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Determination of physical and mechanical properties of carrot (*Daucus carota*) for designing combine harvesting mechanism

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ABSTRACT

The main objective of this study was to measure the properties of the carrot to design carrot (*Daucus carota* L.) harvesting mechanism. Physical properties were beneficial to fix the relative position of carrot harvesting mechanism and mechanical properties were helping in functionality of the carrot combine harvester mechanism. Three carrot cultivars namely Pusa Keshar, Pusa Rudhira and Nantes cultivar were taken for the study. Length of carrot, effective foliage length (stem node), carrot head (crown) above soil surface; weight and upper root diameter were included in physical properties measurement. Pulling and tensile force were included in mechanical properties measurement. The foliage length was found in the range from 46 to 90cm, however, the crown height was observed at 1.5 cm above the soil surface. Carrot root length of Pusa Keshar, Pusa Rudhira and Nantes were 23.10 ± 3.71, 21.68 ± 4.14 and 18.64 ± 3.49 cm, respectively. Average pulling force in undisturbed (unloosen) raised bed highest was observed with Pusa Rudhira (148.93 ± 73.46 N) followed by Pusa Keshar (133.10 ± 62.15) and Nantes (118.18 ± 41.72). While, the pulling force for loosen raised bed were observed in following order Pusa Rudhira (22.41 ± 7.64 N) >Pusa Keshar (21.35 ± 5.84 N) >Nantes (20.21 ± 5.52 N). The loosen soil imposed 5 to 6 time lesser resistance on pulling carrot than unloosen raised bed. Average foliage detachment force (tensile force) from carrot crown was 236.13 ± 20.66, 211.95 ± 16.81 and 243.35 ± 47.73 N for Pusa Keshar, Nantes and Pusa Rudhira, respectively. It was observed that pulling force in loose raised bed was around 10 times lesser than the foliage detachment force.

Key words: Carrot foliage, Physical properties, Pulling force, Tensile force

Carrot (*Daucus carota* L.), is the second most popular root vegetable, after potato in the world. India is one of the largest producers of carrots in world with an annual production of 13 Mt from mere 0.86 Mha land area (Horticultural Statistics at Glance 2017). Carrot is a rich source of beta (β)-carotene, essential micronutrients and contains vitamins, like thiamine, riboflavin, vitamin B-complex and minerals. It helps to prevent diseases and improves eye sensitivity, freshness of skin, hair growth and nourishment for nails (Bogacz-Radomska and Harasym 2018). Production of carrots depends on the adopted agronomical practice. Carrots grown on ridges have higher production due to optimum physical conditions. Nowadays for higher carrot density, the carrots are being grown on raised beds (Fig 1) with four rows on top of 350 mm bed. This type of practice leads to uniform carrot shape, size and weight**.** Traditionally, the carrots are harvested manually, which is very drudgerous, tedious, time consuming and costly operation. Because of these problems there is a need for mechanization of carrot harvesting. Nowadays, diggers are used for the digging carrots from fields. But in digging process, the collection of carrots is done manually. Mechanisation of carrot harvesting can reduce human drudgery of manual collection and can enhance efficiency. Efforts were made by many researchers on development of crop harvester considering different properties. Few physical properties of carrot crop were studied for the development of carrot harvester for Egyptian agricultural condition (Horia *et al*. 2008). Similar study was carried out by Wang *et al*. (2012) to determine physical parameters of sugarbeet for harvester design under natural and loose soil condition. Khura *et al*. (2010), studied physical properties

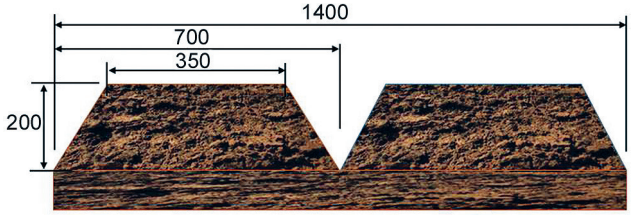

Fig 1 Raised bed for commercial carrot cultivation (All dimensions are in millimetre).

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of onion crop for the development of onion digger. They reported that a total of 94% of the onion bulb were within 60 mm soil depth, the mean peak cutting force to rupture was 72.0, 88.9 and 151.4 N for small medium and large size bulbs, respectively. Similar study was also carried on carrot (Shirwal 2010 and Nath 2019). Considering the above facts, a study was done to determine the physical and mechanical properties of carrot at harvesting stage, and to study the effect of physical properties on the design and development of carrot combine harvester.

MATERIALS AND METHOD

Experimental site and carrot cultivar selection: The experiment was conducted at the experimental farm of the Institute in 2013–15. The carrot varieties (i.e. Pusa Keshar, Pusa Rudhira and Nantes) were selected for the study. First two varieties are Asian cultivars, whereas Nantes is European cultivar. Different dimensions of carrot root and foliage were measured (Fig 2). However, the pulling force was measured at harvesting stage before and after loosening of raised bed observation was recorded from three replications. The carrots were pulled from raised bed plot by holding foliage at a height of 10 cm from its crown. A total 10 samples were selected for measuring physical properties.

Measurement of physical properties: The selected physical properties like root length (cm), foliage length (cm), upper diameter (cm), number of branches, and weight (g) were measured. Pulling force was measured with the help of experimental setup comprised load cell, indicator and frame assembly of holding device and; the tensile force was measured on Texture Analyzer. The length of carrot, length, number of foliage branches, carrot crown head were measured with measuring scale. For designing of the digger, maximum carrot length was considered to minimize carrot damage during digging and loosening of the soil.

The weight of carrot was measured with the help of weighing balance. The weight was measured along with foliage. It was required for the estimation of quantity of material that can be handled by harvesting mechanism. The shape of the carrot was essential for the functional requirements of the harvesting mechanism. The upper diameter was measured with the help of digital Vernier calliper.

Determination of mechanical properties: The mechanical properties considered for the study were, pulling force and tensile force of the foliage stem. To measure pulling force, an S-type load cell (500 N) fitted on portable pulling force measuring frame assembly was designed and used. Portable pulling force measuring frame assembly and foliage holder (Fig 3a, b) was used for measuring the pulling force to uproot the carrot from raised bed. The frame structure was mounted on four wheels to facilitate movement at different sample collection locations. Holding assembly was kept dangling on pulley. The gears (5:1 ratio) were used for transferring manual power to the holding grip. Smaller gear was rotated with wheel handle to transmit power to bigger gear (Table 1). An S-type load cell along with digital indicator was mounted to determine the force required for pulling the root efficiently. The pulling force required gives an estimation of power required to design carrot combine harvester mechanism. The holding assembly was made from a cut piece of rough top conveyor belt (150 × 70 mm). This rough top conveyor belt was supported by a MS flat with one end hinged and other end was provided with hole to tighten both the rough top conveyor belts closer in such a way that it did not allow slippage of the foliage.

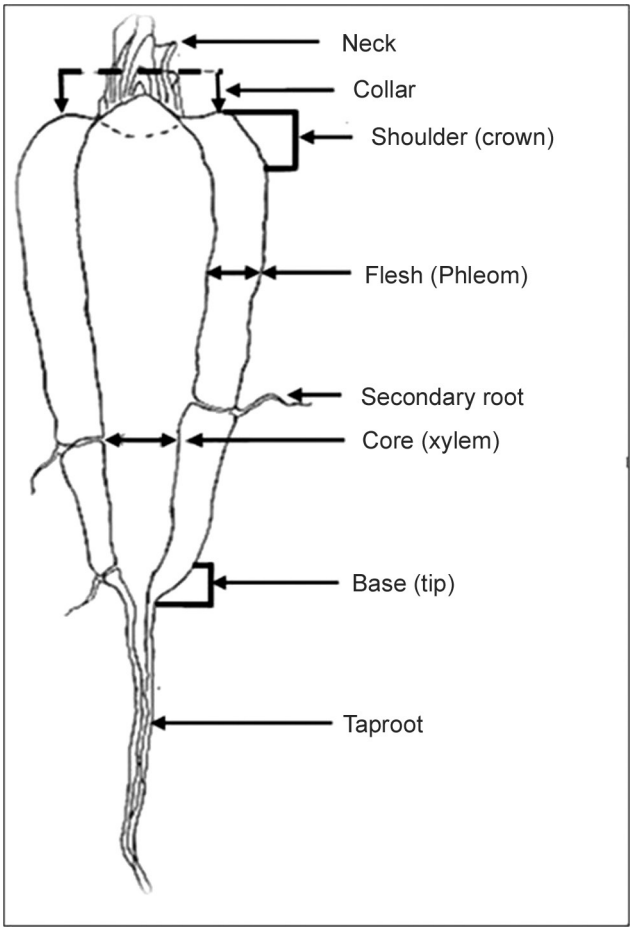

Fig 2 Details of carrot plant.

The tensile force of the carrot stem node was measured with the help of TA+Di Texture Analyser. The carrot stem node was placed in between two holding jaws. In order to prevent rupture of carrot and foliage while holding, rough top conveyor belt pieces were used.The bulk density is the

Table 1 Details of frame assembly for pulling force measurement

Particulars	Dimensions
Total height of frame (mm)	1200 × 500 × 500
Gear (small: big) ratio	5:1
Turning wheel diameter (mm)	220
Transport wheel, 4 no diameter (mm)	150
S-type load cellSensor (N)	500
Portable weighing balance (kg)	50
Holding device (mm)	120 × 7

Fig 3 (a) portable pulling force measuring frame at field and (b) Foliage holder

ratio of weight and volume. Bulk density of carrot was measured using a wooden box having dimensions of 500 × 250 × 250 mm (Khura *et al*. 2010). The box was filled with bulbs without compaction, and then weighed.

Soil moisture is an important property which affects operation of machinery. The moisture content of the soil at harvesting stage was obtained according to ASAE Standard S358.2 (1983) and AOAC (2000). The sample was dried in an oven at 105°C temperature for 24 hr. The moisture content of the sample in percent dry basis was calculated using following equation.

$$M_C = \frac{100\ (W_1 - W_2)}{W_2}$$

where, M_c is the Moisture Content of soil (in % dry basis), W_1 is the initial mass of soil before oven drying (in g) and W_2 is the final mass of the soil after oven drying (in g). Data were analyzed by statistical tool SPSS 21 was used for the analysis.

RESULTS AND DISCUSSION

The root length of carrot varieties, i.e. Pusa Keshar, Nantes and Pusa Rudhira were 15.6–28, 17–30 and 14–30 respectively (Table 2). It was showed that the good agronomic practice yielded good quality carrots. Carrot generally had uniform conical and cylindrical shape. The foliage length was found in the range of 46–90 cm. Therefore, the carrot can be easily picked up by holding foliage at height around 10 to 15 cm from the carrot crown.

Physical properties of carrot cultivars: It was observed that the Pusa Keshar and Pusa Rudhira had similar physical properties compared the Nantes cultivar. As it was indicated earlier that both Pusa Keshar and Pusa Rudhira were the Asiatic variety having longer root and the Nantes variety

Table 2 Physical properties of carrot

Parameters	Root length	Foliage length	Upper diameter	Number of branches	Weight (g)
	---------- (cm)----------				
			Pusa K		
Mean	23.10	68.55	4.28	8.30	235.33
Median	24.00	70.50	4.21	8.00	210.00
Mode	24.00	62.00	4.61	8.00	300.00
Standard Deviation	3.71	9.52	0.99	2.34	81.19
Range	12.40	34.50	4.80	10.00	280.00
Minimum	15.60	52.50	2.00	4.00	100.00
Maximum	28.00	87.00	6.80	14.00	380.00
			Nantes		
Mean	18.64	69.71	4.19	7.63	211.67
Median	23.00	69.00	4.27	7.50	200.00
Mode	23.00	72.00	2.94	6.00	200.00
Standard Deviation	3.49	9.00	0.83	1.81	82.72
Range	13.00	43.73	3.26	7.00	330.00
Minimum	17.00	46.27	2.54	5.00	50.00
Maximum	30.00	90.00	5.80	12.00	380.00
			Pusa R		
Mean	21.68	67.10	4.13	7.93	195.67
Median	21.00	65.00	4.24	8.00	195.00
Mode	21.00	63.00	3.80	8.00	200.00
Standard Deviation	4.14	9.02	0.58	1.89	76.55
Range	16.00	31.00	2.24	7.00	320.00
Minimum	14.00	53.00	2.91	5.00	20.00
Maximum	30.00	84.00	5.15	12.00	340.00

was a European variety with shorter and smooth root. Root length would be important for the depth of digger in carrot combine harvester mechanism. It was observed that Pusa Keshar and Pusa Rudhira had higher root length compared to Nantes cultivar, i.e. 23.10 ± 3.71, 21.68 ± 4.14 and 18.64 ± 3.49 cm respectively (Table 2). Horia *et al*. (2008) reported that average carrot length was 137.14 ± 29.23 mm for Egyptian agricultural condition. It could be inferred that, digger should be operated at the depth of around 25 cm for loosening soil. But as height of raised bed was 20 cm so, the depth of operation of digger below the raised bed could be 5 cm. There would be no considerable economic damage to the carrot root while operating the harvesting mechanism at this depth.Chen *et al*. (2010) predicted that depth for green radish ranged from 15 to 26 cm and that of red radish was from 18 to 24 cm to harvest. In case of onion, Khura *et al*. (2010) reported that the percentage distribution of onion below the ground surface decide the depth of digging operation, so that the maximum number of onion bulbs could be dug with minimum damage.

Effective foliage length was considered very important for the machine to be operated. A machine should be designed in such a way that effective foliage length held in between the conveyor belt to uproot carrot vertically with inclined carrot harvesting mechanism. The maximum effective foliage length was observed in range of 20 to 35 cm, it might be due to the proper agronomical practices (Horia *et al*. 2008).

Pusa Keshar and Pusa Rudhira had almost equal number of branches (NB) 8.3 ± 2.34 and 7.93 ± 1.89 than Nantes (7.63 ± 1.81). At the height of 15.0 ± 5.0 cm from carrot crown the thickness of stem was found to be equal, which can be captured with a gap of 6.0 ± 2.0 mm in between the conveyor belt. Among the cultivars, there were least variations of upper diameter in Nantes 4.19 ± 0.83 cm and more variation in Pusa Kesar and Pusa Rudhira 4.28 ± 0.99 and 4.13 ± 0.58 cm, respectively (Table 2). Khura *et al*. (2010) reported that the number of leaves per plant for onion ranged from 4 to 12, with an average of 7.64 and coefficient of variation of 28.54%.

Physical properties of carrot cultivars: In mechanical property, firstly the pulling force for unloosen raised bed and then loosen raised bed was measured with the help of load cell assisted pulling force measuring system. The average pulling force for unloosen raised bed was 133.10 ± 62.15, 118.18 ± 41.72 and 148.93 ± 73.46 N for Pusa Keshar, Nantes and Pusa Rudhira, respectively and for loosen raised bed the pulling force were 21.35 ± 5.84, 20.21 ± 5.52 and 22.41 ± 7.64 N, respectively (Table 3). Chen *et al.* (2010) reported that maximum pull force for green and red radishes in natural condition during harvest were in the range of 191±113.8 N and 197±107.2 N, respectively.It was observed that, in the loosen soil resistance to lift carrot was 5 to 6 time lesser than undisturbed (unloosen) raised bed. Wang *et al*. (2012) reported that pulling force required to pull out sugar beet was reduced by 30% in loosened soil. So, for efficient digging, a digger to loosen the soil should be incorporated in the raised bed for carrot harvester.

Table 3 Mechanical properties of carrot cultivars

Particulars average	Pusa K	Nantes	Pusa R
Pulling force (undisturbed soil), N	133.10 ± 62.15	118.18 ± 41.72	148.93 ± 73.46
Foliage detachment force, N	236.13 ± 20.66	211.95 ± 16.81	243.35 ± 47.73
Pulling force (Loose soil), N	21.35 ± 5.84	20.21 ± 5.52	22.41 ± 7.64
Foliage cutting force, N	34.80 ± 4.32	25.99 ± 0.87	30.11 ± 8.29
Foliage moisture content, %	99.93	99.93	99.92

Average foliage detachment force (tensile force) from carrot crown was significant; the observed values were 236.13 ± 20.66, 211.95 ± 16.81 and 243.35 ± 47.73 N for Pusa Keshar, Nantes and Pusa Rudhira, respectively. It was found that, there was sufficient tensile force for pulling of carrot from loose raised bed. Foliage detachment force 10 times higher was observed compared to the required pulling force in loose raised bed. It can be inferred that, the chances of breaking the carrot and foliage were very low while pulling the carrot from loose bed. Chen *et al*. (2010) predicted cohesive strength between stem and root of the green radish and the red radish were in the range of $(2.45 \pm 1.23)10^5$ Pa and $(2.17 \pm 1.08)10^5$ Pa, respectively.

Pulling force with respect to root length: The pulling force to uproot the carrot from the raised bed increased with the increase in root length. In Pusa Keshar (Pusa K) variety, the pulling force varied from 46–132 N with increase in root length from 10–25 cm (Table 4). The longer roots tend to remain firmly attached with the soil below, thereby requiring greater pulling force. Similarly, Pusa Rudhira (Pusa R) variety showed the similar results. In these two varieties the root elongate to the firm horizons of soil resulting in higher pulling force. However, it was found that Nantes showed different characteristics than Pusa K and Pusa R. The pulling force increased from 66 to 74 N at root length 10 to 25 cm.The small variation in pulling force of Nantes was apparently due to uniform root characteristics and less secondary roots. As per the findings of Amponsah *et al.* (2017) uprooting force influenced with cassava varieties, its planting position and root depth. Similarly, Wang *et al*. (2012) also reported that the pulling force of sugarbeet has positive relationship with physical dimension and weight of root tuber.

After loosening the soil variation of pulling force with respect to root length was also measured. The pulling force to uproot the Pusa K carrot variety ranged from 16 to 26 N at root length from 10 to 25 cm. The rupture of the bond between soil and carrot by loosening with digger caused the reduction in pulling force. The larger root length of Pusa R offered resistance to the pulling force and increased from 15.7 to 30.15 N. While, the Nantes variety pulling force increased from 15.0 to 25.9 N at root length of 10 to 25 cm (Table 4).Similar finding reported in case of sugar

Table 4 Variation of pulling force with respect to root length, weightand diameter of carrot in unloosen raised bed and the loosened bed

Varieties	*Pulling force in unloosen raised bed*											
	Root length			Root diameter					Root weight			
	10-15	15-20	20-25	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	100-150	150-200	200-250	250-300
Pusa K	45.8	92.4	132.4	45.8	92.4	132.4	134.6	182.2	45.8	91.9	139.6	211.2
Nantes	66.0	79.8	73.8	73.8	109.8	129.6	141.6	160.0	63.8	89.6	134.0	160.3
Pusa R	65.6	103.0	115.2	64.1	89.4	115.2	148.7	128.8	89.4	115.2	103.0	223.8
	Pulling force in loosen raised bed											
Pusa K	16.0	18.77	26.05	16.9	20.2	20.8	27.35	28.15	14.9	17.1	22.4	26.4
Nantes	15.13	20.33	25.85	14.3	19.6	22.4	25.4	26.5	13.75	14.35	16.7	20.4
Pusa R	15.7	23.8	30.15	15.55	21.7	23.5	27.75	25.95	13.2	15.0	19.1	28.9

beet, report showed that the pulling force of sugarbeet has positive relationship with physical dimension and weight of root tuber (Wang *et al*. 2012).

Pulling force with respect to weight

Weight of carrot was classified into four ranges between 100 to 300 g with an interval of 50 g. The pulling force increased with the increase in weight of carrot. The pulling force of Pusa K before loosening ranged from 45.8 to 211.2 N with increase in carrot weight from 100 to 300 g. After loosening the soil with digger (Table 4), the pulling force increased from 14.9 to 26.4 N at 100 and 300 g carrot weight respectively. The pulling force of Pusa R increased to 115.2 N at 200 g and reached to 223.8 N at 300 g carrot weight. The pulling force reduced to 28.9 N after loosening. In case of Nantes, the pulling force increased to 160.3 N at 300 g carrot weight. The loosening of soil a reduction in pulling force to 20.4 N at 300 g carrot weight was observed. It might be due to the physical condition of experimental soil (Wang *et al.*2012).

Pulling force with respect to upper diameter: It was observed that as the upper diameter of carrots increased the pulling force was found to be increasing. As diameter of carrot increased, the circumference of the carrot increased which resulted in more surface area of contact. Increased surface contact area result in adhesion. The lowest diameter ranged from 3.5 to 4.0 cm and the corresponding pulling force was in between 45 to 74 N, whereas for higher ranged from 5.5 to 6.0 cm, the pulling force was in between 129 and 182 N (Table 4).The variation in pulling force due to root diameter before and after loosening the soil, affect the harvesting mechanism of carrot to uprooting from soil. The pulling force increased continuously with the increase in root diameter in all the varieties of carrot. It ranged from 45.8 to 182.2 N as the root diameter increased from 3.5 to 6 cm. After loosening, the same variety had pulling force from 16.9 to 28.15 N. In case of Pusa R, the pulling force increased to the root diameter of 5 cm and then started reducing. Same pattern was found after loosening the soil (Table 4). The pulling force of Nantes variety attained a value of 160 N at root diameter of 6 cm before loosening. After loosening the soil, it required 14.3 to 26.5 N forces to uproot a carrot of 6 cm diameter. It might be due to the increase in root diameter and root depth would result in an equivalent increase in uprooting force requirement (Amponsah *et al.* 2014).

The soil moisture content led to reduction in uprooting force to the carrot from the soil (Table 5).The pulling force reduced for Pusa K with increase in moisture content. The highest reduction was observed in Pusa R. In case of Nantes, the pulling force remained almost constant. Horia *et al*. (2008) predicted similar result in terms of penetration resistance of soil. As the moisture content increases from 21 to 25% the penetration resistance decreases from 145 to 120 N. in case of the bulk density it was observed that the highest soil bulk density (1.588 g/cm^3) was observed with highest moister content and lowest was recorded at lower moisture contents. Moisture content influences the bulk density which affects the penetration resistance and ultimately pulling force (Amponsah *et al.* 2017).

From the present study design parameters for carrot harvesting systems could be determined both in terms of force requirement and dimensional location of components. Effective foliage length was considered as the significant parameter of the carrot harvesting mechanism design. The effective foliage length ranged from 20 to 35 cm, therefore, the carrot harvesting mechanism can easily be positioned below 20 cm for holding and uprooting carrots. Length of foliage was found sufficient enough to hold it with 3 to 4 inch wide rough top conveyor belt. Results confirmed that even if the conveyor belt is holding the foliage at 15 ± 5 cm, there will be no damage to the crown of the carrot ensuring the

Table 5 Pulling force with respect to soil moisture content and soil bulk density

Moisture content (%)	Bulk density (g/cm)	Pulling force (N)		
		Pusa K	Nantes	Pusa R
9.41 ± 0.04	1.385 ± 0.007	153.98 ± 5.16	131.07 ± 4.76	163.73 ± 5.32
12.46 ± 0.58	1.469 ± 0.0039	126.76 ± 7.09	125.02 ± 3.53	128.33 ± 3.68
14.99 ± 0.41	1.588 ± 0.0013	121.78 ± 3.83	121.35 ± 4.87	120.78 ± 3.52

quality harvesting of carrot cultivars.The foliage detachment force (tensile strength) to separate foliage from carrot root was around to be 10 times higher than the pulling force required in the loosened raised bed. The pulling force was affected by carrot root length and diameter, with increase in root length and diameter the pulling force increased. The digging operation loosens the soil bed and breaks the secondary roots bonding with the soil. But, the carrot remains at erect position due to soil support. Therefore the carrots could be easily picked up by holding the effective foliage. Digger should be operated at the depth of around 25 cm for loosening soil. But as height of raised bed is 20 cm so, the depth of operation of digger below the raised bed can be only 5 cm. Operating the harvester at this depth would ensure least damage to the carrot root. The digger would push the carrot, disturbing its natural position in the soil. The space created by the movement of the carrot upwards got filled with loose soil due to gravitational force. This action would keep the carrot at pushed position, facilitate the picking of harvesting mechanism with help of rough top conveyor belt.

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