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Ergonomic assessment of a battery-operated spinach harvester with on field packaging machine

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Abstract

The present study evaluated the ergonomic performance of a battery-operated spinach harvester equipped with an on-field packaging unit under field conditions in middle Gujarat, India. Ergonomic parameters including heart rate, oxygen consumption, energy expenditure, and subjective comfort rating (CR or ODR scale) were measured at three forward speeds (1.0, 1.5, and 2.0 km/h). Results indicated that operator workload increased with forward speed. At 1.0 km/h, mean heart rate was 103.9 bpm, oxygen consumption 0.505 l/min, and energy expenditure 10.6 kJ/min, corresponding to light discomfort (CR scale = 3). At 1.5 km/h, values increased to 107.8 bpm, 0.55 l/min, and 11.5 kJ/min, with moderate discomfort (CR scale = 4). At 2.0 km/h, workload rose further to 113.8 bpm, 0.62 l/min, and 12.9 kJ/min, with high discomfort perception (CR scale = 5). Based on physiological and subjective responses, the optimal operating speed was identified as 1.5 km/h, ensuring acceptable operator workload while maintaining higher field efficiency compared to 1.0 km/h. The study demonstrates that the developed harvester reduces drudgery, minimizes post-harvest losses through integrated packaging, and offers an ergonomically sustainable mechanization solution for smallholder spinach cultivation.

Keywords: Battery-operated spinach harvester, ergonomic assessment, heart rate, oxygen consumption, energy expenditure, CR-10 ODR scale, forward speed

1. Introduction

Agriculture continues to be a highly labour-intensive sector, with women comprising nearly half of the workforce, especially in developing countries such as India. Spinach, in particular, is widely cultivated and consumed due to its high nutrient density. However, leafy vegetables are highly perishable because of their delicate tissues and large surface-to-volume ratio, which makes them vulnerable to rapid wilting and quality deterioration during and after harvesting (Mini and Krishnakumary, 2007) [8].

In India, harvesting of spinach and other leafy crops is still carried out primarily by manual methods. Farmers usually cut plants with sickles, knives, or scissors, or uproot them by hand in early morning hours to maintain freshness. Such operations are labor-intensive, time-consuming, and are typically performed in bending or squatting postures that impose high physical strain on the operator (Gaadhe and Tiwari, 2022) [3]. The repetitive nature of these tasks, along with the need to transport harvested biomass manually, further adds to drudgery and lowers overall efficiency.

The scarcity of agricultural labour and the growing emphasis on sustainable production systems highlight the need for mechanized solutions. Battery-operated harvesting machines are emerging as an eco-friendly alternative, reducing reliance on fossil fuels while enabling small holder farmers to adopt mechanization. When combined with an on-field packaging system, such machines can significantly reduce post-harvest losses and streamline handling operations.

Ergonomic assessment is a critical step in the development and adoption of farm machinery, as it ensures that operator comfort, posture, and workload are optimized. Studies on ergonomics in agricultural machinery have shown that factors such as operator heart rate, working posture, and energy expenditure are key indicators of drudgery and overall efficiency (Nag *et al.*, 1980; Dewangan *et al.*, 2009) [6, 2]. Therefore, the present investigation was undertaken to evaluate the ergonomic performance of a battery-operated spinach harvester equipped with an on-field packaging unit. The study aims to quantify operator workload, reduce drudgery, and establish the machine's effectiveness in improving harvesting efficiency under field conditions.

2. Materials and Methods

2.1 Study Area

2.1.1 Location

Field experiments were conducted at farmers field in Manjipura village near Nadiad, Dist: Kheda, Gujarat to assess the performance of developed machine. The experimental site is located in middle Gujarat Agro-climatic Zone of Gujarat State on N 22°63' latitude and E 72°81' longitude. The variety of spinach was Desi palak of 45 days at the time of harvesting. The experimental field was having sandy loam soil.

Table 1: Details of Ergonomical parameters undertaken during field study

Sr. No.	Independent parameters	No. of levels	Values	Dependent parameters
1.	Forward speed	3	A_1 = 1.0 km/h A_2 = 1.5 km/h A_3 = 2.0 km/h	Heart rate, beat/min. (bpm) energy expenditure comfort rating (ODR rating)

2.1.2 Climate
The climate of area is hot and semi-arid type with an average rainfall of 700 to 1200 mm and average pan evaporation of area 3.74 to 8.60 mm/day. June-2025 is hot month with the mean temperature varying between 35°C to 45 °C.

2.2 Materials
Ergonomical parameters such as heart rate, oxygen consumption rate, energy expenditure comfort rating were measured as below:

2.2.1 Heart rate
The heart rate, expressed in beats per minute (bpm), was recorded using a device that detects heartbeats and displays the corresponding values. During the experiment, a digital heart rate monitor was employed to track the participant's pulse. The heart rate monitor included a sensor and transmitter integrated into a chest belt. The data was wirelessly transmitted to a mobile phone via Bluetooth and accessed using the Android-based POLAR BEAT application. The transmitter's electrodes detected the subject's heartbeat and transmitted the signals to the mobile phone without the need for physical connection. The mobile device received these signals and displayed the heart rate digitally in beats per minute (bpm). The application also provided the option to record and save data from multiple trials during field evaluations. The chest belt used for heart rate monitoring during the experiment is shown in Fig 2. The specifications of heart rate monitor are given in below.

Table 2: Technical specifications of heart rate monitor

1.	Make & Model	POLAR ELECTRO OY. & Polar heart rate sensor H10
2.	Compatibility	iOS mobile devices: iPhone 5 and later, with iOS 11 or later; Android mobile devices with Bluetooth 4.0 capability and Android 5.0 or later.
3.	Battery type	CR 2025
4.	Battery life	400 hours with Bluetooth Low Energy and 5 kHz transmission active
5.	Operating temperature	-10 °C to +50 °C / 14 °F to 122 °F
6.	Display	14 seven segment digit, 2 dot matrix areas, 46 symbols, total 184 segments
7.	Operating temperature	-10 to +50o C
8.	Battery type /life	CR2032 / Avg. 1 year
9.	Memory	One training session
10.	Connector size	34x65x10 mm
11.	Weight	Connector 21 g, strap 39 g
12.	Water resistance	30 m
13.	Connectivity	ANT+, Bluetooth Low Energy, 5 kHz

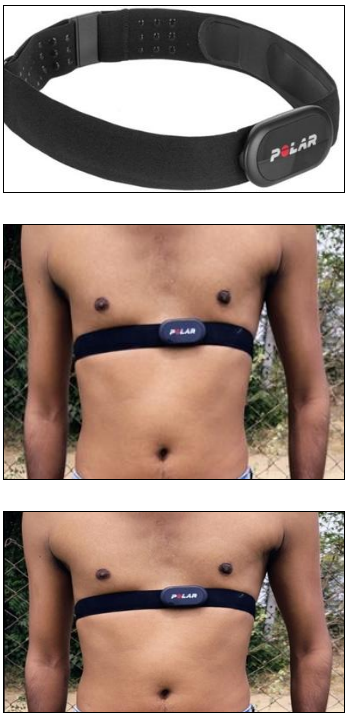

Fig 1: Heart rate measurement

2.2.2 Oxygen consumption rate
The oxygen consumption rate is defined as the amount of oxygen consumed by the tissues of the body. It is measured in l/min or ml/min or ml/kg/min. It was calculated by the following equation (Singh, 2012) [9].

$$Y = 0.0114\,X - 0.68$$

Where,
Y = Oxygen consumption, l/min
X = Heart rate, beat/min

2.2.3 Energy expenditure rate
Energy expenditure rate (kJ/min) was computed by multiplying calorific value of 20.93 kJ/l of oxygen (Nag and Dutta, 1980) [7] by oxygen consumption rate during the experiment.

2.2.4 Comfort Rating
To assess the Body Discomfort Parts Score (BDPS), the human body was segmented into 27 specific regions, following the method proposed by Corlett and Bishop (1976) [1], as illustrated in Fig. 2. Participants were instructed to identify and list all regions where they experienced discomfort, beginning with the area of greatest

discomfort, followed by the next, and continuing in decreasing order of severity (Lusted *et al.*, 1994) [5]. They were guided to rank the body areas, as depicted in Fig. 2, by assigning the first position to the most painful area, the second to the next most painful, and so forth (Legg & Mohanty, 1985) [4]. The listed body regions reflected varying discomfort intensities, from severe to none. These discomfort levels were then grouped into categories, each assigned a specific rating based on its severity.

Body discomfort was assessed using the Overall Discomfort Rating (ODR). A 7-point scale, as suggested by Corlett and Bishop (1976) [1], was used for this evaluation as a; 0 = No discomfort, 1 = Very very light discomfort, 2 = Very light discomfort, 3 = Light discomfort, 4 = Moderate discomfort, 5 = Heavy discomfort, 6 = Very heavy discomfort, 7 = Extreme discomfort.

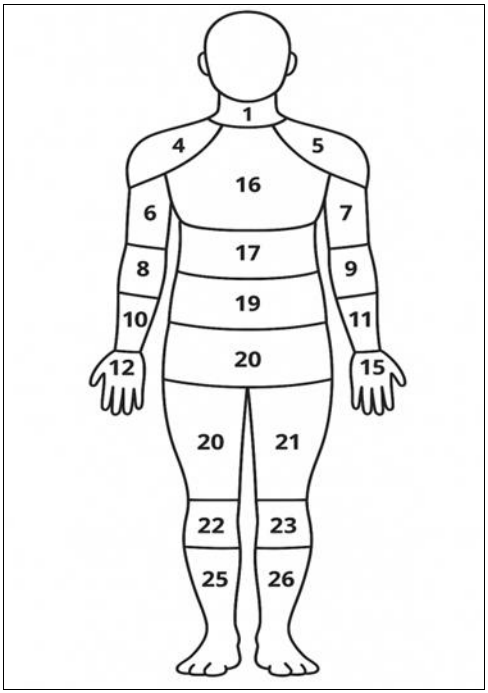

Fig 2: Regions for evaluating body parts discomfort score

1.	Neck	15.	Right Palm
2.	Clavicle Left	16.	Upper Back
3.	Clavicle Right	17.	Mid Back
4.	Left Shoulder	18.	Lower Back
5.	Right Shoulder	19.	Buttocks
6.	Left Arm	20.	Left Thigh
7.	Right Arm	21.	Right Thigh
8.	Left Elbow	22.	Left Knee
9.	Right Elbow	23.	Right Knee
10.	Left Fore arm	24.	Left Leg
11.	Right Forearm	25.	Right Leg
12.	Left Wrist	26.	Left Foot
13.	Right Wrist	27.	Right Foot
14.	Left Palm		

3. Results and Discussion

3.1 Heart Rate

The mean heart rate of the operator increased with an increase in forward speed (Table 1). At 1.0 km/h, the heart rate varied between 103-105 bpm with an overall mean of 103.9 bpm. At 1.5 km/h, it ranged between 106-109.3 bpm (mean 107.8 bpm), while at 2.0 km/h, the range was 113-115 bpm (mean 113.8 bpm).

The incremental rise in heart rate with speed can be attributed to greater muscular effort required for maneuvering and handling vibrations transmitted from the cutter bar and conveyor at higher speeds. According to ISO ergonomic guidelines, heart rates below 110 bpm correspond to “acceptable workload for sustained agricultural tasks”, while values >115 bpm suggest moderate to heavy workload requiring rest periods. Hence, operation at 1.0-1.5 km/h is ergonomically favorable, whereas 2.0 km/h imposes higher strain. Optimal Heart Rate: 107.8 bpm at 1.5 km/h (balanced between performance and operator safety).

3.2 Oxygen Consumption and Energy Expenditure

Oxygen consumption followed a linear increasing trend with forward speed. At 1.0 km/h, mean oxygen consumption was 0.505 l/min, increasing to 0.55 l/min at 1.5 km/h and further to 0.62 l/min at 2.0 km/h. This increase directly translated to energy expenditure rates of 10.6 kJ/min, 11.5 kJ/min, and 12.9 kJ/min, respectively.

In terms of workload classification, energy expenditure below 12 kJ/min is considered light work, while values between 12-16 kJ/min fall in the moderate category. Thus, harvesting at 1.0 and 1.5 km/h can be classified as light workload, while 2.0 km/h approaches the moderate workload zone.

Optimal Energy Expenditure: 11.5 kJ/min at 1.5 km/h (comfortably within light workload).

3.3 Subjective Perception of Workload (CR-10 ODR Scale)

The subjective ratings using Borg’s CR-10 scale were consistent with physiological responses. At 1.0 km/h, the operator rated the workload as 3 (light); at 1.5 km/h, the scale increased to 4 (somewhat hard); and at 2.0 km/h, operators perceived the task as 5 (hard).

The parallel increase in both physiological indicators (heart rate, oxygen uptake) and subjective perception validates the ergonomic assessment.

Optimal CR Rating: 4 (at 1.5 km/h), indicating sustainable workload.

3.4 Overall Ergonomic Assessment

The ergonomic parameters clearly demonstrate that operator strain increases with forward speed. While the machine can be operated safely at all tested speeds, 1.5 km/h represents the optimal forward speed, balancing field efficiency and ergonomic safety:

Heart rate: 107.8 bpm (below critical limit of 110 bpm).

Oxygen consumption: 0.55 l/min.

Energy expenditure rate: 11.5 kJ/min.

CR Rating: 4 (“somewhat hard,” but sustainable).

Operation at 1.0 km/h, though ergonomically the least demanding, compromises field efficiency, while 2.0 km/h, despite higher field capacity, imposes a near-moderate workload, which may not be sustainable for prolonged field operations.

Thus, the ergonomic optimum forward speed of the battery-operated spinach harvester with on-field packaging was identified as 1.5 km/h, ensuring acceptable physiological strain with efficient harvesting performance.

Table 3: Optimal value of ergonomical parameters

Forward Speed (km/h)	Heart Rate (bpm)	Oxygen Consumption (l/min)	Energy Expenditure (kJ/min)	CR Scale
1.5	107.59	0.547	11.44	4

4. Conclusion

The ergonomic assessment of the developed battery-operated spinach harvester with on-field packaging revealed a clear relationship between forward speed and operator workload. Operator heart rate, oxygen consumption, energy expenditure, and discomfort ratings increased progressively with speed. Among the tested conditions, 1.5 km/h emerged as the optimal operating speed, with mean values of 107.6 bpm heart rate, 0.55 l/min oxygen consumption, 11.44 kJ/min energy expenditure, and a CR rating of 4. These values fall within the light workload category, indicating sustainable operation without excessive physiological strain. Although 1.0 km/h imposed the least physical demand, it compromised field efficiency, while 2.0 km/h approached the moderate workload threshold, making it less suitable for prolonged operation.

Thus, the developed machine offers a practical balance between ergonomic safety and operational performance, reducing drudgery associated with manual spinach harvesting and contributing to sustainable mechanization for smallholder farmers.

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