Design of an Economic Penetration Test Apparatus and Its Applications in the Food Industry

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Abstract

The penetration test is important to mimic objects that are punctured in daily life and is one of the most important test methods for product quality control, ingredient formulation, process improvement, and consumer satisfaction. In the food industry, it has been widely used to measure product firmness, gel strength, and texture consistency. This paper presents the design and methodology of a simple penetration test apparatus that can be used to quantitatively characterize the sample's firmness. This apparatus is cost effective, easy to build, and can be operated on any stable platform. It is portable and can be used in a field such as a fruit farm. This economic apparatus provides consistent data and is used to test several common food products, such as cucumbers, figs, and bananas. In addition, this apparatus has been used to investigate the ripeness of a banana over time. It is concluded that the penetration test apparatus can provide fairly good reproducibility.

Introduction

For many, biting into a piece of chocolate with an unusual mouthfeel or unexpected hardness can be a common and unsatisfactory experience. Such consumers' sensory experience and satisfaction is unlikely to turn into a profitable business for a food company. In order to quantitatively characterize the food texture and relate to the consumers' experience, food scientists generally use five main mechanical properties (hardness, cohesiveness, viscosity, elasticity and adhesiveness) to describe the food texture (Boonyai *et. al.* 2004). These properties can be measured with instruments such as texture profile analysis (TPA) (KPM Analytics, 2026), rheometer, NIR spectroscopy, etc.

A texture analyzer is an instrument used in the food industry to objectively quantify the physical, sensor properties of food. Typically, the instrument is equipped with a load cell that applies force to a food sample using various fixtures. As the food samples are compressed or penetrated, the force and displacement is recorded as a function of time by the instrument's data collection system.

A penetration or puncture test is a method used to evaluate the resistance of a material when a probe is driven into it. Performing such penetration tests to evaluate the texture on food products requires specialized, standardized approaches. The ASTM International (American Society for Testing Materials) is a globally recognized, non-profit organization that develops and publishes technical standards for various materials, products, processes, and systems. There is no single, universal ASTM method for the penetration testing across all food products, due to their nature of wide variations in firmness. Nevertheless several methods are available for specific categories of the food sample. For example, ASTM D217 (ASTM International [ASTM], 2017) describes the standard test method for cone penetration and is designed for measuring the consistency and firmness of semi-solid food products, such as butter, peanut butter, and gelatin. ASTM E1875 (ASTM International [ASTM], 2020) is the standard penetration test to provide guidelines for the sensory evaluation of food texture, color, and odor. ASTM D1321 (ASTM International [ASTM], 2010) is the standard for needle penetration, where a standardized 2mm needle probe is used to evaluate the hardness and structure of waxes, fats, and so on. ASTM F1306 (ASTM International [ASTM], 2021) describes the method to measure the peak force and energy required to break the barrier of the food sample at specific dimensions, using a slow, control velocity profile.

There are many different commercial texture analyzers available on the market. Each has their own advantages in design, sensitivity, resolutions, and operation range. The drawback is that such instruments are expensive. Moreover, they usually require commercially developed software to operate. This restricts their usage in non-profit organizations and/or high school laboratories for education purposes. This project is to design an economic apparatus using a needle to test the penetration of food products. This is not intended to replace the standard test method and the commercially available texture analyzers. Instead, it is to provide a concept and protocol for building an economic and affordable apparatus of penetration testing. This protocol has been used to test several common household fruits such as cucumbers, peaches, figs, and bananas. Reproducibility and the application of this penetration test to monitor the fruit ripenness is proposed.

Experiment and Methodology

Experiment Setup

The ASTM D1321 (ASTM, 2010) describes details of the penetration test procedure. (A standard needle is schematically shown in **Figure 1** with detailed dimensions. The penetration depth of the needle into the sample surface is recorded as a 100 ± 0.15 g load force is placed on the needle for 5.0 ± 0.1 seconds. The main challenge of this is the timing, especially when the soft food production is measured. The needle likely continues the penetration beyond the 5 second time period when applying a constant 100 gram force load to the soft species. This causes relatively larger variation when a stop watch is used. The objective of this work is to improve this measurement variation by utilizing a new approach. **Figure 2** shows the schematic illustration of the proposed apparatus. A disposal needle is glued to a metal block and the total weight is measured at 8.0 grams. An acrylic guidance tube is installed vertically to ensure the needle can fall freely through it. The friction associated with the needle's free fall is negligible, which ensures that good repeatable results are obtained. A camera is used to record the whole penetration process. In order to ensure synchronization of the needle free fall and camera recording process, an electromagnet and an ON/OFF switch is used. The needle diameter is measured at 0.59 mm, as can be seen in **Figure 3**. The needle's diameter is also used as a scale for the camera, which is used for the image processing to get the penetration depth. Most of the parts for this apparatus were purchased from Amazon, with a total cost of less than \$90. This includes \$27.99 for a clamp stand, \$28.41 for a digital microscope, \$6.99 for an electromagnet, \$6.98 for a power supply, and \$7.99 for a box of disposable needles. Alternatively, a smartphone can be used as an alternative to the digital microscope for easier accessibility. In contrast, a commercial texture profile analyzer can exceed \$1,000 for basic versions and upwards of \$10,000 for lab grade devices.

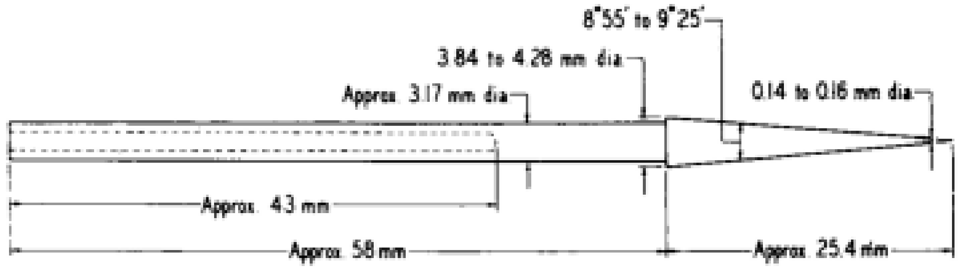

Figure 1: Dimensions of a standard needle, ASTM D1321 (ASTM, 2010)

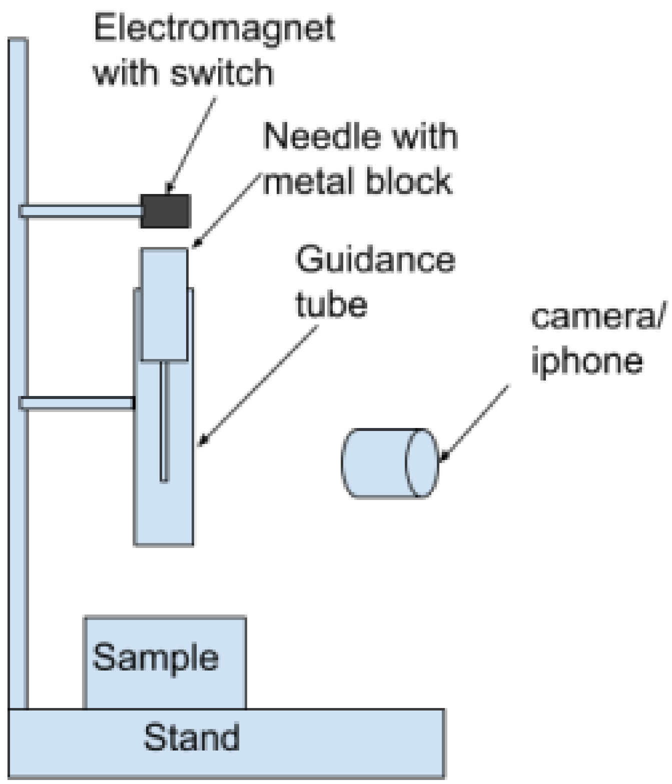

Figure 2: Schematic illustration of the apparatus

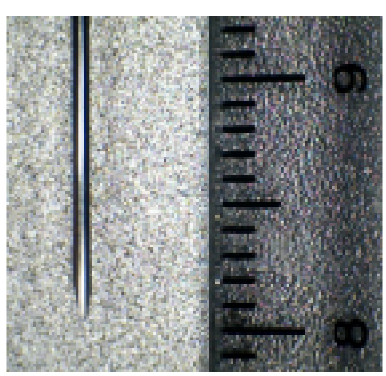

Figure 3: The needle with the scale

Experiment Test Protocol

As the penetration depends on the environment temperature, it is important to maintain the temperature constant in order to obtain ideal reproducible results. A thermal chamber can be used for temperature control. For simplicity, all experiments were conducted in an air conditioned room where the temperature is recorded as 25 ± 1.0℃. The following test procedure is as below:

1. Place the sample on the bottom of the stand and secure it with a clamp.
2. Turn on the switch to activate the electromagnet such that the needle is held in place.
3. Turn on the camera to record the video, then turn off the switch to deactivate the electromagnet. The needle is released and freely falls to penetrate the sample.
4. Stop the video recording.
5. Clean the needle with an alcohol pad.

Results and Discussion

Several fruits have been tested with this apparatus. **Figure 4** shows an example of the image after a typical penetration test on a cucumber. The needle has been penetrated into the sample. The penetration depth is analyzed by an open-source tool called ImageJ (Schneider et al., 2012). It is important to check the reproducibility of this apparatus. **Table 1** shows the penetration depth (PEN) of the needle free-fall from a height of 25 cm into a cucumber sample in five different locations. Good reproducibility is observed, which confirms that the free fall of the needle for the penetration test is acceptable.

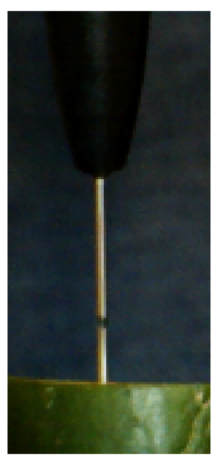

Figure 4: Example of a penetration test on a cucumber

Table 1: The PEN for needle free-falls from a height of 25 cm into a cucumber.

Cucumber	Test 1	Test 2	Test 3	Test 4	Test 5
PEN (mm)	8.62	8.51	8.49	8.58	8.66

Note that the above penetration tests were conducted on the fresh-cut surface of the same cucumber. The tests were also repeated on the same cucumber in the lateral direction. An average of the penetration depth of 3.54 ± 0.08 mm was obtained, which is less than half of the penetration depth to its fresh-cut surface. This is mainly due to the fact that a cucumber skin provides protection. The needle falling from the same height experiences much higher resistance when it travels through the cucumber skin.

It is interesting to test for other fruits using this apparatus at the same kinetic energy level. We selected figs because our experiment coincided with the fig harvest season, so there was an abundance of samples to test. As fig sizes vary, it is important to adjust the electromagnet position in order to maintain penetration height (the end of the needle to the surface of the sample) constant. Table 2 shows the PEN for 5 fig samples. The average PEN and the standard deviation are also shown. Compared to the previous study on the cucumber sample, the PEN for figs have much higher standard deviations. This is due to the fig samples having different maturity as can be virtually observed.

Table 2: Penetration depth for the needle free-falls from a height of 25 cm into figs.

Fig	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Average	StDev.
PEN (mm)	6.37	6.15	7.93	9.89	5.06	7.08	1.88

Based on the previous study, the PEN value seems to have correlation to the fruit's maturity. Indeed, many researches have been focused on the fruit maturity and its monitoring using different techniques. Jaywant et al. (2022) provides a good review on the sensors and instruments for Brix measurements, which is the sugar content. It is interesting to use this apparatus to test on a banana over several days. The hypothesis is that the PEN of the banana sample could be used as an indicator for its maturity.

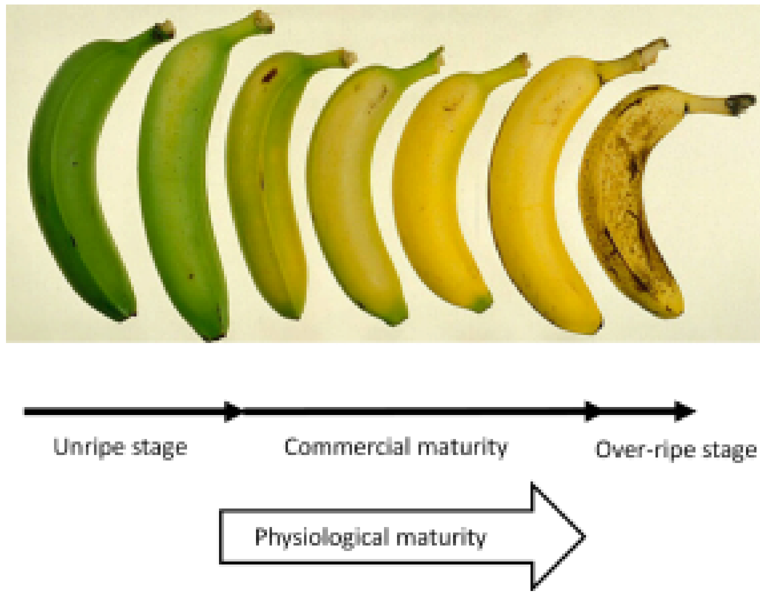

Figure 5: Different stage of banana maturity (adopted from Jaywant et al. 2022)

A banana purchased from Walmart supermarket was used for this experiment. The banana was divided into five zones, shown by the red marker in **Figure 6**. Three penetration tests will be conducted in each zone over 5 days. Three tests were conducted in each zone for each day. The banana was stored at room temperature and was kept away from other fruit to prevent unknown effects on the maturity process. The average PEN and its standard deviation results were shown in **Table 3** over 5 days.

Figure 6: Banana at day 0 for the maturity experiment

Table 3: The PEN for the needle free-falls from a height of 25 cm into a banana.

Banana	Day 1	Day 2	Day 3	Day 4	Day 5
PEN	1.73 ± 0.04	2.25 ± 0.05	4.09 ± 0.06	6.81 ± 0.09	$11.26 \pm 0.$

(mm)					10

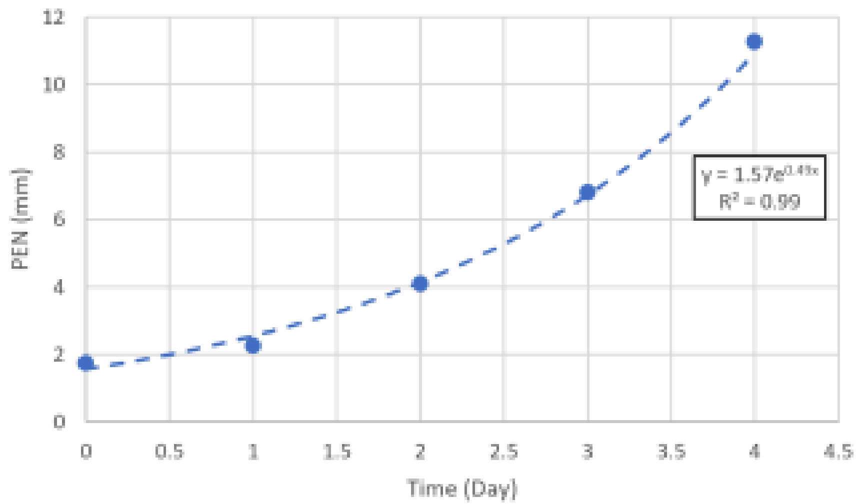

Figure 7: PEN of a banana as a function of time

Figure 7 shows the PEN as a function of the time (in days). Clearly the PEN increases with the storage duration of the banana. These data can be fitted with an exponential function ($y = 1.57e^{0.49x}$), with $R^2 = 0.99$, as shown in **Figure 7**. Indeed, such an exponential function can only work in a limited timeframe, as the PEN is expected to reach a plateau when the banana approaches a fully ripened stage. Regardless, this demonstrates that the penetration apparatus can be used to monitor the ripening process during shelf life. It can also be used to quantitatively determine the ripeness or maturity of fruits.

Conclusion

An economic penetration apparatus has been designed and built. Paired with a camera and an open source software, the penetration process can be captured and analyzed. This apparatus has been tested on some common household fruits with fairly good reproducibility. In addition, it has been applied in monitoring the maturity process of a banana over 5 days, demonstrating its robustness in the investigation. This apparatus can be adapted in a high school laboratory for education purposes.

With a total cost of less than $90, the developed apparatus ranged roughly from 10 to 100 times less than a commercially available texture profile analyzer, simultaneously yielding results with fairly good reproducibility compared to a commercially purpose-built device. Given its substantially lower cost and ease of use, this apparatus provides an accessible and affordable alternative to educational institutions or organizations that may not have the resources for a professional instrument. Furthermore, its portability and modularity enables its use as a field instrument for on-site testing.

References

ASTM International. (2010). *Standard test method for needle penetration of petroleum waxes* (ASTM D1321-10). doi.org

ASTM International. (2017). *Standard test methods for cone penetration of lubricating grease* (ASTM D217-17). doi.org

ASTM International. (2020). *Standard test method for dynamic Young's modulus, shear modulus, and Poisson's ratio by sonic resonance* (ASTM E1875-20). doi.org

ASTM International. (2021). *Standard test method for slow rate penetration resistance of flexible barrier films and laminates* (ASTM F1306-21). doi.org

Boonyai, P., Bhandari, B., & Howes, T. (2004). Stickiness measurement techniques for food powders: A review. *Powder Technology*, *145*(1), 34–45. doi.org

Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. Nature Methods, 9(7), 671–675. doi:10.1038/nmeth.2089

Jaywant, S. A., Singh, H., & Arif, K. M. (2022). Sensors and instruments for Brix measurements: A review. *Sensors*, *22*(6), Article 2290. doi.org

KPM Analytics. (2026). *Your analytical solutions partner for better quality & reduced costs*. https://www.kpmanalytics.com/.