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Development of a handheld precision penetrometer system for fruit firmness measurement

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ABSTRACT

A novel design for a handheld precision penetrometer with control of probe speed, angle and depth of penetration was developed and used to measure the firmness of rose apple and jujube samples. Its performance was compared with two traditional handheld penetrometers used in the produce industry, one with an analog force gauge and the other with a digital force gauge. The prototype instrument had penetration speeds of 4.49, 3.23 and 2.10 mm s^{-1} when the force resisted at the probe tip were 0, 50 and 100 N, respectively. A performance study involving four human operators showed the prototype instrument performance was superior to either of the traditional penetrometers in terms of measurement precision. For rose apple samples, the range of error in firmness value were 0–9.81 N, 0–7.10 N and 0–1.60 N for traditional analog, manual digital and the prototype instrument, respectively. For jujube samples, the range of error in firmness value were 0–9.81 N, 0.20–10.00 N and 0–2.60 N for traditional analog, manual digital and the prototype instrument, respectively. Comparison in firmness value among four operators by statistical analysis with a paired sample *t*-test found that the effect of operator on firmness value was significant when measuring firmness on rose apple samples by traditional analog and manual digital instruments. There was no significant influence of operator when measuring firmness on rose apple and jujube samples by the prototype instrument.

1. Introduction

Firmness is an important index to evaluate fruit maturity and quality. Firmness of fruit is commonly measured to determine the appropriate maturity stages, a proper time for harvest and transport. Proper identification of the optimum firmness and quality can reduce mechanical damage such as distortion, bruising and cracking during transportation. Also, firmness in storage is also measured to assessment of fruit quality. Each type of fruit shows a unique optimal firmness value when they are ripe and ready for consumption. For example, kiwifruit are considered ready for eating with firmness values between 5 and 10 N (Stec et al., 1989), apples with firmness value not less than 44.5 N are required by consumers in Canada (Prange et al., 1993) and firmness values between 2.52–4.75 N are acceptable for sweet cherry (Hampson et al., 2014).

Historically, firmness measurements are conducted by forcing the probe of a penetrometer into the flesh of a sample to a fixed depth; the maximum force is recorded as the firmness (Abbott, 1999). Currently, there are many instruments for measuring firmness and they can be classified into two types: portable or handheld penetrometers and non-portable universal testing instruments. Handheld penetrometers are typically small in size, light weight, low cost and their precision depends on operator strength and skill level. Handheld devices are normally used in a field, orchard, or packing shed, without ready access to AC electrical power and are based upon the original mechanical spring forge gauge design of Magness and Taylor (1925). Non-portable penetrometers are large in size and mass, expensive and used when high precision results are required.

Factors that affect the precision in firmness measurements have been well studied. The three principal factors that affect the precision of produce firmness measurement are: speed, angle and depth of penetration (Bourne, 1974; Breene and Joen, 1974; Harker et al., 1996; Delong and Prange, 2000; Kupferman and Dasgupta, 2001). Firmness measurement, using the same manual, analog force gauge penetrometer on apple and kiwifruit found that firmness values differed among operators but were much more consistent when multiple measurements were made by the same operator within a short time period (Harker et al., 1996; Lehman-Salada, 1996). Another study found that measurements made by the same operator on different days on uniform sheets of expanded polyethylene showed differences in firmness value

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using the Magness-Taylor penetrometer (Nicholas, 1960). These results illustrate that differences in the physical characteristics of the measurement parameters of the traditional Magness-Taylor method can cause differences in firmness values (Abbott and Watada, 1976). Normally, differences in the speed at which the probe penetrates the flesh will affect the firmness value due to the visco-elastic nature of the material with higher penetration speeds giving higher firmness values than low speed rates of penetration (Feng et al., 2011; Li et al., 2016). Several studies of handheld instruments, where the operator applied the input force, showed consistent difficulty to control speed rate and depth of penetration, especially in fruit with hard tissue or high firmness (e.g., Abbott and Watada, 1976; Harker et al., 1996). Non-portable penetrometers can eliminate these types of problems because speed rate, angle and depth of penetration are uniformly controlled by using a motorized drive and computer control system, and therefore are not dependent on operators. However those instruments are typically expensive and not convenient for carrying into a field or orchard. Thus the objective of this research was aimed to design a lightweight, non-motorized system to control speed, angle and depth of penetration on a prototype handheld penetrometer with high precision for firmness measurement, and to compare its performance with other traditional handheld penetrometers of the Magness-Taylor type.

2. Materials and methods

2.1. Sample preparation

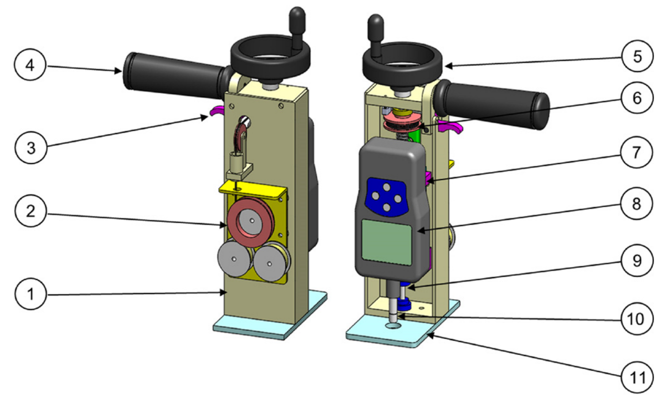
One hundred eighty rose apples (*Syzygium aguem*, cv. Tabtim Chan) and jujubes (*Ziziphus mauritiana*, cv. Nomsoad) were collected from an orchard in Ratchaburi, Thailand. All samples were symmetrical in shape and had no defects or bruises to minimize errors in firmness measurement associated with these types of localized abnormalities. The fruit were stored in a laboratory with a controlled temperature of 25 °C for 2 h before starting to measure firmness. Samples were separated into two levels of firmness value, and both rose apples and jujube were used for low and high firmness values, respectively. The skin in the measured area was removed before firmness measurement using commercial peeler by one operator for all samples to avoid errors from the skin that affect to firmness value in the same sample.

2.2. Design and operation

2.2.1. Design

The design concept was to control three influential factors identified by previous research: probe speed, angle and depth of penetration, and to be portable and designed for use in a field without AC electrical power. The key element in the new prototype instrument (Fig. 1) consisted of a linear motion element with a penetration distance control and constant force system, all mounted on support frame that was made with aluminum to reduce weight. The linear motion control system consisted (Fig. 2) of a linear slide bearing block with a 20 mm rail mounted on the frame and the block was attached with a 9.5 mm diameter threaded shaft to propel the block along the rail. A digital force gauge (Model Digital, Nidec-SHIMPO, China) was also installed on the block in the direction of movement to allow the probe of the force gauge to penetrate a fruit. The distance control system (Fig. 2) used a miniature adjustable-speed control (1780 N maximum force, 19 mm stoke) damper set up in front of the block where the tip of damper made contact with the frame to allow setting the penetration distance. A transparent plastic plate with a hole (16 mm diameter) was mounted on the frame under the probe tip where the hole was concentrically located about the probe. The transparent plate allowed the operator to see and aim the probe tip at the desired penetrated location and to control the penetration depth relative to the fruit surface.

To control the penetrometer probe travel speed, without the complexity of an active feedback control system, an orifice-based hydraulic flow control design was utilized. A constant force spring (Model ML-2920, AMETEK, PA, USA) was installed on the frame and the tension cable of the spring was attached to a 25 mm diameter pulley that was fixed onto the threaded shaft (Fig. 2). This spring was used as an input force to drive the probe of the digital force gauge to penetrate into the fruit. Due to the short travel of the penetrometer (less than 10 mm) and the resulting small change in radius of curvature of the spring during travel, this style of constant force spring exerts a nearly constant tension on the cable during travel. In an orifice-based hydraulic flow control,



No.	List
1	Main frame
2	Constant force spring
3	Trigger
4	Handle
5	Handwheel with revolving handle
6	Thread rod with pulley
7	Linear guide blocks and rail
8	Digital force gauge
9	Damper
10	Probe
11	Transparent plate

Fig. 1. The prototype handheld precision penetrometer instrument.

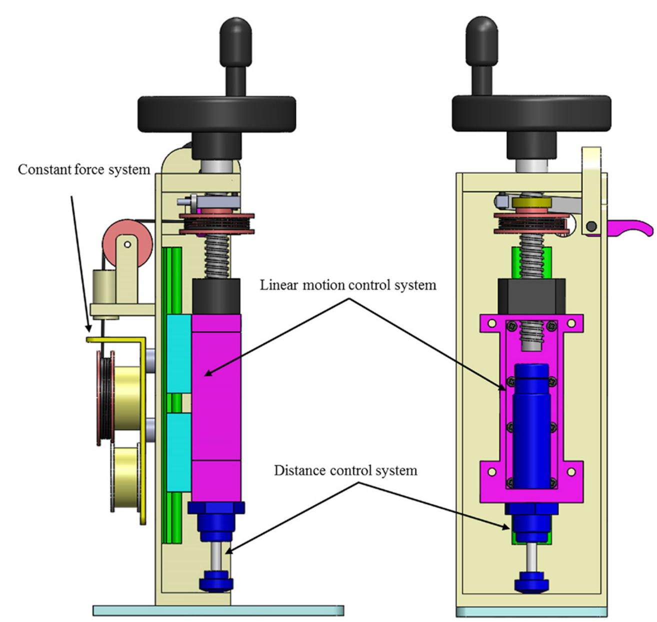


Fig. 2. Mechanism of the prototype instrument consisting of linear motion control, distance control and constant force systems.