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Gender-responsive farm mechanisation for women smallholders in India: ergonomic risk, physiological workload and implement–user mismatch

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Abstract

Women perform a large share of field work on India's small farms, yet many implements are not sized for their bodies or strength. This study assessed the ergonomic fit of seven implements on smallholder farms (0.7–0.8 ha) in two villages of Meerut district, Uttar Pradesh. Eighteen body dimensions and grip strength were measured in 60 women and 30 men. Women then operated a reaper binder, brush cutter, rotary-blade attachment, mist blower, easy seedling transplanter, seed-cum-fertiliser drill and three-tyne weeder, while heart rate, perceived exertion, body-part discomfort, RULA and OWAS scores and trunk flexion were recorded. Women were on average 13.4 cm shorter than men, with a 9.6 cm lower standing elbow height and 34% lower grip strength. Handles of 98–110 cm on the weeder, brush cutter and mist blower were 3–15 cm above the women's mean elbow height. The easy transplanter gave the highest cardiac cost (44 beats min^{-1}) and a RULA score of 6, whereas the seed-cum-fertiliser drill and three-tyne weeder stayed below the 30 beats min^{-1} threshold and scored RULA 2. Across implement means, trunk flexion was strongly associated with RULA score ($r = 0.97$) and body-part discomfort ($r = 0.95$), while implement mass showed no significant association with any workload measure. Operating posture therefore appears to be a better guide to ergonomic risk than implement mass. We propose preliminary targets for adjustable handle height (88–101 cm), grip diameter (3–4 cm) and trunk flexion (≤ 20°), with work–rest guidance, which should be validated in larger field studies.

Keywords Gender-responsive mechanisation · Women farm workers · Ergonomics · RULA · Anthropometry · Sustainable smallholder agriculture

Highlights

- Seven farm implements were scored for physiological and postural load with women as operators on smallholder farms.
- Trunk flexion was more closely linked than implement weight to postural risk and discomfort.
- Design limits for handle height, grip diameter and posture are proposed for women-friendly implements.

1 Introduction

Small farms hold the key to food security in South Asia. More than 80% of the world's farms are smaller than 2 ha [1], and in India the average operational holding was only 1.08 ha in 2015–16 [2]. Women make up a large and growing part of the workforce on these farms, as men move to non-farm jobs [3, 4]. Social sustainability of farming therefore depends on whether the tools that women use are safe, efficient and suited to their bodies. This concern links directly to the Sustainable Development Goals on gender equality (SDG 5), safe and decent work (SDG 8) and the productivity of small-scale food producers, particularly women (SDG 2.3) [5].

Farm mechanisation in India has grown, but its level is still well below that of China and Brazil [6, 7]. In the upper Gangetic Plains, tractors and threshers are common, while planting, weeding, transplanting and harvesting still rely heavily on hand labour [8]. When machines do arrive, they are rarely designed for women. Most implements are sized from male body dimensions and strength [9, 10]. A handle set too high, a grip too thick or a load too heavy forces the operator into awkward postures, and such postures are a well-known cause of work-related musculoskeletal disorders in agriculture [11–13]. Women in Indian agriculture already report high rates of back, shoulder and wrist pain, and improved tools designed for them have been shown to reduce drudgery [14, 15].

Judging whether an implement suits women needs more than a time-and-motion study. Heart rate and energy expenditure show the cardiovascular cost of the work [16–18]; RULA and OWAS show the postural risk to the body [19, 20]; and subjective scales of exertion and discomfort capture what the worker feels [21, 22]. These methods are well validated [23, 24], and anthropometric data allow the findings to be turned into design limits [10, 25]. Recent reviews, however, note that most farm ergonomics studies assess one task or one tool, often on research stations, and rarely combine physiological, postural and anthropometric measures [26,

27]. Earlier work on small-farm implements in India has likewise focused on machine performance [28] or on single hand tools [14].

This study examines the ergonomic fit of farm implements used by women on smallholder farms in western Uttar Pradesh. It adds to earlier work in three ways. First, seven implements, from a self-propelled reaper binder to hand-pushed tools, were evaluated with women as operators on farmers' own fields. Second, anthropometric, physiological and postural measures were combined for every implement, so that the source of risk, and not only its size, could be identified. Third, the results were turned into preliminary design targets and work–rest guidance for manufacturers, standard-setting bodies and extension agencies. Field capacity, labour requirement and operating cost of these implements on the same farms are reported in a companion manuscript [29]. The present paper uses only the anthropometric and ergonomic data, which are not reported there or elsewhere.

The objectives were to:

1. measure the body dimensions and grip strength of women farm workers and compare them with those of men;
2. quantify the physiological and postural workload of seven implements operated by women;
3. identify which implement features explain the ergonomic risk; and
4. propose design criteria and work–rest limits for gender-responsive mechanisation on small farms.

2 Materials and methods

2.1 Study area and participants

The study was carried out during the rabi season of 2019–20 and the kharif season of 2020 in Pahadpur (Mawana block) and Pawersa (Sardhana block), two villages of Meerut district, Uttar Pradesh (Table 1). Both villages had been adopted for the demonstration of improved farm technologies. The average holding was 0.7–0.8 ha. Thirty farm families provided fields for the trials under their usual crop management. The overall approach is shown in Fig. 1.

Table 1 Agro-climatic and soil characteristics of the study villages, Meerut district, Uttar Pradesh

Parameter	Pahadpur	Pawersa

Location	29° 6′ 51″ N, 77° 50′ 33″ E	29° 5′ 48″ N, 77° 48′ 21″ E
Altitude (m above mean sea level)	237	231
Annual rainfall (mm)	about 800	about 790
Soil texture	Silt loam	Sandy loam
Bulk density (Mg m^{-3})	1.40	1.38
Organic carbon (%)	0.62	0.58
Soil pH	7.8	7.9
Average holding (ha)	0.8	0.7
Main crops	Wheat, sugarcane, vegetables	Wheat, maize, vegetables

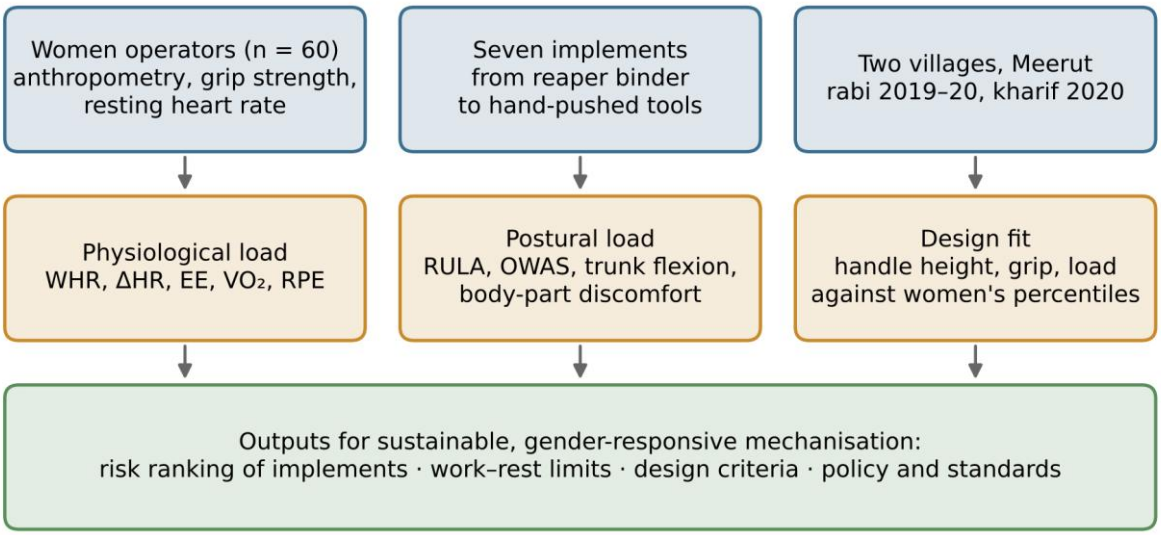

Fig. 1 Framework of the study

Sixty women farm workers (30 from each village), aged 18–55 years and with at least three years of farming experience, took part. Thirty men from the same villages were measured for comparison. All participants were healthy and free of reported musculoskeletal complaints.

2.2 Implements

Seven implements were chosen because they are relevant to local cropping, are available through government mechanisation schemes and cover a wide range of mechanisation, from a self-propelled machine to hand-pushed tools (Table 2, Fig. 2). Manual transplanting and hand weeding with a khurpi were observed as reference practices.

Table 2 Main specifications of the implements evaluated

Implement	Make or source	Power source	Mass (kg)	Main features	Cost (Rs)
Self-propelled reaper binder	BCS India Pvt. Ltd., Ludhiana	10 hp diesel engine	450	Cutter bar 1.22 m; 775 strokes min^{-1}	2,70,000
Brush cutter	STIHL FS-120	1.3 kW petrol engine	6.5–9.2	Shoulder harness; 40-tooth cutting blade; 95 dB	35,000
Rotary blade attachment	Fitted to STIHL FS-120	1.3 kW petrol engine	6.5–9.2	16 tiller blades in two sets; 450 mm width	30,000
Mist blower	STIHL SR-420	2.6 kW petrol engine	11.1	13 L backpack tank; 101–114 dB(A)	40,000
Easy seedling transplanter	Local manufacture	Manual	3.0	Handle height 1000 mm; handle diameter 25 mm	3,000
Seed-cum-fertiliser drill (punch type)	Kheton	Manual	2.5–3.0	Seed and fertiliser hoppers; spring-actuated jaws	2,500
Three-tyne weeder (push type)	Falcon; ICAR–IARI design	Manual	4.0–5.0	Three sweep tynes at 15 cm spacing	3,000

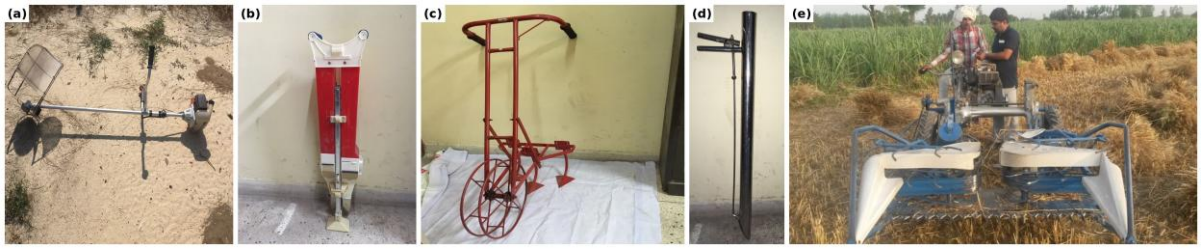

Fig. 2 Implements evaluated: (a) brush cutter; (b) seed-cum-fertiliser drill; (c) three-tyne weeder; (d) easy seedling transplanter; (e) self-propelled reaper binder

2.3 Anthropometry

Eighteen body dimensions were measured with an anthropometer (least count 1 mm) and a flexible tape, and grip strength with a Jamar digital hand dynamometer, following standard protocols [9, 10]. Measurements were taken in the morning, before field work. The 5th and 95th percentiles were estimated from the mean and standard deviation using Eq. (1):

$$P_5 = M - 1.645 \times SD; \quad P_{95} = M + 1.645 \times SD \tag{1}$$

where M is the mean and SD the standard deviation. Women and men were compared by Student's t-test.

2.4 Physiological workload

Each woman operated the implements on farmers' fields under normal working conditions (Fig. 3). Working heart rate (WHR, beats min^{-1}) was recorded with a Polar H10 chest-strap monitor at 1-s intervals and averaged over 5-min periods. Resting heart rate (RHR) was taken after 10 min of seated rest on each trial day. The cardiac cost of work was found from Eq. (2), and energy expenditure (EE, kJ min^{-1}) from Eq. (3), the relation developed for Indian women [18]:



Fig. 3 Field trials with women operators: (a) seed-cum-fertiliser drill; (b) and (c) easy seedling transplanter; (d) mist blower demonstration; (e) reaper binder in wheat

$$\Delta HR = WHR - RHR \tag{2}$$

$$EE = 0.159 \times WHR - 8.72 \tag{3}$$

Oxygen uptake (VO_2, mL kg^{-1} min^{-1}) was estimated from EE with an energy equivalent of 20.9 kJ per litre of oxygen [16], using the mean body mass of the women (BM = 50.2 kg):

$$VO_2 = \frac{EE \times 1000}{20.9 \times BM} \tag{4}$$

Workload was classed from EE as very light (up to 5.0 kJ min^{-1}), light (5.1–7.5), moderately heavy (7.6–10.0), heavy (10.1–12.5), very heavy (12.6–15.0) or extremely heavy (above 15.0) [18]. A ΔHR of 30 beats min^{-1} was taken as the limit for work sustained over an 8-h day [17]. Perceived exertion was rated on the Borg 6–20 scale after each 30-min session [21]. Body-part discomfort (BPD) was rated for nine body regions immediately after each trial and summed [22].

2.5 Posture

Each operation was video-recorded for 60 min, and postures were sampled every 30 s. At least 15 postures per implement were scored by RULA, and the most frequent grand score was taken as representative [19]. The same postures were coded by OWAS, which assigns an action category from 1 (no action needed) to 4 (action needed immediately) [20]. Trunk flexion was measured from video stills in ImageJ, with at least 20 measurements per implement. Recommended work bouts and rest allowances were set for each implement from its cardiac cost relative to the 30 beats min^{-1} limit and from its RULA action level [19, 30].

2.6 Statistical analysis

Data were analysed in IBM SPSS Statistics 26. One-way analysis of variance tested the effect of implement on each ergonomic variable, with site–replicate combinations as experimental units ($n = 6$ per implement), and means were separated by the least significant difference (LSD) test at $p \leq 0.05$. Pearson correlations were computed between implement means of the ergonomic variables, trunk flexion and implement mass ($n = 7$ implements; $n = 6$ for mass, excluding the self-propelled reaper binder, which the operator does not carry). With $n = 7$, $|r|$ must exceed 0.75 for significance at $p = 0.05$.

3 Results and discussion

3.1 Anthropometry and design mismatch

Women differed from men in every dimension measured ($p < 0.001$; Table 3). They were 13.4 cm shorter on average, their standing elbow height was 9.6 cm lower, and their grip strength was 34.2% lower. Elbow height matters most for hand-pushed and hand-held implements, because it sets the comfortable handle height [10, 15]. The weeder, brush cutter and mist blower had handle heights of 98–110 cm, which lay 3–15 cm above the women's mean elbow height of 94.6 cm and, at the upper end, above their 95th percentile (101.3 cm). Operating such handles makes the worker lift her shoulders and upper arms out of the neutral range, which

raises the postural score [19]. The lower grip strength also means that a handle designed for a man's grip asks a woman to work closer to her maximum, and the risk of fatigue rises accordingly [31].

Table 3 Anthropometric characteristics of women (n = 60) and men (n = 30) farm workers, Meerut district

Parameter	Women, mean ± SD	Women, 5th–95th percentile	Men, mean ± SD	p	Design use
Stature (cm)	152.4 ± 5.2	143.8–161.0	165.8 ± 6.1	< 0.001	Handle and seat height
Body mass (kg)	50.2 ± 6.8	39.0–61.4	62.4 ± 8.1	< 0.001	Carried load
Standing elbow height (cm)	94.6 ± 4.1	87.9–101.3	104.2 ± 4.8	< 0.001	Handle height
Shoulder height (cm)	122.8 ± 4.6	115.2–130.4	134.5 ± 5.3	< 0.001	Backpack strap position
Grip strength (N)	196.3 ± 22.1	160.0–232.7	298.4 ± 31.4	< 0.001	Handle diameter and force
Forward reach (cm)	64.2 ± 3.8	57.9–70.5	74.6 ± 4.4	< 0.001	Control placement
Hand breadth (cm)	7.8 ± 0.6	6.8–8.8	8.9 ± 0.7	< 0.001	Grip width
Resting heart rate (beats min^{-1})	76.8 ± 5.1	–	70.4 ± 4.7	< 0.01	Workload baseline

Note: Percentiles from Eq. (1). The acceptable working heart rate (RHR + 30 beats min^{-1}) was 107 beats min^{-1} for women and 100 beats min^{-1} for men.

3.2 Physiological workload

Implements differed significantly in working heart rate, cardiac cost, exertion and discomfort ($p \leq 0.01$; Table 4, Fig. 4). Three groups emerged. The seed-cum-fertiliser drill, the three-tyne weeder and the rotary blade attachment were light work, with cardiac costs of 12–25 beats min^{-1}, well within the 30 beats min^{-1} limit. The reaper binder, mist blower and brush cutter were moderately heavy, with cardiac costs of 31–39 beats min^{-1}, at or above the limit. The easy transplanter was heavy work, with a cardiac cost of 44 beats min^{-1}, close to that of manual transplanting (47 beats min^{-1}). Exertion ratings followed the same order, from 9 (very light) for the drill to 15 (hard) for the transplanter.

Table 4 Physiological workload and discomfort of women operators with different implements (mean ± SD)

Implement	WHR (beats min^{-1})	ΔHR (beats min^{-1})	EE (kJ min^{-1})	VO_2 (mL kg^{-1} min^{-1})	RPE (6–20)	BPD score	Workload class

Seed-cum-fertiliser drill	88.0 ± 3.7	12 ± 1.6	5.27 ± 0.59	5.02 ± 0.56	9 ± 0.7	5 ± 0.3	Light
Three-tyne weeder	95.0 ± 4.2	19 ± 2.2	6.38 ± 0.67	6.09 ± 0.64	10 ± 0.8	7 ± 0.4	Light
Rotary blade attachment	102.0 ± 5.1	25 ± 2.8	7.50 ± 0.81	7.15 ± 0.77	11 ± 0.8	8 ± 0.5	Light
Reaper binder	108.0 ± 4.6	31 ± 3.2	8.45 ± 0.73	8.06 ± 0.70	12 ± 1.1	9 ± 0.4	Moderately heavy
Mist blower	110.0 ± 4.9	33 ± 3.4	8.77 ± 0.78	8.36 ± 0.74	13 ± 1.0	11 ± 0.7	Moderately heavy
Brush cutter	115.7 ± 3.2	39 ± 2.1	9.68 ± 0.51	9.22 ± 0.49	13 ± 0.9	14 ± 0.6	Moderately heavy
Easy transplanter	120.0 ± 6.8	44 ± 4.2	10.36 ± 1.08	9.87 ± 1.03	15 ± 1.3	16 ± 0.8	Heavy
Manual transplanting (reference)	124.0 ± 7.2	47	10.99 ± 1.14	10.47 ± 1.09	–	19 ± 1.1	Heavy
LSD (p = 0.05)	4.2	3.8	–	–	1.2	0.9	–

Note: WHR, working heart rate; ΔHR, cardiac cost of work (Eq. 2); EE, energy expenditure (Eq. 3); VO_2, oxygen uptake (Eq. 4); RPE, Borg rating of perceived exertion; BPD, body-part discomfort. Workload class after Varghese et al. [18]. ΔHR for manual transplanting is WHR minus the mean RHR.

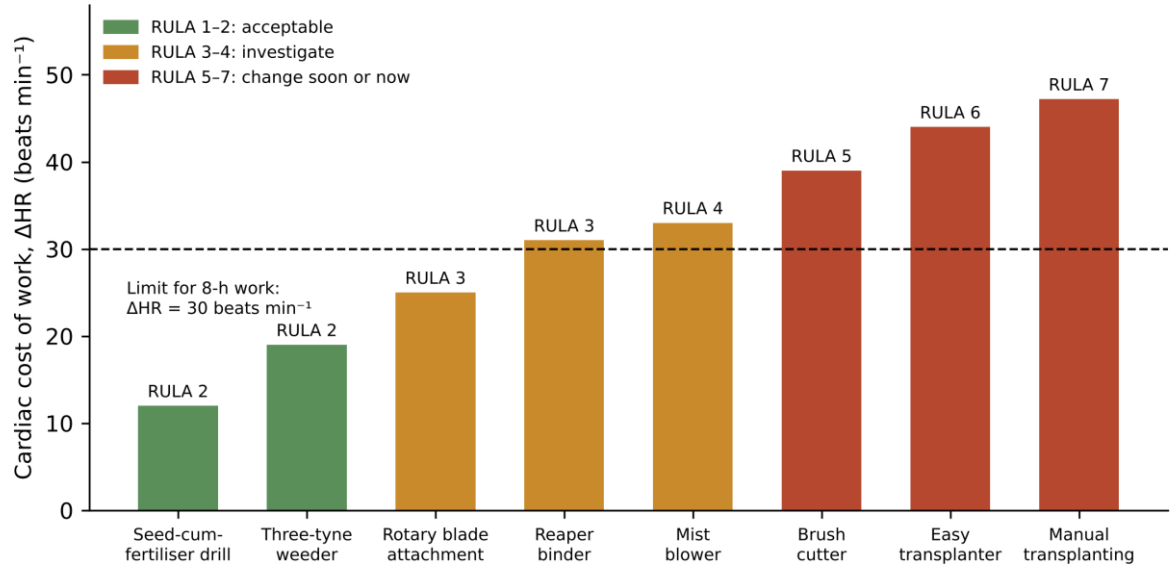

Fig. 4 Cardiac cost of work (ΔHR) for women operators using each implement. The dashed line indicates the 30 beats min⁻¹ threshold used in this study for sustained work.

3.3 Postural risk

Postural scores ranged from acceptable to high risk (Table 5). The drill and the weeder were operated upright, with trunk flexion of 5–10°, and scored RULA 2 and OWAS action category

1. The reaper binder and rotary blade attachment scored RULA 3. The mist blower (RULA 4) and brush cutter (RULA 5) required action in the near future. The easy transplanter scored RULA 6 and OWAS action category 3, meaning that the posture should be corrected soon, because the operator bent the trunk 50–70° at each seedling placement. Hand weeding with a khurpi, observed for comparison, required 70–90° of trunk flexion and placed the work in OWAS categories 3–4, with discomfort scores of 18–22.

Table 5 Postural assessment by RULA and OWAS for each implement

Implement	RULA score	RULA action level	OWAS code	OWAS action category	Trunk flexion (°)	Redesign priority
Seed-cum-fertiliser drill	2	Acceptable	1111	1, no action	5–10	None
Three-tyne weeder	2	Acceptable	1111	1, no action	5–10	None
Rotary blade attachment	3	Investigate	1121	1, no action	15–20	Low
Reaper binder	3	Investigate	1121	1, no action	10–15	Low
Mist blower	4	Investigate	2121	2, near future	20–30	Moderate
Brush cutter	5	Investigate and change soon	2131	2, near future	30–45	Moderate
Easy transplanter	6	Investigate and change soon	2231	3, as soon as possible	50–70	High
Manual transplanting (reference)	7	Change immediately	–	–	–	–

Note: RULA: 1–2 acceptable; 3–4 investigate; 5–6 investigate and change soon; 7 change immediately [19]. OWAS action categories 1–4 [20].

3.4 What drives the risk: posture rather than weight

Across the seven implements, trunk flexion was strongly correlated with RULA score ($r = 0.97$, $p < 0.001$), body-part discomfort ($r = 0.95$, $p = 0.001$) and cardiac cost ($r = 0.88$, $p = 0.009$) (Table 6, Fig. 5). RULA and discomfort scores were almost perfectly correlated ($r = 0.99$), which shows that the observer's postural score and the worker's own rating of discomfort agreed closely. Implement mass, by contrast, was not correlated with any workload variable ($|r| \leq 0.32$, $p \geq 0.54$). The heaviest hand-handled implement, the 11.1 kg mist blower, produced less discomfort than the 3 kg transplanter. What mattered was how far the implement made the woman bend. This finding has a direct design message: lowering the weight of an implement will do little for women operators unless it also lets them work upright [13, 32].

Table 6 Pearson correlation coefficients among ergonomic variables, trunk flexion and implement mass (implement means)

Variable	WHR	ΔHR	RULA	BPD	Trunk flexion
ΔHR	1.00**				
RULA score	0.94**	0.95**			
BPD score	0.96**	0.97**	0.99**		
Trunk flexion	0.86*	0.88**	0.97**	0.95**	
Implement mass[a]	0.32	0.28	0.14	0.16	−0.04

Note: n = 7 implement means; n = 6 for implement mass, excluding the self-propelled reaper binder. * $p < 0.05$; ** $p < 0.01$. ΔHR was obtained by subtracting the women's mean resting heart rate (76.8 beats min^{-1}) from each implement's mean WHR, so the two variables are perfectly correlated at the level of implement means.

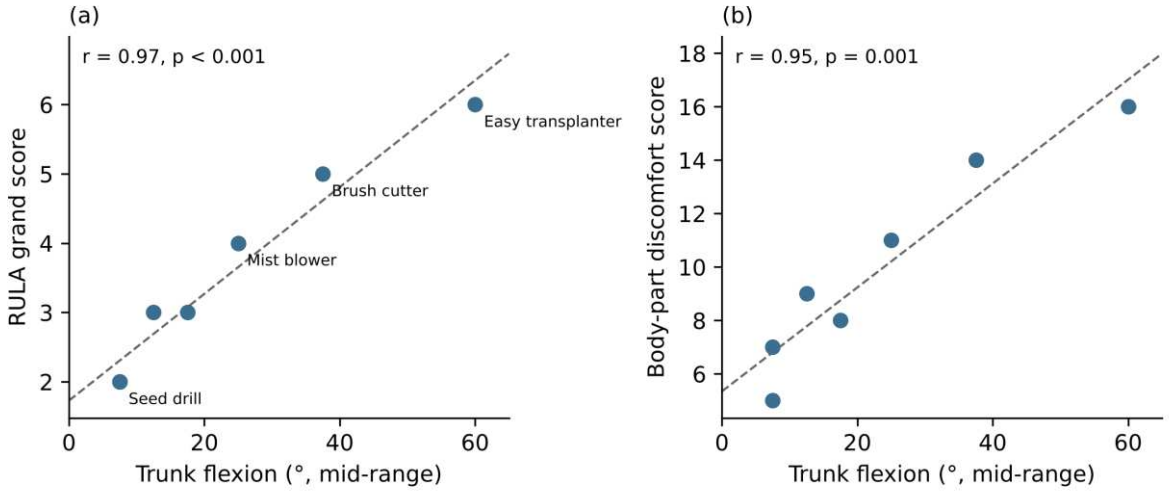

Fig. 5 Relationship of trunk flexion with (a) RULA score and (b) body-part discomfort score across the seven implements

3.5 Findings for individual implements

Easy seedling transplanter. The transplanter halved the time needed to transplant a hectare on these farms [29], but it was the hardest implement for women to use. Bending to place each seedling drove the trunk to 50–70°, and the operators reported the most discomfort in the lower back, wrists and shoulders. Sustained trunk flexion of this kind raises the compressive load on the lumbar spine [13, 32]. Three changes should help: a wheeled, height-adjustable carrier for the seedling tray, a tapered jaw tip that enters the soil with less force, and a handle that adjusts to the operator's elbow height. Until then, continuous transplanting should be limited to 25–30 min, followed by rest.

Brush cutter. The cardiac cost (39 beats min^{-1}) was the second highest, and the posture (RULA 5) was poor because the operator leaned forward 30–45° and held the shoulders raised to keep the cutter at height. Discomfort was centred on the wrists, forearms and shoulders. Hand-held brush cutters also transmit vibration to the hands, and daily exposure above the European action value of 2.5 m s^{-2} is linked to vascular and nerve damage [33–35]. Because women have less grip strength, they need more relative effort to control the cutting torque. Anti-vibration handles and gloves, and work bouts of no more than 30–40 min, are advised. The brush cutter and the mist blower did not differ in heart rate ($p = 0.22$) or discomfort ($p = 0.18$).

Mist blower. The full 11.1 kg backpack was 22% of the women's mean body mass. Walking on uneven ground with this load while aiming the lance pushed the cardiac cost (33 beats min^{-1}) just above the limit, and the trunk was flexed 20–30°. Discomfort was greatest in the lower back and shoulders. A padded hip belt that shifts part of the load from the shoulders to the pelvis, and partial filling of the tank, should reduce the strain [36]. A work bout of 40–45 min is suggested.

Reaper binder. The cardiac cost (31 beats min^{-1}) was at the limit, but the posture was good (RULA 3, trunk flexion 10–15°), compared with the 70–90° bend of sickle harvesting. Discomfort was mostly in the lower back, probably from vibration transmitted through the seat. A cushioned, vibration-damping seat should help [35]. Because of its cost, the machine suits shared access through custom hiring centres.

Seed-cum-fertiliser drill and three-tyne weeder. These were the best-suited implements for women. Both were used upright, kept the cardiac cost within the limit (12 and 19 beats min^{-1}) and scored RULA 2. The two did not differ in heart rate ($p = 0.14$) or discomfort ($p = 0.22$), and both were significantly less demanding than all other implements ($p \leq 0.05$). Weeding is the most frequent field task on small farms, and late weeding can cut yields by 30–60% [37]. A low-cost weeder (Rs 3,000) that needs no fuel and removes the deep bend of khurpi weeding is therefore an immediate, practical gain for women farmers.

Rotary blade attachment. This attachment fell in the middle (cardiac cost 25 beats min^{-1}, RULA 3). Its load is shared almost equally between the engine and the tiller head, so both hands carry it evenly, and the trunk stays within 15–20°. For a farmer who already owns a brush cutter, it adds weeding capacity at a small extra cost.

3.6 Work–rest limits

The work-bout durations and rest allowances proposed here follow the relative cardiac costs and RULA scores (Table 7). They are preliminary recommendations derived from the observed trials, not experimentally validated safe exposure limits.

Table 7 Recommended maximum work bouts and rest allowances for women operators

Implement	Maximum continuous work bout (min)	Rest allowance (% of work time)	Suitability for women
Seed-cum-fertiliser drill	60–70	10–15	Recommended
Three-tyne weeder	55–65	12–18	Recommended
Reaper binder	50–60	15–20	Suitable, with a cushioned seat
Rotary blade attachment	45–55	20–25	Suitable
Mist blower	40–45	22–28	Suitable after harness redesign
Brush cutter	30–40	25–30	With precautions against vibration
Easy transplanter	25–30	30–35	Redesign needed

3.7 Design criteria for women-friendly implements

The results inform the preliminary design targets in Table 8. These targets draw on the women's 5th–95th percentile dimensions (Table 3) and the risk patterns observed in this study (Section 3.4); they require validation before being adopted as standards.

Table 8 Proposed ergonomic design criteria for implements used by women on small farms

Feature	Criterion	Basis
Handle height	Adjustable over 88–101 cm	5th–95th percentile standing elbow height of women (Table 3) [15]
Trunk posture	Design for trunk flexion ≤ 20°	Trunk flexion was the strongest predictor of RULA and discomfort (Table 6)
Grip diameter	3–4 cm	Women's hand breadth (6.8–8.8 cm) and grip strength [10, 31]
Carried load	Backpack implements ≤ 12 kg, with a hip belt; push–pull tools ≤ 5 kg	Mist blower load (22% of body mass) raised ΔHR above the limit [36]
Hand–arm vibration	Daily exposure below 2.5 m s^{-2} A(8); anti-vibration mounts	EU action value [33, 34]

Feature	Criterion	Basis
Work–rest schedule	Linked to RULA level: ≤ 2, 60–70 min; 3–4, 40–55 min; 5, 30–40 min; ≥ 6, ≤ 25–30 min	Tables 5 and 7

3.8 Implications for sustainable and gender-responsive mechanisation

Mechanisation that saves labour but injures the worker is not sustainable. The results show that implements suited to women already exist, such as the drill and the weeder, and that others need only modest changes to their handles, harnesses or seed feeding to become suitable. Farmer interviews also pointed to barriers beyond design. Holdings of 0.7–0.8 ha are split into several plots, which keeps the annual use of powered machines low and makes ownership costly [6]. Powered implements costing Rs 18,000–2,70,000 usually need credit that small farmers find hard to get, and repair services are concentrated in district towns. Women had less exposure than men to machine operation and safety training.

Four actions follow. First, Indian standards for hand tools and small implements should include ergonomic tests based on the body dimensions of women, using criteria such as those in Table 8 [9]. Second, high-cost machines should reach small farms through custom hiring centres run by farmer producer organisations. Third, women-led groups for shared ownership, with training in safe operation and basic repair, would widen access and build local skills [3, 4]. Fourth, operating manuals and training by Krishi Vigyan Kendras should include the work–rest limits in Table 7. Together, these measures would support SDG targets on gender equality, decent work and the productivity of women food producers [5].

The study has limits. It covered two villages and two seasons in the irrigated western plain zone. Correlations were based on seven implement means and should be confirmed with more implements. Energy expenditure was estimated from heart rate rather than measured directly, and vibration was not measured. Long-term studies are needed to test whether the proposed design changes reduce musculoskeletal disorders among women farm workers.

4 Conclusions

This study assessed seven implements with women as operators on small farms in western Uttar Pradesh. The main conclusions are:

1. Women were 13.4 cm shorter than men, with a 9.6 cm lower elbow height and 34% less grip strength. Handles on the weeder, brush cutter and mist blower were 3–15 cm above the women's mean elbow height.
2. The seed-cum-fertiliser drill and three-tyne weeder were the best-suited implements, with cardiac costs within the 30 beats min^{-1} limit and RULA scores of 2.
3. The easy transplanter was the most demanding (cardiac cost 44 beats min^{-1}, RULA 6) and needs redesign; the brush cutter and mist blower need vibration and harness improvements.
4. Trunk flexion, not implement weight, explained the postural risk and discomfort (r = 0.95–0.97). Designs that let women work upright matter more than lighter designs alone.
5. Adjustable handles of 88–101 cm, grips of 3–4 cm, trunk flexion of no more than 20° and RULA-based work–rest limits are proposed as design criteria for women-friendly implements.

Building these criteria into standards, custom hiring and training would make farm mechanisation safer and fairer for the women who do much of the work on India's small farms.

Declarations

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Author contributions V. P. Chaudhary: conceptualisation, methodology, investigation, data curation, formal analysis, supervision, writing of the original draft, and review and editing. Nisha Verma: conceptualisation, methodology, investigation, supervision, and review and editing. All authors read and approved the final manuscript.

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Data availability The datasets generated and analysed during this study are available from the corresponding author on reasonable request.

Ethics approval The study was approved by the Institute Ethics Committee constituted by the Director, ICAR–Indian Institute of Farming Systems Research, Modipuram, Meerut. It was a

non-invasive observational study of adult workers during their routine farm tasks and followed the principles of the Declaration of Helsinki.

Consent to participate Written informed consent was obtained from all participants. They were told the aims of the study and their right to withdraw at any time.

Consent for publication Written consent for publication of identifiable photographs was obtained from the participants shown in Fig. 3.

Competing interests The authors declare no competing interests.

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