Development of a sensor-based system to evaluate the actuating force of walk-behind type paddy transplanter

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An embedded system with flexi force sensors was developed to evaluate the actuating force required for the control levers of the walk-behind type paddy transplanter in static and field conditions. For measuring the force, three flexi force sensors were attached to the distal phalanges of the thumb, index finger and middle finger of the operator, so that the sensors could measure the force applied for engaging or disengaging the levers. These sensors were interfaced with Arduino Uno through a signal conditioning circuit, and the measured forces were recorded with the help of an SD card module. A maximum of 17.00 ± 5.00 N force was required to control the accelerator lever, while the left and right steering levers required an actuating force of 17.02 ± 5.58 N. For engaging brakes/clutch, lesser force (15.20 ± 4.87 N) was required compared to disengaging the lever (31.74 ± 9.80 N) under actual field conditions. To start the transplanting mechanism, a much higher actuating force (68.00 ± 12.23 N) was required; however, to stop the mechanism, a comparatively smaller force (19.60 ± 10.26 N) was required. For controlling the gear shift lever in forward and reverse positions, a maximum actuating force of 28.14 ± 5.72 N was required.

Keywords: Actuating force, flexi force sensor, levers, remote-controlled paddy transplanter.

THE general force measurement system consists of a load cell/force transducer and related equipment, whereas in the case of sensor-based systems, force sensors that produce an equivalent voltage in terms of force are used. A load cell is commonly used to measure mass in industrial applications. Several different forms of load cells are available. Most load cells are electronic based on the strain gauge principle, although pneumatic and hydraulic types also exist. Tension and compression load cells have been used by various researchers under the ICAR-All India Co-ordinated Research Project (AICRP) on Ergonomics and Safety in Agriculture for the measurement of strength parameters to decide the maximum control actuating force of tractor operators[1]. An integrated foot transducer (IFT) was also developed by Hota *et al.*[2] to measure the forces applied by the lower limbs of farm machinery operators. The IFT system consists of load sensors, which are sandwiched in a structure with a plastic foam sponge placed between two shoe-shaped flat aluminum plates that fit the operator's feet through a pair of velcro strips.

In the 1970s, Franklin Eventoff discovered that certain materials could change resistance when subjected to force[3]. These are known as force-sensitive resistor (FSR) sensors which allow measuring static and dynamic forces applied to a contact surface. The flexi force sensor is one such example of a variable FSR sensor. Each FSR sensor consists of three different layers, viz., a plastic conductive layer with a semiconductor layer, a spacer layer and printed electrodes[4,5]. The air gap is maintained by a spacer mounted around the edges of the membrane and by the rigidity of the two membranes. Since the entire detection area of the sensor is treated as a single point of contact, the applied load can be evenly distributed over the detection area to ensure accurate and reproducible force readings[6]. The resistance of the foil changes as the material to which the gauge is attached undergoes tension or compression due to changes in length and diameter. The change in resistance can be read by connecting an ohmmeter to the two outer pins of the sensor connector and applying force to the detection area[6]. The major advantages of FSR sensors are their small size (thin), good shock resistance, low power requirement, fast response to force changes, robustness against noise, simple conditioning circuits, ability to fabricate using flexible materials, and low unit cost compared to other commercial force sensors[6].

Keeping in view the above advantages, a hand-approaching flexi force touch sensor was used to measure the actuating force of control levers of a paddy transplanter under laboratory and actual field conditions. The observed force limits were finally used for designing the remote-controlled system for the two-wheel paddy transplanter[7,8].

Material and methods

The forces required for actuating the various control levers of a walk-behind paddy transplanter were measured in the Department of Farm Machinery and Power Engineering,

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Figure 1. View of the walk-behind-type paddy transplanter in operation.

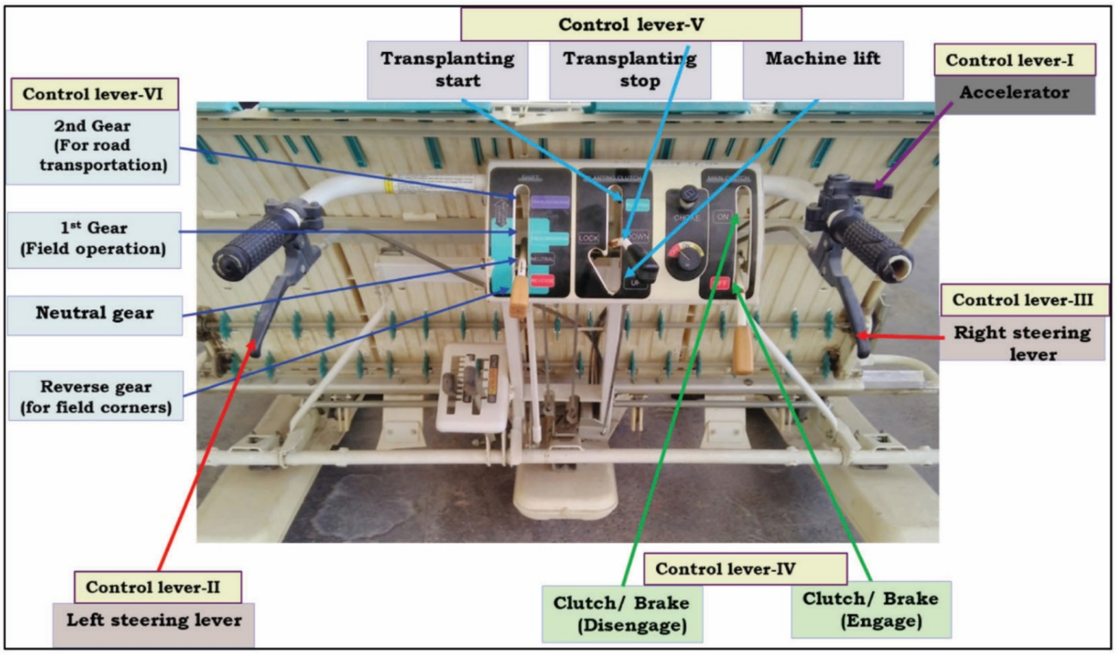

Figure 2. View of various control levers of walk-behind-type paddy transplanter.

Table 1. Major specifications and performance parameters of walk-behind-type paddy transplanter

Particulars	Specifications
Make/model and type of transplanter	Kubota make; NSP-4W, MZ175-B-1, walk-behind type paddy transplanter
Type of engine	Air-cooled, four-cycle, OHV petrol engine, contact-less magneto ignition, hand recoil starter system
Power required	2.6 kW, 171 cc, 3000 rpm
Steering mechanism	Differentially enabled
Weight (kg)	160
Number of rows × distance between rows (mm)	4 × 300 (fixed)
Distance between hills/plants (mm)	120 and 140

Punjab Agricultural University (PAU), Ludhiana, India, during 2019–2020. A two-wheel walk-behind paddy transplanter (Kubota NSP-4W, model MZ175-B-1) was selected for the study (Figure 1). Table 1 presents the major specifications and performance parameters of the walk-behind-type paddy transplanter.

All the control of the transplanter were push/pull in both the upward and downward directions, except for the accelerator knob (Figure 2). The accelerator knob (lever I) is a thumb-controlled push/pull lever in forward and reverse directions. Steering of the transplanter is achieved by differentially driven wheels with separate clutches for left

Table 2. Specifications of flexi force touch sensor selected for the study

Parameters	Specifications
Type of load cell/sensor	Ultra-thin and flexible printed circuit
Make/model	Tekson, Inc., South Boston, USA
Load capacity (N)	445
Rated output (V)	0.25–1.25
Display	Through arduino serial port
Temperature range (°C)	–9 to +60
Axis for measuring force	Three – X, Y and Z

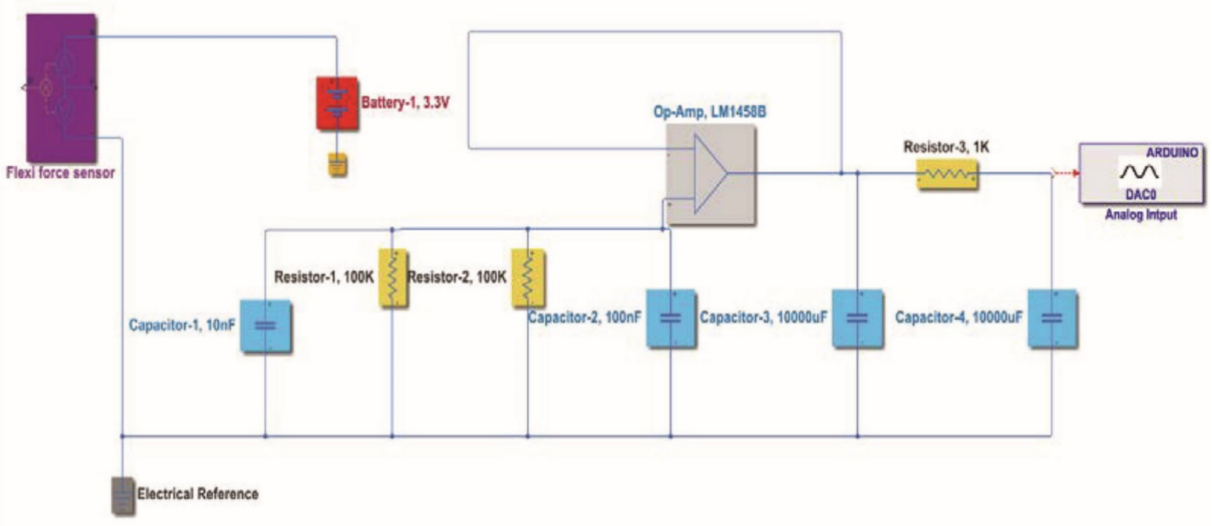

Figure 3. Schematic diagram of signal conditioning circuit used in the system.

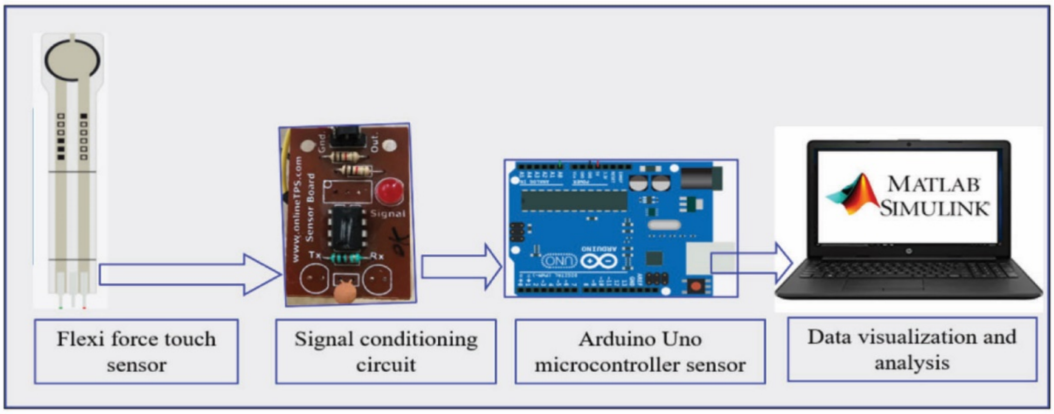

Figure 4. Block diagram showing composite unit for operating flexi force touch sensors.

(lever II) and right (lever III) turns. The main clutch (lever IV) is used to transmit power to the drive wheels, hydraulics and transplanting mechanism. The planting clutch (lever V) lifts, lowers and controls the transplanting mechanism. The shift clutch (lever VI) provides neutral, forward and reverse movement of the transplanter in the field and on the road.

To measure the actuating force of control levers of the walk-behind paddy transplanter, an embedded system with flexi force sensors (Tekson Inc., USA)[9] (Table 2) was designed (Figure 3). These sensors were calibrated against known weight values in the laboratory before integration. The least count of the developed sensor was 0.01 N. The flexiforce sensors were interfaced directly with Arduino Uno on the analogue pin as the microcontroller had an inbuilt ADC (analogue to digital converter, thus eliminating the use of an external ADC chip). During the initial laboratory trials, there were some fluctuations in the data received

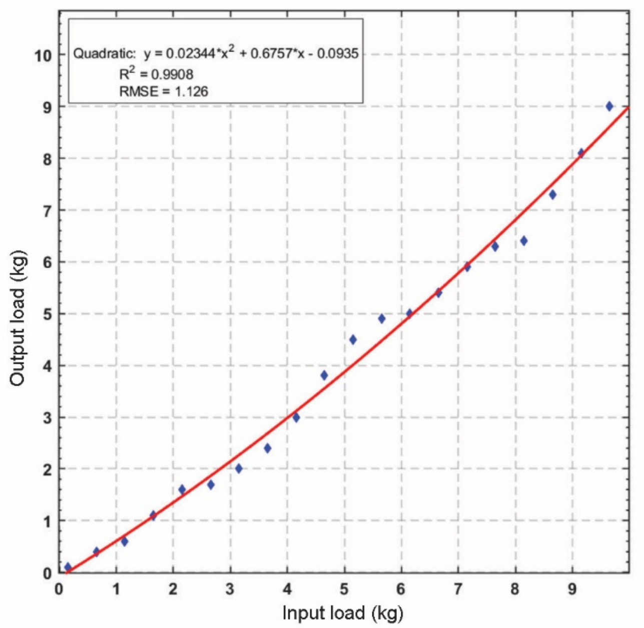

Figure 5. Calibration curve of input–output load on flexi force sensor.

from the sensors, for which a signal conditioning circuit was designed which amplified and filtered the output from the sensors (Figure 3). Further data analysis was measured using the final system with MATLAB software (rev. 2020b, The Mathworks, Inc., Mass., USA).

The signal conditioning circuit designed for the flexi force touch sensors had Op-Amp IC (LM1458B) at its core. The circuit had two stages: amplification and filtration. The Op-Amp was used in a differential mode where, at non-inverting pin, flexi force sensors were connected, and the inverting pin was used for feedback (Figure 4). The amplified output was then filtered using two filter stages: capacitor filter and RC filter to remove any fluctuations. The final output was fed to the Arduino UNO microcontroller for further processing.

The resistance of flexi force sensors changes in correspondence to the force being measured. To convert the change in resistance to voltage fluctuations, a voltage divider circuit was used. The voltage across the voltage divider circuit was fed into the OP-AMP IC for amplification, and the output is described by the following equation.

$$V_{\text{out}} = \frac{R_{\text{m}}V}{R_{\text{m}} + R_{\text{fsr}}},$$

where V_{out} is the output voltage, R_{m} the measuring resistor, V the voltage and R_{fsr} is the resistance of flexi force sensor.

Calibration of flexi force touch sensor

To determine the electrical output of the sensor related to an actual engineering unit, calibration was done by applying a known force to the sensor and equating the sensor resistance output to this force. A linear interpolation was done by plotting a curve between zero load and the known calibration loads (conductance, $1/R$) to determine the actual force range that matches the sensor output range[9].

Figure 5 presents graphically the output results of calibration considering the mean values of dead weights imposed over and removed from 0 to 10 kg and 10 to 0 kg, respectively. The calibration results of FSR were analysed, and a linear equation was developed to determine the correlation, coefficient of determination, adjusted R^2 and standard error of estimate/root mean square error (RMSE).

Three flexiforce touch sensors were placed on the distal phalanges of the thumb, index finger and middle finger of the operator (Figure 6). The control levers were engaged and disengaged, applying force by distal phalanges under laboratory and actual field conditions. The observed values of actuating force are to be used to select the configuration of electrical linear actuators/electric motors leading to the development of a remote-controlled actuating system[8]. Therefore, it was decided to consider the values of peak actuating force observed through sensors to actuate the control levers.

Statistical analysis of actuating forces exerted by load cells/sensors on various control levers

The data of actuating force obtained from the flexi force touch sensors were statistically analysed using one-way ANOVA followed by Tukey's post-hoc comparison and paired *t*-test (SPSS software (v 26.0, IBM SPSS Statistics) with five replications at a 5.0% significance level. The whisker boxplot charts were prepared using MATLAB

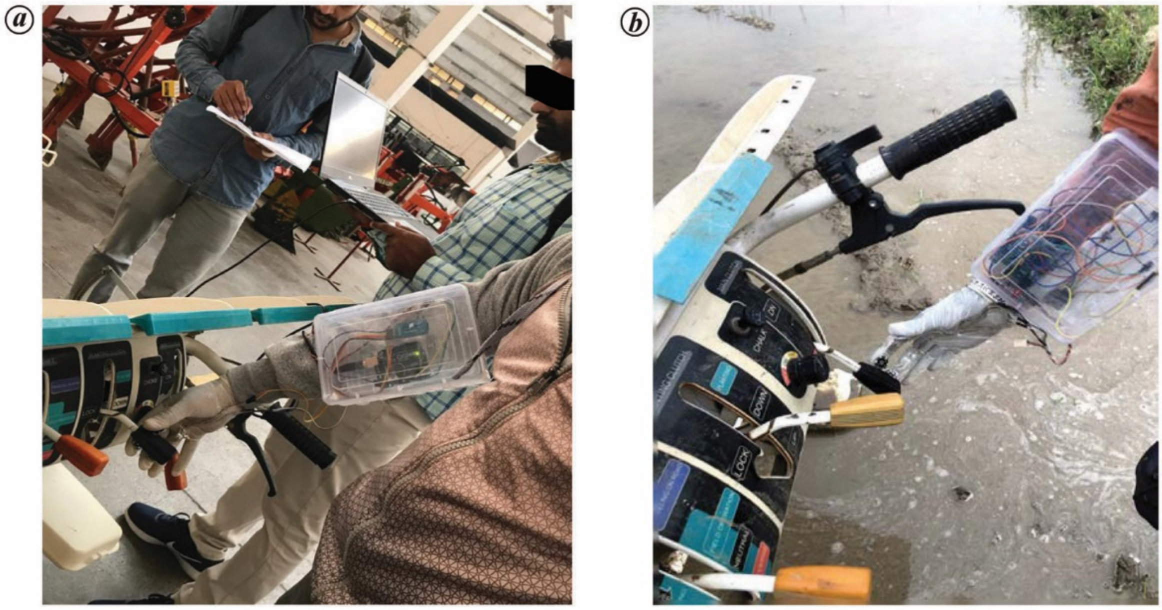

Figure 6. Measurement of actuating force by flexi force touch sensor under (***a***) laboratory and (***b***) field conditions.

software (rev. 2020b, The Mathworks, Inc., Natick, Mass., USA). These charts were of the five-number summary system, viz. minimum, lower quartile (Q_1 = 25th percentile), median (Q_2 = 50th percentile), upper quartile (Q_3 = 75th percentile) and maximum values, which gives a good identification of centre and distribution of the data.

Results and discussion

Actuating force measured for control lever I (accelerator lever) of paddy transplanter

The mean actuating force to actuate the accelerator lever at a high position under laboratory conditions was 16.04 ± 3.89 N, while under field conditions, it was 17.00 ± 5.00 N. Similarly, when the accelerator was in a lower position, the mean actuating force under laboratory and field conditions was 16.06 ± 3.81 and 17.00 ± 5.00 N respectively (Table 3). Since the lever was fixed once while starting the machine, no significant difference ($P < 0.05$) was observed while actuating the accelerator lever in a high or low position under laboratory and field conditions. The results were also found to be in accordance with the findings of Mehta *et al.*[1]. It was reported that based on the fifth percentile values of push/pull strength of Indian agricultural workers, the force required for the operation of hand throttle lever and speed selection lever on a tractor should not exceed 25 and 46 N respectively. The upper limit of hand-control levers could be selected up to 96.5 N (ref. 10), 168.2 N (ref. 11), 230 N (ref. 12) and 400 N (ref. 13). For operating the hand control throttle lever, the maximum actuating force should not exceed 230 N (ref. 13) and 300 N (ref. 14).

Actuating force measured for control levers II and III (left and right steering levers)

The levers II and III were used to steer the transplanter in the left or right direction respectively. While engaging lever II (left steering lever), a significantly higher force ($P < 0.05$) was observed while operating under field conditions (18.68 ± 4.86 N) compared to stationary position under laboratory conditions (17.02 ± 5.58 N). No significant difference was observed between the lever and right steering. However, no force was required to release both levers while disengaging them.

Actuating force required for control lever IV (main clutch/brake lever)

As indicated in Table 3, to actuate the main clutch/lever, a significantly higher force ($P < 0.05$) was necessary while operating the machine under field conditions (15.20 ± 4.87 N) compared to the force observed under stationary field conditions (13.4 ± 5.46 N). Further, while pulling the lever in the upward direction to disengage the same, the actuating force measured under field conditions was 30.54 ± 9.6 N, which was significantly higher than that measured under laboratory conditions. The results also depict that the control lever requires significantly less force to stop the transplanter compared to the force required for the onward movement of the transplanter under both laboratory and field conditions. This might be due to the safety aspect, i.e. to switch 'on' the power transmission, higher force should be applied, while in case of any emergency, less force would be applied to stop the transmission and transplanter immediately.

Table 3. Mean actuating force (N) observed by the flexi force sensor during various positions of control levers

Control lever	Position of control lever	Actuating force (N)	
		Laboratory conditions	Field conditions
Lever I	Accelerator (high)	$^{A}16.04^{de} \pm 3.89$	$^{A}17.00^{de} \pm 5.00$
	Accelerator (low)	$^{A}16.06^{de} \pm 3.81$	$^{A}16.00^{de} \pm 3.08$
Lever II	Left steering lever	$^{B}17.02^{de} \pm 5.58$	$^{A}18.68^{cde} \pm 4.86$
Lever III	Right steering lever	$^{B}17.00^{de} \pm 3.39$	$^{A}18.80^{cde} \pm 2.59$
Lever IV	Main clutch/brake lever (engage)	$^{B}13.40^{de} \pm 5.46$	$^{A}15.20^{de} \pm 4.87$
	Main clutch/brake lever (disengage)	$^{B}30.53^{bc} \pm 9.60$	$^{A}31.74^{bc} \pm 9.80$
Lever V	Transplanting (start)	$^{B}65.13^{a} \pm 2.68$	$^{A}68.00^{a} \pm 12.23$
	Transplanting (stop)	$^{A}21.50^{bcd} \pm 10.98$	$^{A}19.60^{cde} \pm 10.26$
	Transplanting mechanism (lift)	$^{A}32.30^{b} \pm 8.42$	$^{A}33.80^{b} \pm 7.12$
	Transplanting mechanism (down)	$^{B}18.90^{cde} \pm 4.21$	$^{A}21.40^{bcde} \pm 5.03$
Lever VI	Gear shift lever (N-1)	$^{B}7.30^{e} \pm 2.16$	$^{A}8.86^{e} \pm 2.92$
	Gear shift lever (1-2)	$^{B}6.10^{e} \pm 1.14$	$^{A}7.82^{e} \pm 1.11$
	Gear shift lever (2-1)	$^{A}24.93^{bcd} \pm 7.00$	$^{A}28.14^{bcd} \pm 5.72$
	Gear shift lever (1-N)	$^{B}13.40^{de} \pm 4.67$	$^{A}15.30^{de} \pm 5.79$
	Gear shift lever (N-R)	$^{B}22.50^{bcd} \pm 5.60$	$^{A}25.14^{bcd} \pm 5.32$
	Gear shift lever (R-N)	$^{A}17.65^{de} \pm 6.34$	$^{A}19.30^{cde} \pm 5.29$
R^2-value (coefficient of determination)		0.861	0.850
Coefficient of variance		21.235	27.905
RMSE		5.931	6.362
P-value		<0.0001	<0.0001
F-value		26.58	24.28

Values are expressed as mean ± standard deviation. Different superscripts in capital letters show significant differences between the laboratory and field conditions ($P < 0.05$) using paired t-test. Different superscripts in small letters show significant differences within the positions of control lever ($P < 0.05$) using Tukey's test.

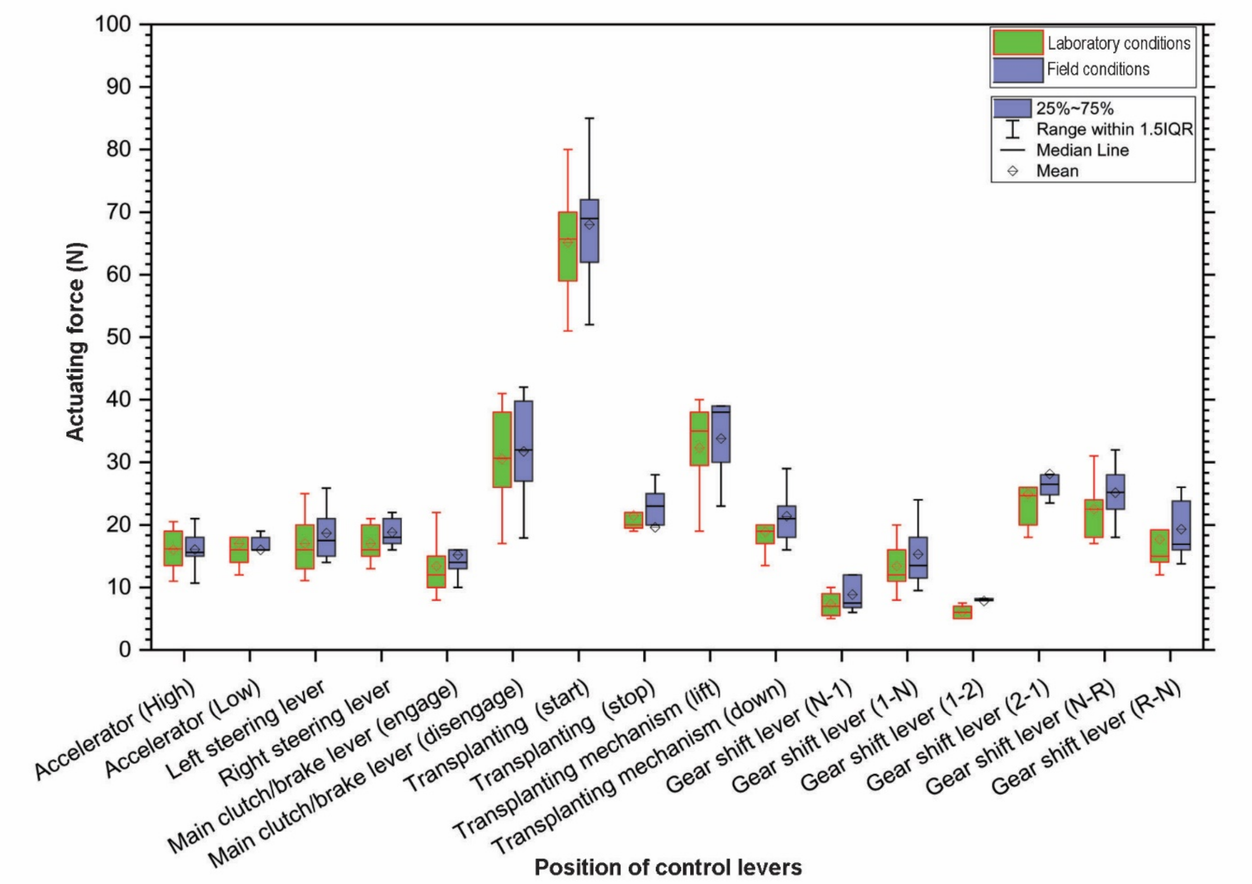

Figure 7. Actuating force measured for various position control levers of paddy transplanter under laboratory and actual field conditions.

Actuating force required for control lever V (transplanting lever)

Lever V consists of three positions, viz. ‘on’, ‘off’ and ‘lift’, which are used to start the transplanting operation, stop the same and lift the transplanting mechanism while entering and exiting from the field. To start the transplanting operation, the lever has to be pulled upwards, where a maximum force of 68.08 ± 12.23 N was measured under field conditions, which was found to be significantly higher ($P < 0.05$) than that measured under laboratory conditions (65.13 ± 2.68 N). Further, for stopping the transplanting mechanism, no significant difference was observed between the laboratory (21.50 ± 10.98 N) and field conditions (19.60 ± 10.26 N). It was also observed that while pushing the lever in the downward direction to stop the transplanting mechanism, significantly lesser force was required compared to that required in the upward direction to start the transplanting mechanism (Figure 7). That might also be due to safety considerations, i.e. to start the transplanting mechanism, a higher force should be applied. On the contrary, less force is needed to stop the transplanting mechanism immediately if the operator faces any obstacle. Upon completing a row, during the turning process, lifting the transplanting mechanism required more force on the lever than lowering the lever to initiate the transplanting mechanism in a new row.

Actuating force required for control lever VI (gear shift lever)

Lever VI (gear shift lever) has four positions: second gear, first gear, neutral gear and reverse gear (2-1-N-R). These positions can be selected by the upward and downward movement of the gear shift lever. Initially, the transplanter should be kept at a neutral position – N. For its forward movement in the field, the lever has to be shifted upward to engage the first gear, for which a higher actuating force of 8.86 ± 2.92 N was measured under field conditions compared to that measured under laboratory conditions. Further, to engage the lever in the second gear for the movement of the transplanter, a maximum force of 7.82 ± 1.11 N was measured under field conditions, which was significantly higher ($P < 0.05$) than that measured under laboratory conditions (6.10 ± 1.14). For operating the transplanter in the reverse direction, first, the lever must be kept at a neutral position – N. Then it has to be shifted to lever position ‘R’, for which higher force (25.14 ± 5.32 N) was measured under field conditions. The post-hoc testing revealed that within the various position of control levers; the actuating force measured by all the selected load cell/sensors for transplanting lever (lever-V) was found significantly higher ($P < 0.05$) than the force measured to actuate all other control levers (Figure 7). This force limit was substantially higher than the lowest 5th percentile values of the single hand push and pull strength of agricultural workers in India[15–17].

The ongoing discussion has focused on assessing the force requirements for operating various control levers, particularly in the context of farming equipment. After comprehensive testing and analysis, it has been determined that the force necessary to manipulate most control levers aligns well within the limits of hand pull and push force exerted by fifth percentile male and female farm workers. This study ensures that the control levers are user-friendly and accessible to a vast majority of farm workers, regardless of their physical strength. However, the study identified an outlier in the transplanting lever V, which demanded a significantly higher actuating force compared to other levers. Addressing this higher force requirement for lever V is crucial to maintain uniformity and optimize the usability of control levers across the farming equipment. Additionally, the research considered anthropometric dimensions to further validate the usability implications. By taking into account the hand pull and push force exerted by individuals at the 5th percentile of strength[17], the study inferred that if this group of individuals can effectively operate the control levers, then the entire population, including those with greater strength, will be proficient in using them. This consideration emphasizes the importance of accommodating a diverse range of farm workers, promoting inclusivity, and ensuring safety in agricultural practices. Moving forward, implementing the recommended modifications to bring the actuating force of lever V within the recommended limits will enhance the overall efficiency and accessibility of control levers, contributing to improved productivity in the agricultural sector.

Conclusion

In the present study, before developing a remote-controlled system for walk-behind paddy transplanters, the actuating forces applied to the control levers were measured through a flexiforce sensor under laboratory and actual field conditions.

A maximum of 17.00 ± 5.00 N force was required to control the accelerator lever, while the left and right steering levers required an actuating force of 18.68 ± 4.86 N and 18.80 ± 2.59 N respectively, under actual field conditions.

For engaging brakes/clutch, lesser force (15.20 ± 4.87 N) was required compared to disengaging the lever (31.74 ± 9.80 N) under actual field conditions.

To start the transplanting mechanism, a high actuating force (68.00 ± 12.23 N) was required. However, to stop the mechanism, a comparatively smaller force (19.60 ± 10.26 N) was required.

For controlling the gear shift lever in the forward and reverse positions, a maximum actuating force of 28.14 ± 5.72 N was required.

The hand-approaching flexi force touch sensor was easy, comfortable, and precise for measuring the actuating force of various control levers under laboratory and actual field conditions. Further, the observed force limits will be useful for designing a remote-controlled system for two-wheel walk-behind-type paddy transplanters.

Conflict of interest: The authors declare that they have no conflict of interest.

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