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ERGONOMIC RISK ASSESSMENT AND REBA-BASED ANALYSIS OF WORKING POSTURES DURING HARVESTING IN VERTICAL AQUAPONICS SYSTEMS

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ABSTRACT

Urbanization, shrinking arable land, and climate uncertainties have driven the search for sustainable food production systems. Vertical aquaponics offers a promising solution by integrating soilless cultivation, artificial lighting, and controlled environments. Yet, despite technical advances, ergonomic risks during manual harvesting remain largely overlooked. This study evaluates the postural load of lettuce harvesting in a vertical aquaponics setup using the Rapid Entire Body Assessment (REBA) method. A female worker representing 95% of Turkish women in stature was selected, and body postures were further analyzed through inverse kinematics and anthropometric modeling. The task yielded a REBA score of 5, classified as "medium risk," lower than scores typically reported in field harvesting. However, environmental conditions such as high humidity and temperature in closed-loop aquaponics may amplify worker fatigue. By integrating ergonomic assessment with anthropometric modeling, this research provides one of the first systematic evaluations of harvesting ergonomics in vertical aquaponics systems. The findings highlight the need for worker-centered design to ensure both the health of operators and the long-term sustainability of urban food production.

Key words: *Vertical aquaponics, Harvesting, REBA, Ergonomics, Posture.*

INTRODUCTION

The increasing population in urban areas, the reduction of arable land, and climate-induced uncertainties have raised serious concerns regarding the long-term sustainability of traditional agricultural systems. In response, vertical farming and aquaponic systems have emerged as promising alternatives, providing sustainable and integrated production opportunities within spatially constrained environments (Despommier, 2010; 2013; Touliatos et al., 2016; Pinstrup-Andersen, 2018).

Vertical aquaponic systems, by integrating artificial lighting, controlled climate, and soilless cultivation, enhance water and space efficiency while simultaneously improving overall productivity (Khandaker and Kotzen, 2018; Brooke, 2019; Pinho et al., 2017; Taha et al., 2022). In tower-type systems, the absence of natural light necessitates the use of energy-efficient LED technology, which is essential for ensuring economic sustainability (Kotzen et al., 2019; Kusuma et al., 2020; Wheeler, 2023). In parallel, advances in genetic improvement allow for the development of crop varieties specifically adapted to these controlled environments (Kaiser et al., 2024; Folta, 2019).

While the technical efficiency of vertical aquaponic systems has been widely examined, the ergonomic dimension—particularly with regard to harvesting operations—remains underexplored. Yet, safeguarding workers' musculoskeletal health is a critical determinant of both the sustainability and economic viability of such systems. Manual harvesting tasks, often involving repetitive arm movements and awkward postures, are known to cause musculoskeletal disorders (MSDs), with the lower back, neck, and shoulders being the most affected regions (Benos et al., 2020).

Addressing this gap, the present study systematically evaluates harvesting tasks in vertical aquaponic systems using the Rapid Entire Body Assessment (REBA) method. In doing so, it contributes to bridging technical innovation with human-centered design, thereby integrating ergonomics into the broader framework of sustainable food production systems.

MATERIALS AND METHODS

To evaluate workers ergonomically in a vertical aquaponic system, commonly recommended design parameters were used. The system specifications comprise a fish tank with a height of 30 cm and a width of 35 cm, a column height of 150 cm, an overall system height of approximately 180 cm, a plant spacing of 30 cm, and the integration of a pump with sufficient capacity to maintain continuous water circulation (Singh and Dunn, 2021). To ensure accessibility for a wider population, anthropometric measurements corresponding to the 5th percentile of Turkish females were used as a reference.

Within the scope of this study, workers' postures during lettuce harvesting in a vertical aquaponic setup were analyzed. The body posture of workers was assessed using the Rapid Entire Body Assessment (REBA) method (Hignett and McAtamney, 2000).

Based on the 2021 anthropometric survey, average body measurements for Turkish females were identified. These measurements were derived from reference points inspired by Leonardo da Vinci's "Vitruvian Man" model (Gaiani et al., 2015). Parameters not directly measured in the survey, including shoulder height, eye height and hand length calculated proportionally to overall body height. The ratios were determined based on established anthropometric sources including the NASA 3000 Standard (1987), Panero and Zelnik (1979), DIN 33402, and the Bodyspace study by Pheasant and Haslegrave (2005).

REBA score is often used to assess body posture, task characteristics, and musculoskeletal stress. The score ranging from 1 to 12, is categorized into various risk levels. A score of 3 or below is considered acceptable. Higher scores indicate the need for immediate intervention in the work system. If conditions are not improved, worker health, labor efficiency, and overall productivity may decline over time. REBA scoring is performed using three interrelated tables: **Table A** evaluates load, neck, trunk, and leg positions; **Table B** assesses coupling, upper arm, lower arm, and wrist postures; **Table C** provides the final score based on the previous scores calculated by Tables A and B.

The **activity score,** which considers factors such as movement frequency and intensity (e.g., static postures, repetitive motion over 4 times per minute, major posture changes in short timeframes, or unstable base of support), is added to the overall score to determine the final REBA score. Based on these parameters, workers' postures during the harvesting process were evaluated using the REBA method, and optimal lettuce harvesting zones were calculated accordingly. Harvesting outside of these zones increases the risk of developing musculoskeletal disorders. According to the Table A, neck, trunk, and leg scores were calculated based on body segment lengths and the positions of the lettuces.

Neck score was determined based on the neck angle and shoulder height was used as the origin point of the coordinate system. An angle between 0–20° was scored as 1, while angles greater than 20° or extension of the neck were scored as 2. Since the worker was assumed to be looking towards the lettuce, the neck angle was calculated as the angle between the eye level and the lettuce position. The trunk score was determined based on the degree of trunk flexion: a score of 1 was assigned for upright posture, 2 for 0–20°, 3 for 20–60°, and 4 for angles exceeding 60°. If the lettuce was located within arm's reach (from shoulder to palm), the trunk angle was assumed to be 0°. Trunk flexion was only considered necessary when the target was beyond the reachable area, under the assumption that the elbow was fully extended (180°). The trunk angle was calculated using the same inverse kinematics principle as for the arm. For the leg score, it was assumed that both feet remained on the ground and the knees were not flexed during the harvesting activity. An extra point for the load score was not added, as the lettuce heads were assumed to weigh approximately 350 g, and the root resistance during pulling was considered below 2kg.

According to the B score table, the lower arm, upper arm, and wrist scores were calculated using the same approach as in the A score, considering body segment lengths and the position of the lettuce. Arm movements were simplified by assuming planar motion, reducing the arm's degrees of freedom (DOF) to two, and inverse kinematic calculations were performed accordingly. It was also assumed that the wrist mostly remained aligned with the lower arm during the harvesting process. The lower arm and wrist scores were based on elbow and wrist joint angles. An elbow angle between 60º and 100° was scored as 1, otherwise, it was scored as 2. A wrist angle between 0–15° received a score of 1. The upper arm score reflects the shoulder angle. Scores were assigned as follows: 1 for angles between 0º and 20°, 2 for 20º and 45°, 3 for 45º and 90° and 4 for angles greater than 90°. Extra coupling score was not added as lettuces have well-fitting grip. The location of the palm or lettuce position relative to the shoulder, was used in conjunction with trigonometric functions to determine the required body segment angles as follows.

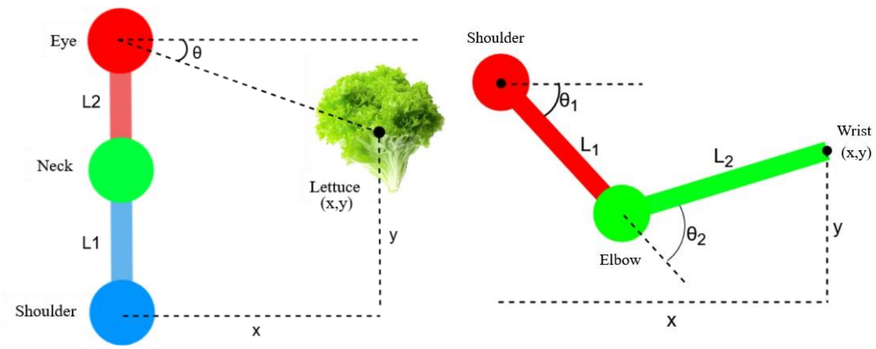

Figure 1. Neck and Arm Geometry

Neck angle θ can be calculated using triangulation and inverse tangent function (Figure 1).

$$\theta = \tan^{-1}\left[\frac{l_2-(y-l_1)}{x}\right] \quad (1)$$

Elbow Angle θ_2 can be derived in terms of x and y using trigonometry.

$$x = l_1.\cos(\theta_1) + l_2.\cos(\theta_1+\theta_2) \quad (2)$$

$$y = l_1.\sin(\theta_1) + l_2.\sin(\theta_1+\theta_2) \quad (3)$$

$$x^2+y^2 = l_1^2+l_2^2+2l_1.l_2[\cos(\theta_1).\cos(\theta_1+\theta_2)+\sin(\theta_1).\sin(\theta_1+\theta_2)] \quad (4)$$

$$x^2+y^2 = l_1^2+l_2^2+2l_1.l_2.\cos(\theta_2) \quad (5)$$

$$\cos(\theta_2) = \frac{x^2+y^2-(l_1^2+l_2^2)}{2.l_1.l_2} \quad (6)$$

$$\theta_2 = \pm\cos^{-1}\left[\frac{x^2+y^2-(l_1^2+l_2^2)}{2.l_1.l_2}\right] \quad (7)$$

After calculating the elbow angle θ_2, the shoulder angle θ_1 can be determined using geometric relationships involving triangulation, as shown below.

$$\tan(\beta) = \frac{l_2.\sin(\theta_2)}{l_1+l_2.\cos(\theta_2)} \quad (8)$$

$$\tan(\gamma) = \frac{y}{x} \quad (9)$$

$$\theta_1 = \gamma - \beta = \tan^{-1}\left[\frac{y}{x}\right] \pm \tan^{-1}\left[\frac{l_2.\sin(\theta_2)}{l_1 + l_2.\cos(\theta_2)}\right] \quad (10)$$

Once the A and B scores are determined, they are cross-referenced in Table C to calculate the C score. The final REBA score is obtained by adding the activity score to the C score (Figure 2). Because lettuce harvesting is slow, involves changing positions, it was assumed that there was no significant repetitive motion. Therefore, the activity score was evaluated as 1, considering that certain body parts (such as the arm) are held in position for a long period of time.

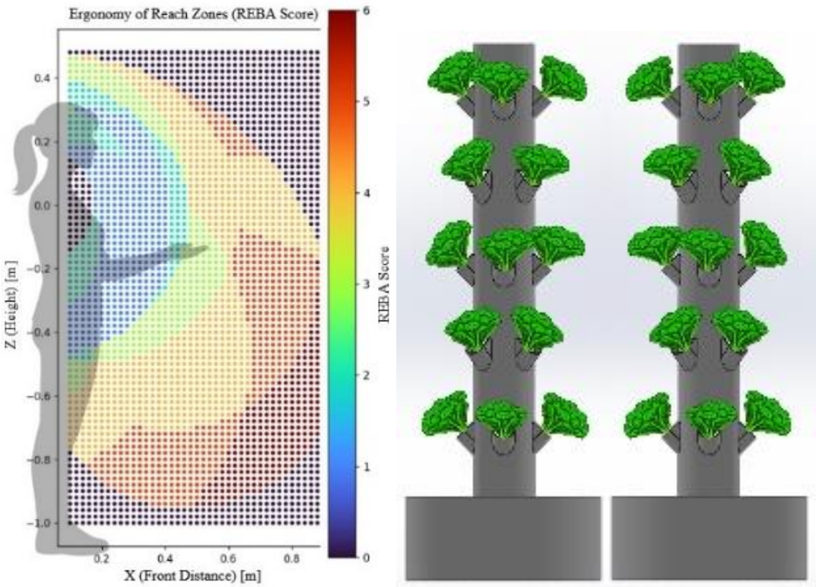

Figure 2. Heat Map of C Scores at 2-cm Resolution (0's are non-reachable areas)

RESULTS AND DISCUSSION

Ergonomic risks contributing to musculoskeletal disorders (MSDs) among agricultural workers have been extensively evaluated in various studies using the Rapid Entire Body Assessment (REBA) method. Zhang et al. (2019) reported an average REBA score of 9.1 during apple harvesting. Similarly, Kamendra et al. (2022) observed that this score reached up to 11.6 in traditional corn harvesting methods, but was reduced to 5.3 with the adoption of improved equipment. Likewise, Boriboonsuksri et al. (2022), in a study on mango harvesting, and Widyanti (2018), in research covering various agricultural tasks, also reported high REBA scores, indicating considerable ergonomic risk. In this study, the harvesting task performed by an operator with a height of 1.50 m in a vertical aquaponic system was evaluated as having a REBA score of 5, indicating a moderate level of ergonomic risk (Table 1). This value is lower than those reported in conventional agricultural practices; however, the level of ergonomic risk may increase depending on system height and crop type. These findings suggest that vertical aquaponic systems may reduce ergonomic risk compared to traditional open-field agriculture, but system-specific design parameters remain critical in shaping worker safety. Environmental factors further influence ergonomic risks. Elevated temperature and relative humidity can lead to fatigue, reduced concentration, and muscle strain, thereby decreasing overall performance (Yale EHS, 2017; Magnavita et al., 2011). In addition to heat-related illnesses, the long-term risk of musculoskeletal disorders also increases under such conditions (Parsons, 2000). In enclosed aquaponic systems, temperatures may exceed 30 °C, while humidity levels can reach 80–90%. Continuous water circulation, fish tanks, and plant transpiration contribute to the rise in humidity. Moreover, the differing harvest times of plants and fish complicate the adjustment of environmental parameters. These results emphasize the necessity of integrating both physical ergonomics and environmental ergonomics in evaluating aquaponic systems.

Table 1. REBA Scores and Body Segment Angles of Vertical Farm Workers (5% Women)

Score Points	Musculoskeletal Disease Risk	Women (5%) REBA Score	Heights From the Ground (cm)	Neck Joint Angle (°)	Shoulder Joint Angle (°)	Elbow Joint Angle (°)	Hip Joint Angle (°)
1	Insignificant	5	53.8	66.9	49.4	0	53.8
2-3	Low Risk	4	83.8	56.1	45.9	0	6.1
4-7	Moderate Risk	2	113.8	32.2	21.1	86	0
8-10	High Risk	3	143.8	−12.8	89.1	53	0
11-12	Very High Risk	no reach	173.8	no reach	no reach	no reach	no reach

CONCLUSION

This study highlights that harvesting tasks in vertical aquaponic systems present a moderate level of ergonomic risk (REBA score: 5), which is lower than those commonly reported in conventional agricultural practices. Nevertheless, ergonomic risk is influenced by system height, crop type, and environmental conditions such as temperature and humidity. The findings suggest that while vertical aquaponic systems can mitigate some ergonomic risks compared to traditional farming, they require careful design and management to ensure worker health and long-term system sustainability. Integrating ergonomic assessment into the planning and operation of such systems will not only improve worker well-being but also contribute to the economic and environmental sustainability of urban agriculture.

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