experiments showed little affect on tongue model height at column break off, as seen in Figure 5.

Secondly, the tongue size experiments indicate that tongue model height at column pinch off and column height at column pinch off can be divided into two distinct regions. In the first region, both tongue model height and column height increase with radius until a critical tongue radius in the range of 25-35 mm, as illustrated in Figures 6 and 7. After this point the second region begins and both heights decrease as radius continues to increase.

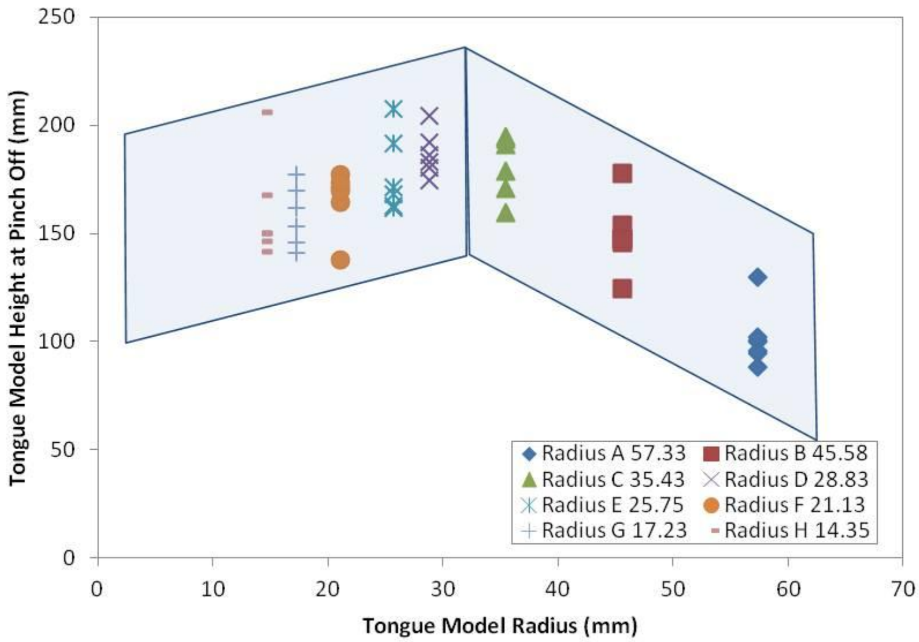


Figure 6: Size Variability Data: Tongue Height at Column Pinch Off, region 1 is increasing on the left and region 2 is decreasing on the right. Also, a critical point range is indicated by the transition from region 1 to region 2 in the radius range of 25 mm to 35 mm. A similar trend is seen in Figure 7.

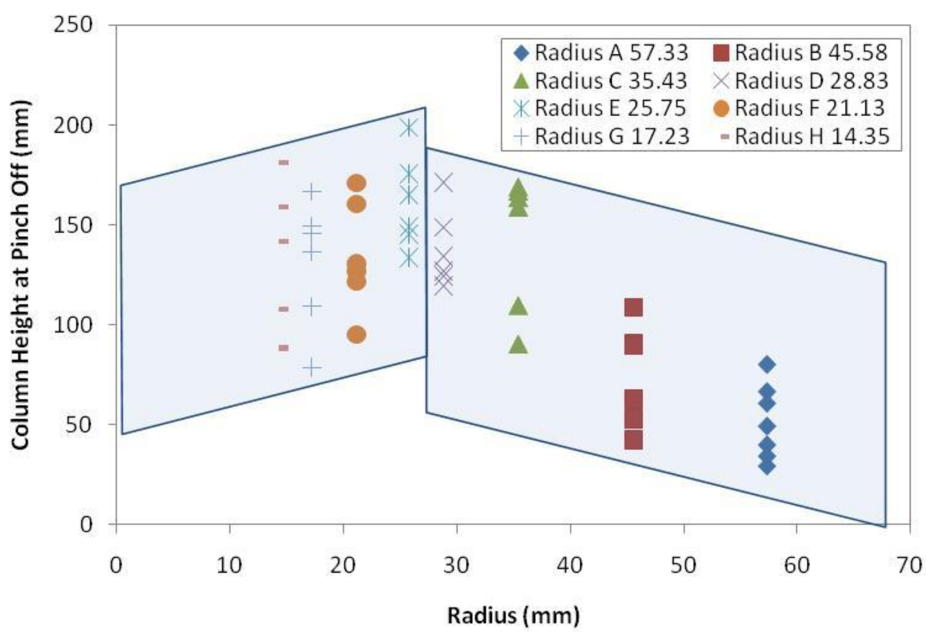


Figure 7: Size Variability Data: Column Height at Column Pinch Off, region 1 is increasing on the left and region 2 is decreasing on the right. Also, a critical point range is indicated by the transition from region 1 to region 2 in the radius range of 25 mm to 35 mm. A similar trend is seen in Figure 6.

From the tongue roughness variation experiment it can be concluded that geometrical surface roughness, at least in the scale and range of the sandpaper used, does not play a major role in liquid column uptake by the tongue. Though the smoother surfaces appeared less wettable by observation and did appear to have a larger droplet, it is likely that gravity is more dominant than the forces caused by the droplet causing it to have no affect on lapping. This result was noted by Reis et al. for theoretical and practical reasons (a high Bond number and high Reynolds number and that the rough part of tongue was assumed not to touch liquid), but is confirmed by the results of this study. This conclusion was necessary to eliminate factors irrelevant to the lapping mechanism so attention could be focused on factors relevant to the study. Also, it was necessary to develop the tongue size experiment since it suggests that any roughness grade is acceptable for use as a control variable because geometrical roughness is irrelevant to column uptake.

From the tongue size variation experiment three conclusions can be made: two correlating to tongue size and one relating to lapping frequency.

Relating to tongue size, it is concluded that tongue radii larger than the approximate critical point (30 ± 5 mm in radius) are ineffective for lapping. This is likely because larger tongues cannot pull an uptake column as high, significantly reducing lapping efficiency. The critical point range, consistent for multiple properties of lapping including tongue model height at column pinch off and column height at column pinch off, suggests that for vertebrates with tongue radii larger than approximately 30 ± 5 mm other methods of ingesting fluid may be more efficient than touch lapping method investigated in cats and dogs. Other methods may include a scooping technique or a hybrid lapping technique that combines multiple uptake methods.

It can also be concluded that there are two distinct regions correlating to tongue radius: one increasing and one decreasing, as seen in Figures 6 and 7. From the smallest radius used in experimentation (2.5 mm by Reis et al. 2010[1]) until the critical point (30 ± 5 mm radius) there is an increasing trend for both tongue model height at column pinch off and column height at column pinch off. This trend was discussed by Reis et al. for tongue radii smaller than the minimum radius of 14.35 mm used in this study. For tongue radii larger than this critical radius, a decreasing trend is seen in the tongue model height at column pinch off and the column height at column pinch off. One explanation for this is that larger tongues uptake a liquid column with greater instability. Because larger tongues have more surface area it is possible for air to be trapped under the tongue at the moment it comes into contact with the liquid surface. This may explain the “plop” sound heard during the larger tongue model trials and indicate less adhesion between the tongue and the fluid. If this is true, tongues with radii smaller than the critical radius uptake a more stable liquid column compared to tongues with larger radii. Figure 4 shows this instability phenomenon by the series of video frames for large and small tongue radii. Thus the tongue model height at column pinch off and column height at column pinch off both increase with of radius until the critical radius is reached.

Also, from this size study, it is concluded that the lapping frequency of vertebrates with incomplete cheeks decreases as vertebrate mass, and thus tongue radii, increases. This directly relates to Reis et al.'s finding that feline lapping frequency is proportional to feline mass in the form of a scaling power law, as seen in

Equation (1). In this manor, it can be concluded that, for the animal data collected, the scaling power law described by Reis et al. seems to extend outside the feline family to lapping vertebrates with incomplete cheeks. Or, at least to those who lap with a touch lapping method similar to cats and dogs.

## Implications and Conclusion

The critical radius range found in this investigation indicates a specific tongue radius where simple touch lapping becomes ineffective. For vertebrates who cannot create suction and have tongue radii less than this critical radius the best lapping method appears to be the touch lapping mechanism. For vertebrates with tongue radii larger than this critical radius the best method of liquid ingestion is more likely a scooping or hybrid lapping/scooping technique. This is consistent with the conclusion that tongue radius increases with vertebrate mass and that lapping frequency decreases with vertebrate mass.

There are several postulations that may explain the natural characteristics of this lapping system. One explanation is that lapping characteristics (such as frequency and tongue size) follow a predator-prey model. In this model, smaller vertebrates lap more quickly because they are more vulnerable to becoming prey for larger vertebrates. In direct correlation, smaller vertebrates have less time to drink at a water source. A larger vertebrate, on the other hand, has few, if any, natural predators and therefore has more time to drink at a water source. Thus a larger vertebrate can lap more slowly because it has no concern about becoming prey. Following this reasoning, smaller vertebrates lap more quickly due to an enhanced need for survival while larger vertebrates, without predators, have the luxury of lapping slowly. Similarly, tongue radius of the vertebrate correlates to a faster or slower frequency based on predatory relationships.

Another explanation is that to remain dry while lapping, larger animals must lap farther away from the liquid surface, also discussed by Reis et al.. Larger vertebrates often have whiskers or other facial features that may hinder lapping close to the liquid surface or become irritated when wet. For this reason, larger vertebrates have a larger tongue radius to uptake a liquid column higher. This permits the face to stay dry but also causes the lapping frequency to decrease. Since it takes more time for the uptake column to travel higher above the liquid surface and more time for the tongue to extend back to the liquid, the lapping frequency will be reduced.

A further explanation is that tongue size is optimized to ingest the maximum amount of liquid for vertebrates with incomplete cheeks. This may explain the critical radius found in the tongue size model study. If tongues correlate to ingesting the greatest amount of volume based on possible predator prey relationships, physical characteristics, ingestion needs, or muscle constraints then tongues may only be beneficial for lapping until this critical radius is reached (in the range of 25 mm to 35 mm, which is approximately the radius of a large tiger tongue). If a tongue is larger than this radius it might be assumed touch lapping is not the optimum ingestion technique for maximum volume intake for this vertebrate. Also, this may restrict vertebrates with larger tongue radii to lap at a slower frequency, consistent with this investigation's frequency analysis.

In addition it is noteworthy that lapping and liquid uptake do not appear to be significantly affected by geometrical roughness. This investigation suggests that a surface only needs to be hydrophilic for an uptake column to form. This is noteworthy because it indicates that if a vertebrate did lap with the rough portion of its tongue, as some appear to, then the filiform papillae or fungiform papillae would not significantly influence the column shape or mechanics. This result has implications for works in soft robotics,[1] and future research in lapping or ingestion mechanics. It should also be noted that while tongue roughness does not appear to affect liquid uptake, it is sometimes necessary for vertebrate grooming and hygiene.

In summary, lapping mechanics in vertebrates with incomplete cheeks is likely optimized for ingestion and physical necessities, is not affected by tongue roughness, and is ineffective as the sole method of liquid uptake for larger vertebrates. This is a relatively new field of study whose results have implications for areas broader than the simple modeling of vertebrate tongues.

**Future Research**

Future research endeavors may include determining the effects of chemical roughness on fluid uptake and lapping mechanics, determining how frequency affects column uptake height, and investigating tongue size in vertebrates.

**Acknowledgments**

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No animals were harmed at any point in this investigation. This project was discussed with the Pacific Lutheran University Animal Care and Use Committee before research began.

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