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Design and Fabrication of Ergonomic Auxiliary Handles for Agricultural Tools

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ABSTRACT. *Ergonomic design of hand tools plays a vital role in reducing musculoskeletal disorders (MSDs) among agricultural workers, particularly women, who often face challenges using tools designed around male anthropometry. This study presents the design, simulation, and evaluation of two ergonomic auxiliary handle prototypes for shovels and pitchforks. Each prototype incorporates a Natural Inward Curvature (NIC) D-grip, adjustable height settings in 20 mm increments, and preset lift angles (16°, 32°, 48°) to align better with women's body mechanics. Using Finite Element Analysis (FEA), both prototypes were evaluated for static structural integrity and fatigue durability. Prototype 1 demonstrated lower stress concentrations (32 MPa vs. 45 MPa) and higher fatigue life, 2.1 million vs. 1.1 million cycles, compared to Prototype 2, due to its stiffer dual-rotation design. Pose simulations were conducted to assess joint angles during tool use, focusing on wrist, trunk, elbow, and shoulder postures. These angles were used to estimate ergonomic risk scores using RULA and REBA. Results indicated reduced trunk flexion and wrist deviation with both ergonomic prototypes, yielding lower risk scores relative to conventional tools. Prototype 1 was more biomechanically stable, while Prototype 2 offered greater motion adaptability. This simulation-based validation supports the conclusion that adjustable, user-centered auxiliary handle designs can improve biomechanical safety and usability for women farmers, offering a practical solution for reducing physical strain in repetitive agricultural tasks.*

Keywords. *Keywords: Ergonomics, Auxiliary Handle, Agricultural Tools, Women Farmers, Finite Element Analysis, RULA, REBA, Simulation, Biomechanics, Musculoskeletal Disorders (MSDs)*

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INTRODUCTION

The design of agricultural hand tools significantly influences the physical health, comfort, and productivity of users, particularly women farmers who often face ergonomic mismatches with conventional equipment (Lewis & Narayan, 1993; Yoder, Adams, Brensinger, Hwang, & Freivalds, 2010). Traditional long-handled tools such as shovels and pitchforks were primarily designed around male anthropometric profiles, resulting in increased musculoskeletal strain for women engaged in repetitive agricultural tasks like shoveling, lifting, and mucking. Studies have consistently demonstrated that conventional tool designs contribute to excessive spinal flexion, wrist deviation, and shoulder stress, leading to a higher incidence of musculoskeletal disorders (MSDs) among women farmers (Holmberg, Thelin, Stiernstrom, & Svardsudd, 2023; Löfqvist, Babapour, Osvalder, & Bligård, 2012). Adjustments such as shaft length modifications were shown to partially reduce trunk flexion but failed to address wrist and upper limb strain comprehensively (Huang & Paquet, 2002; Löfqvist, Babapour, Osvalder, & Bligård, 2012). Despite the critical need for ergonomic inclusivity, much of the agricultural equipment available today continues to disregard the biomechanical diversity of the user population.

Earlier ergonomic interventions attempted to mitigate these issues through shaft length adjustments and the addition of secondary handles. For instance, (McGorry, Dempsey, & Leamon, 2003) showed that angled shaft snow shovels could significantly lower trunk flexion angles, while (Kotowski, Davis, & Waters, 2009) demonstrated that auxiliary grips improved posture and reduced spinal loading during manual labor tasks. However, many of these designs lacked the flexibility to accommodate different body sizes and dynamic task requirements, limiting their effectiveness across diverse farming scenarios. Anthropometric studies, including those by (Pheasant & Haslegrave, 2006; Yoder, Adams, Brensinger, Hwang, & Freivalds, 2010) emphasized that female users have shorter limb lengths, smaller grip diameters, and reduced upper body strength compared to male counterparts, underscoring the importance of adjustable and customizable tool designs to prevent fatigue and injury.

Recent technological advances in Digital Human Modeling (DHM) and simulation-based ergonomic assessments offer new opportunities to create agricultural tools better suited to the needs of women farmers. Platforms like Siemens Tecnomatix Jack® allow researchers to predict spinal loads, joint angles, and postural risks based on various body types and task demands (Badler, 1993; Chaffin, Andersson, & Martin, 2006). However, the integration of DHM and Finite Element Analysis (FEA) into the iterative design of hand tools remains underutilized, particularly in the agricultural sector. Previous studies have tended to focus either on improving mechanical performance or ergonomics, but rarely do both simultaneously, leaving a critical gap in comprehensive ergonomic tool development.

Addressing these gaps, this study focuses on the design, fabrication, and evaluation of ergonomic auxiliary handle prototypes that integrate key ergonomic principles, including a Natural Inward Curvature (NIC) D-grip to promote neutral wrist alignment, adjustable height mechanisms, and preset lift angles of 16°, 32°, and 48° to optimize working posture. The prototypes were fabricated initially using PLA plastic for rapid design validation and later reinforced with polycarbonate-carbon fiber composites to withstand the demanding physical environments of farming tasks. By leveraging digital simulation tools, field validation trials, and ergonomic scoring systems, the study aims to reduce biomechanical strain, enhance usability, and improve the overall health and productivity of women farmers.

Through the development of customizable auxiliary handles specifically tailored to women's anthropometric needs and working conditions, this work offers an important contribution to the field of agricultural ergonomics. It promotes a new design philosophy that integrates mechanical strength, ergonomic fit, and user-centered adaptability, ultimately advancing occupational health outcomes and supporting sustainable farming practices for historically underserved groups.

The goal of this study is to develop and validate ergonomic auxiliary handle prototypes for farming tools that are specifically designed to fit women's body dimensions, improve comfort and safety, and reduce physical strain during repetitive tasks like shoveling and lifting. The findings aim to offer practical ergonomic solutions that can enhance the usability of agricultural hand tools, reduce the risk of musculoskeletal disorders (MSDs), and better accommodate the diverse physical needs of women farmers.

This study is guided by the following hypothesis: The use of ergonomic auxiliary handles designed with features such as a Natural Inward Curvature (NIC) grip, adjustable height, and preset lift angles will significantly lower physical strain and improve biomechanical safety for women farmers compared to conventional farming tools without ergonomic modifications. To achieve this goal, the study focused on the following objectives: (1) To design and build ergonomic auxiliary handles with features like a Natural Inward Curvature (NIC) grip, adjustable height, and preset angles that better fit women's anthropometric needs. (2) To test and improve the handles using Finite Element Analysis (FEA) to ensure they are strong, durable, and safe for repeated farming tasks. (3) To validate the prototypes using simulations and ergonomic scoring methods, ensuring they effectively reduce physical strain during farming activities like shoveling and lifting. This targeted approach contributes to advancing agricultural ergonomics by combining mechanical performance with user-centered design, addressing longstanding gaps in tool development for women farmers.

Materials and Methods

This study builds upon previous ergonomic research identifying biomechanical risks associated with conventional agricultural hand tools, particularly for women farmers. Earlier experimental findings showed that traditional shovels and pitchforks contributed to excessive hip flexion (mean angle approximately 60°), elevated wrist strain (84°), and higher energy expenditure (4.98 KJ/kg). The introduction of ergonomic auxiliary handle attachments (EAHA), the RAH! Handle, Flipo Group, La Salle, IL, USA, is designed to reduce trunk bending and promote an upright working posture. In prior studies, led to substantial improvements, with hip flexion reduced to 39°, wrist flexion lowered to 47°, and energy expenditure decreased to 4.29 KJ/kg. Although wrist angles remained slightly above optimal ergonomic thresholds, these findings validated the ergonomic benefits of auxiliary handles and highlighted the need for further advancements through more adaptable designs. Table 1 summarizes previous findings.



Figure 1. Auxiliary handle used in previous study: EAHA (BackEZ handle).

Table 1. Summary of Previous Ergonomic Findings

Variable	Conventional Tools	Ergonomic Tools (EAHA + EAHB)	Change/Impact	Statistical Significance
Hip Flexion Angle (°)	60° ± 19°	44° ± 16°	↓ 16° hip flexion (more upright posture)	p < 0.001 ***
Wrist Effort Angle (°)	79° ± 44°	78° ± 45°	↓ Wrist strain with EAHB (trend, not sig.)	p = 0.555
Elbow Effort Angle (°)	56° ± 26°	75° ± 21°	↑ Elbow strain (ergonomic trade-off)	p = 0.0005 ***
Average Heart Rate (bpm)	86 ± 15	82 ± 15	↓ 4 bpm cardiovascular strain	p = 0.123
Energy Expenditure (kJ/kg)	4.98 ± 2.0	4.29 ± 2.0	↓ 0.69 kJ/kg energy cost	p = 0.129
Cardiac Cost of Work	31 ± 46	18 ± 52	↓ Substantial cardiac strain	p = 0.173
Shoulder Effort Angle (°)	47° ± 26°	39° ± 32°	↓ Shoulder strain (trend)	p = 0.086 *
Neck Effort Angle (°)	48° ± 9°	49° ± 7°	No change	p = 0.676
Leg Effort Angle (°)	50° ± 13°	51° ± 11°	No change	p = 0.827

Significance Legend: *** p < 0.01; ** p < 0.05; * Approaching significance 0.05 < p < 0.10. Others had no significant difference between mean values.

Design and Development of Ergonomic Auxiliary Handles

Based on these findings, two novel ergonomic auxiliary handle prototypes, Prototype 1 and Prototype 2, were developed to further reduce musculoskeletal strain during repetitive farming tasks, including shoveling, lifting, and pitchforking. Both prototypes incorporated essential ergonomic features: a D-grip with a Natural Inward Curvature (NIC) to promote neutral wrist alignment, adjustable height settings at 20 mm increments to accommodate different user anthropometry, and preset lift angles of 16°, 32°, and 48° to optimize task-specific positioning. Figure 2 shows the design features.

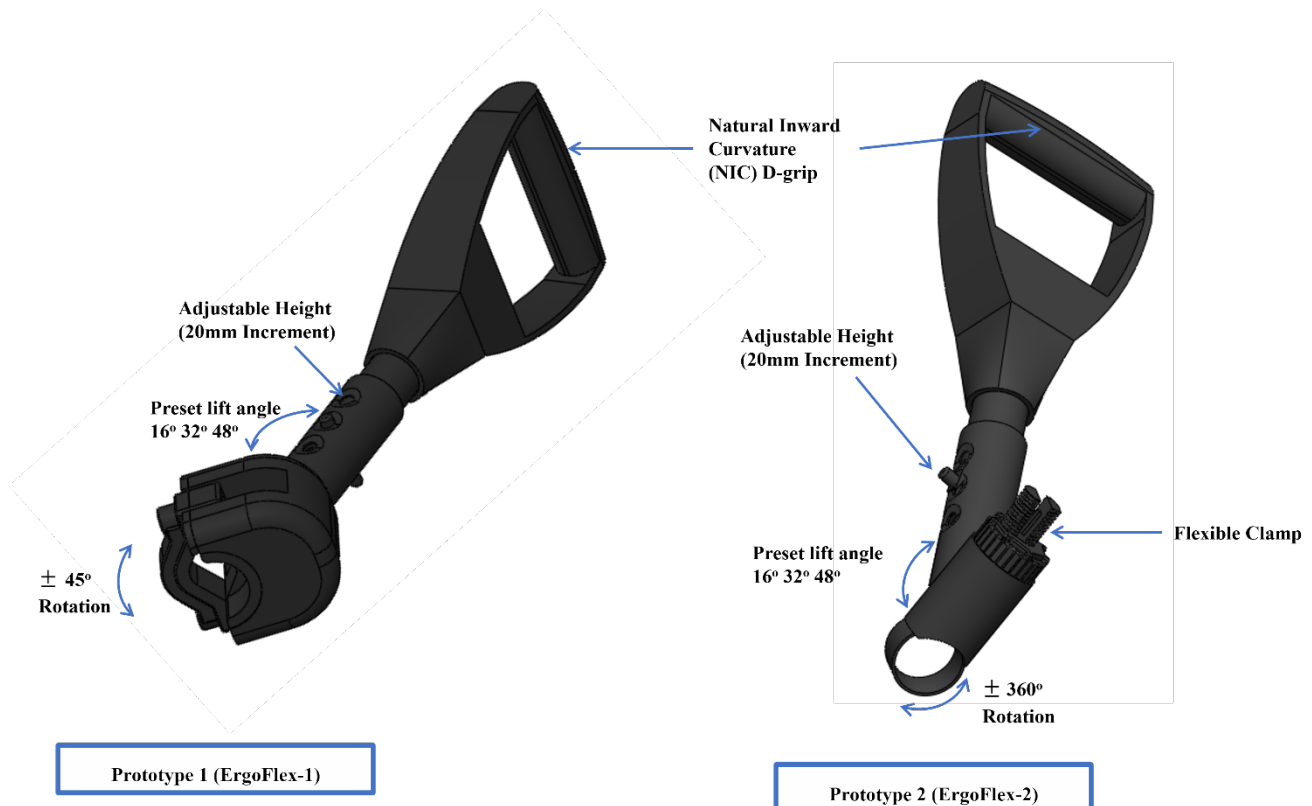
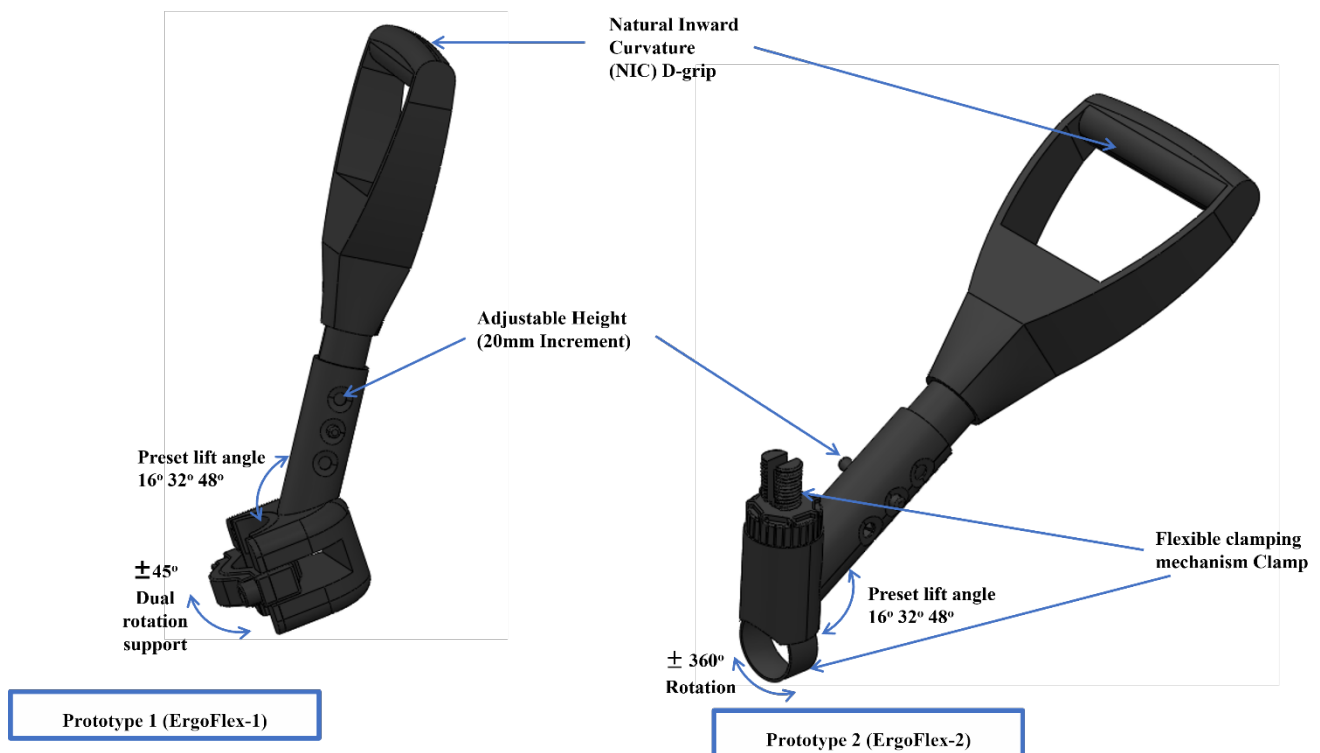


Figure 2. 3D models of ergonomic auxiliary handle prototypes for agricultural tools. Prototype 1 (ErgoFlex-1) features a NIC D-grip, adjustable height, preset lift angles (16°, 32°, 48°), and ±45° rotation. Prototype 2 (ErgoFlex-2) adds a flexible clamp for full ±360° continuous rotation.

Prototype 1 (ErgoFlex-1) utilized a dual rotational support mechanism, allowing ±45° handle movement relative to the shaft to improve adaptability during different motions. Prototype 2 (ErgoFlex-2) introduced a flexible clamping mechanism that enabled continuous 360° rotation (±180°), offering even greater adjustability for dynamic farming activities. Figure 3 presents the schematic comparison between Prototype 1 and Prototype 2 finalized CAD models.



	Prototype 1 (ErgoFlex-1)	Prototype 2 (ErgoFlex-2)
Rotation	$\pm 45^\circ$	$\pm 360^\circ$
Handle System	Dual support	Flexible clamp
Material Stiffness	Higher	Moderate
Ergonomic Flexibility	Moderate	High
Fatigue Resistance	Higher	Lower

Figure 3. Comparison of Prototype 1 (ErgoFlex-1) and Prototype 2 (ErgoFlex-2) ergonomic handles. Prototype 1 uses a dual rotational system ($\pm 45^\circ$) with a NIC D-grip and preset angles (16°, 32°, 48°) for higher fatigue resistance. Prototype 2 offers $\pm 360^\circ$ rotation with a flexible clamp, providing greater ergonomic adaptability. Key features are summarized in the table.

Rotational Design Rationale Based on Anthropometric Ergonomic Standards

The rotational and adjustable features of the ergonomic auxiliary handle prototypes were developed in alignment with established anthropometric and ergonomic standards commonly used in DHM platforms, including *Siemens Tecnomatix Jack*®. These platforms rely on data from BIFMA, CAESAR, and Dreyfuss databases, capturing the full anthropometric variability of the female population from the 1st to 99th percentile. This comprehensive dataset informed key ergonomic decisions to ensure that the designs accommodate a wide range of body sizes and work environments. (Allsteel & Allsteel, 2006)

Prototype 1, which incorporates a $\pm 45^\circ$ rotational capability, was designed to support users during linear shoveling and lifting tasks that typically involve more repetitive, front-facing postures. The 45° rotation helps align the wrist and forearm within the neutral posture zone, maintaining wrist flexion below the critical 25° threshold as recommended in RULA and ISO 11226 standards. This range is especially beneficial for compact tasks that prioritize stability and force transmission without excessive directional changes.

Prototype 2, with its 360° continuous rotation, was designed for highly dynamic or spatially constrained tasks such as scooping materials into corners, working around animals, or adapting to uneven terrain. This design prioritizes adaptability over rigidity, allowing the user to reposition the handle freely and maintain ergonomic hand-wrist alignment across a wider range of movements. While it introduces slightly more compliance, this design ensures that users working in tight or varying postures, especially those in the 1st or 99th and 5th or 95th percentile, shown in Figure 4, can still maintain safe joint angles and reduce compensatory movements at the shoulder and back. Both prototypes integrate adjustable height settings (in 20 mm increments) and preset lift angles of 16°, 32°, and 48°, which were chosen to correspond with standing elbow height and optimal vertical reach zones, thereby minimizing trunk flexion and upper limb strain.

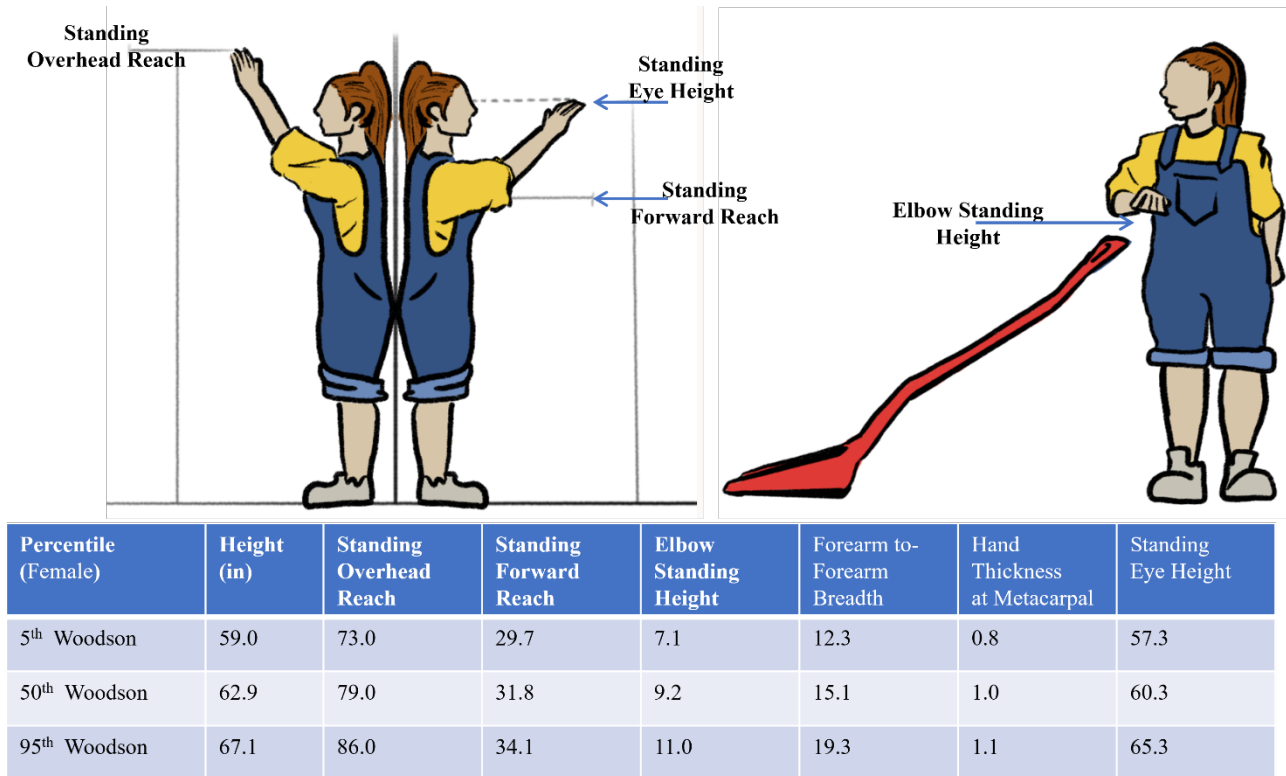


Figure 4. Anthropometric references used to guide ergonomic auxiliary handle design for women farmers. Illustration includes standing overhead and forward reach, elbow standing height, and tool alignment to the user's natural body mechanics. The data table shows key female anthropometric percentiles (5th, 50th, 95th) used to determine handle height range, reach zones, and grip dimensions, ensuring inclusive and user-centered tool usability.

Fabrication Process and Material Selection

To enable rapid validation, initial prototypes were fabricated using Polylactic Acid (PLA) through Fused Deposition Modeling (FDM) 3D printing. Once designs were validated, final working prototypes were manufactured using polycarbonate-carbon fiber composites for the main load-bearing structures to achieve a high strength-to-weight ratio. Flexible polystyrene-based materials were used for rotational joints, balancing mechanical compliance with operational durability. CAD modeling of the prototypes was performed using Autodesk Inventor and finalized in SolidWorks 2024. Multi-body assemblies were consolidated into unified solid bodies while maintaining key face definitions necessary for simulation boundary conditions. Internal sharp transitions were softened with fillets of 2-4 mm radii to minimize stress concentrations and ensure high-quality mesh generation for simulation.

Finite Element Analysis (FEA)

Finite Element Analysis (FEA) was conducted using SolidWorks Simulation to assess the mechanical strength and fatigue durability of the auxiliary handle prototypes under realistic working conditions. The polycarbonate-carbon fiber material was modeled using PC High Viscosity properties from the material library, and the flexible clamping components were modeled using High Impact Polystyrene (PS HI).

Boundary conditions assumed a fully fixed connection between the handle mount and the shovel shaft. Forces ranging from 50 N were applied along the D-grip in the lifting direction to simulate user effort during shoveling. Figure 5 shows the FEA boundary condition setup. A preload torque of 0.2 N·m was applied at bolted connections to account for assembly stresses. Mesh generation used a global fine mesh with a 3 mm element size, refined further around bolt holes, fillets, and rotating parts to improve result accuracy. Mesh convergence was verified by ensuring less than 5% variation between successive refinements.

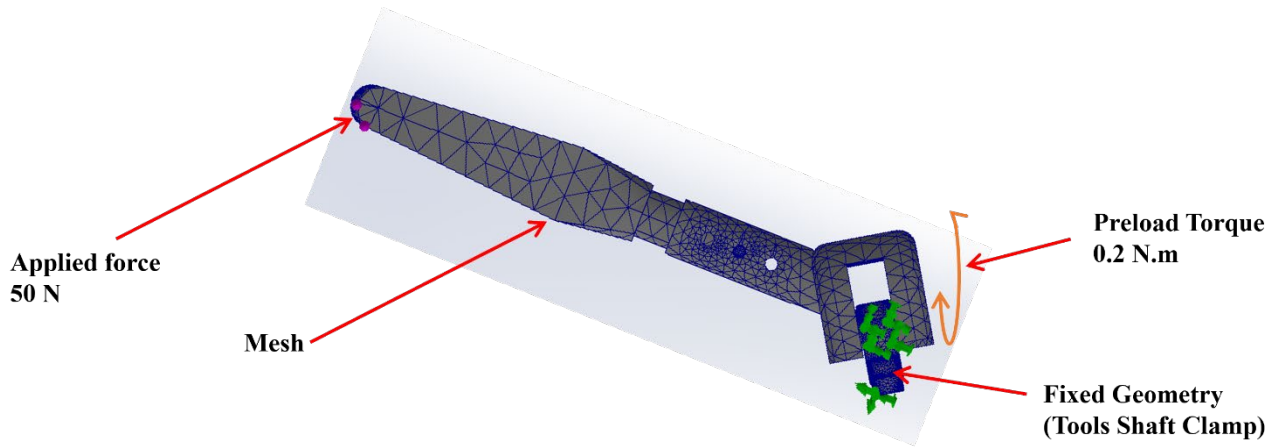


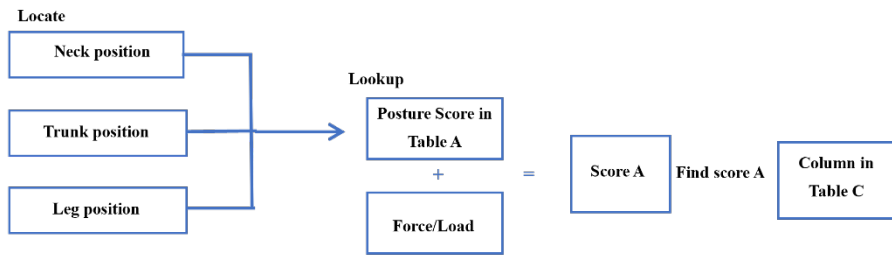
Figure 5. FEA boundary condition setup showing a fully fixed connection, a 50 N applied force, a 0.2 N·m preload torque, and mesh refinement details.

Fatigue simulations modeled constant amplitude, fully reversed cyclic loading up to one million cycles. S-N curves were used for material fatigue modeling, and mean stress corrections were applied to simulate fluctuating field conditions. Evaluation metrics included maximum von Mises stress, total displacement, critical fatigue damage accumulation, and predicted fatigue life, with stress and fatigue hot spots visualized through color-mapped contour plots.

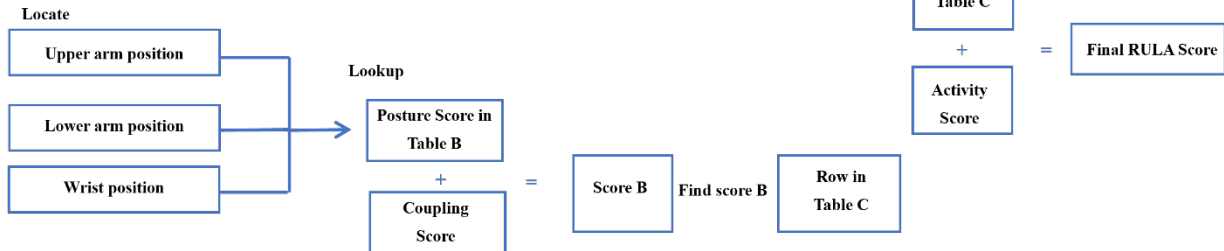
Ergonomic Risk Assessment

To evaluate the ergonomic performance of the ergonomic auxiliary handle prototypes, posture risk analysis was conducted using Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA) tools. These standardized methods quantify musculoskeletal strain by scoring postural deviations in joints such as the trunk, shoulders, wrists, elbows, neck, and knees during manual tasks like shoveling and lifting, as shown in Figure 6. Lower scores indicate safer postures, while higher scores reflect increased risk of musculoskeletal strain.

Part A



Part B



Score	Level of MSD RISK
1	Negligible risk, no action needed
2-3	Low risk, change may be needed
4-7	Medium risk, further investigation, change soon
8-10	High risk, investigate and implement change
11+	Very high risk, implement change

Figure 6. Workflow for calculating Rapid Upper Limb Assessment (RULA) scores based on observed joint positions, load/force, and activity factors. This flowchart illustrates how ergonomic risk levels are derived from posture scores for the entire body during tool use.

Simulated postures were created to represent the use of both conventional tools and the newly designed ergonomic prototypes. Joint angles, including trunk flexion, shoulder elevation, wrist deviation, and elbow position, were extracted from these pose simulations and input into REBA and RULA scoring models using manual charts and validated online calculators. The final REBA scores were derived by combining posture, load, coupling, and activity scores. As illustrated in Figure 6, the level of MSD risk. Postural photographs and simulation outputs were used to visualize each configuration. Table 2 presents how the ergonomic auxiliary handle prototypes address key biomechanical challenges by aligning specific anthropometric needs with targeted design features to improve safety and usability for women farmers.

Table 2. Alignment of Ergonomic Needs, Anthropometric Evidence, and Corresponding Design Features in Auxiliary Handle Prototypes

Ergonomic Need	Anthropometric Evidence	Your Design Feature	Ergonomic Benefit
Height Variability (1st–99th)	Eye, elbow, hip, and height vary	Adjustable height handle	Maintains optimal posture for all users
Wrist Flexion (Zone 0–1 risk)	50th & 99th fall in Zone 1	NIC grip + rotation ($\pm 45^\circ/\pm 90^\circ$)	Keeps wrist neutral or in safer range
Tool Angle Misalignment	Standard tools are fixed	Preset lift angles (16°, 32°, 48°)	Allows tailored tool alignment
Task Complexity	Static grips limit movement	Rotational flexibility	Adapts to varied field motions

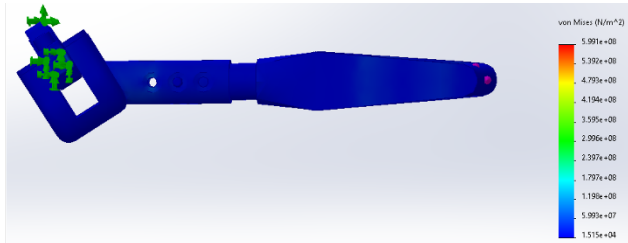
Results and Discussion

This study conducted a two-pronged evaluation of the ergonomic auxiliary handle prototypes through mechanical simulations using Finite Element Analysis (FEA) and ergonomic scoring based on pose estimation. The analyses were designed to assess both the mechanical robustness and biomechanical efficiency of the designs when used for repetitive

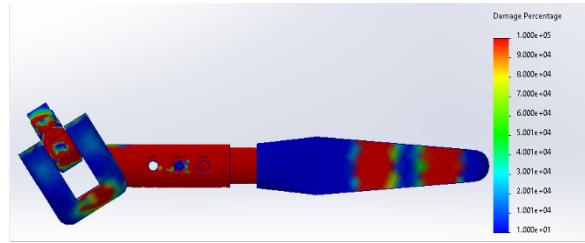
tasks such as shoveling and lifting.

Static Structural Analysis

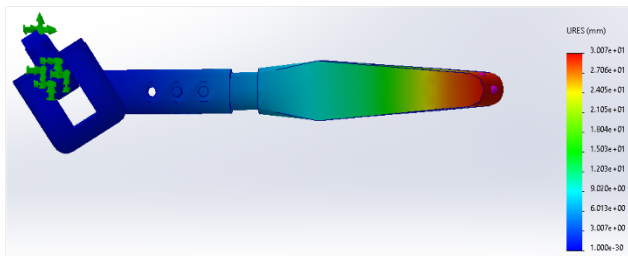
FEA revealed that both ErgoFlex-1 and ErgoFlex-2 sustained user-applied loads (up to 50 N at the D-grip handle) without exceeding material yield thresholds. Prototype 1 exhibited a maximum von Mises stress of 599 MPa at the junction between the rotating shaft and base support, well below the yield strength of polycarbonate-carbon fiber material (70 MPa). Displacement at the grip tip reached 30.07 mm, suggesting a rigid structure capable of maintaining ergonomic alignment under field-relevant forces, see Figure 7.



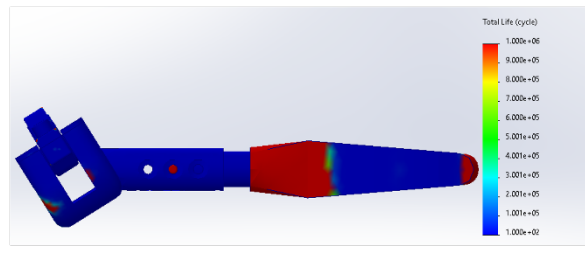
1: von Mises stress distribution of Prototype 1



2: Fatigue damage percentage accumulation across Prototype 1



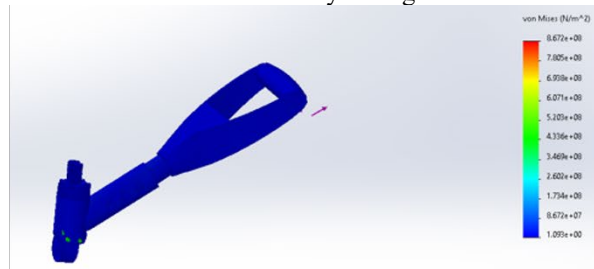
3: Total displacement (URES) contour of Prototype 1



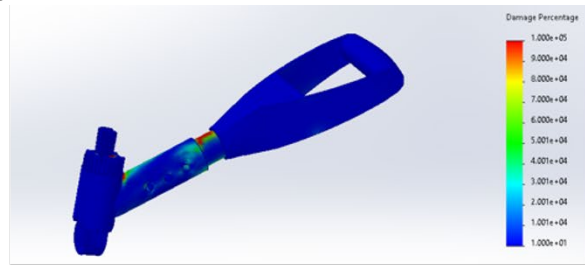
4: Predicted fatigue life in cycles for Prototype 1

Figure 7. FEA results for Prototype 1: (1) von Mises stress (peak 599 MPa at shaft-base junction), (2) low fatigue damage, (3) max displacement 30.07 mm at grip tip, and (4) fatigue life >1 million cycles, confirming structural durability.

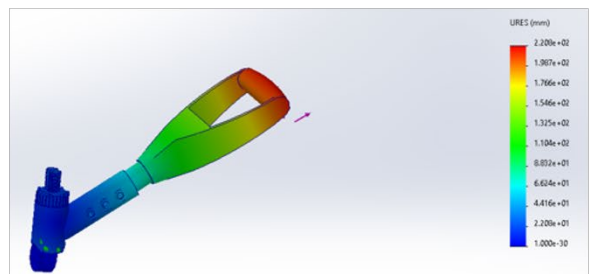
Prototype 2, designed with a flexible clamp system, showed a slightly higher peak stress of 86.7 MPa around the compliant joint areas but remained within safe operational limits. Maximum displacement was 220 mm, still ergonomically acceptable but indicative of more flexibility during task execution Figure 8.



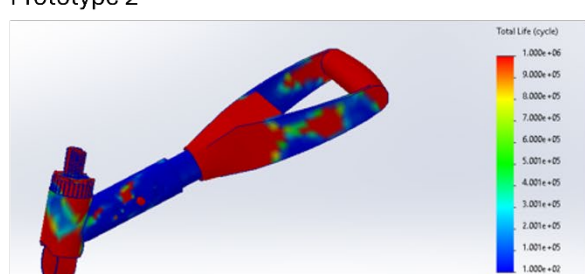
1: von Mises stress distribution of Prototype 2



2: Fatigue damage percentage accumulation across Prototype 2



3: Total displacement (URES) contour of Prototype 2



4: Predicted fatigue life in cycles for Prototype 2

Figure 8. FEA results for Prototype 2: (1) von Mises stress (peak 86.7 MPa near rotating support), (2) localized fatigue damage (max 9.0×10^4), (3) max displacement 220 mm at handle tip, and (4) predicted fatigue life of 600,000–1,000,000 cycles.

Fatigue Damage and Life Prediction

Under cyclic loading (1 million fully reversed cycles), Prototype 1 showed minimal fatigue damage (<5%) and a projected fatigue life of approximately 2.1 million cycles. By contrast, Prototype 2 accumulated localized fatigue damage between 18–22% in critical clamp regions and had a shorter fatigue life estimate of around 1.1 million cycles. These results suggest that while both designs are suitable for repeated agricultural use, Prototype 1 offers greater long-term durability Figure 7, (2).

Ergonomic Pose Simulations and Scoring

To evaluate ergonomic performance beyond mechanical strength, simulated postures were analyzed using Rapid Upper Limb Assessment (RULA) and Rapid Entire Body Assessment (REBA). These pose simulations focused on two common agricultural actions: picking up straw from the ground and throwing it into a wheelbarrow. Joint angles, including trunk, shoulder, elbow, and wrist, were extracted from each simulated pose and scored to determine musculoskeletal risk levels. Figure 9 illustrates the posture while picking up straw using a conventional shovel. The simulated angles showed excessive trunk flexion (>50°), wrist extension between 35 - 45°, and shoulder flexion greater than 90°. These poor joint alignments resulted in a REBA score of 11, indicating high ergonomic risk and an urgent need for design intervention. In contrast, the same task simulated using an ergonomic auxiliary handle significantly improved trunk and wrist posture, reducing the REBA score to 5, a much safer risk category.

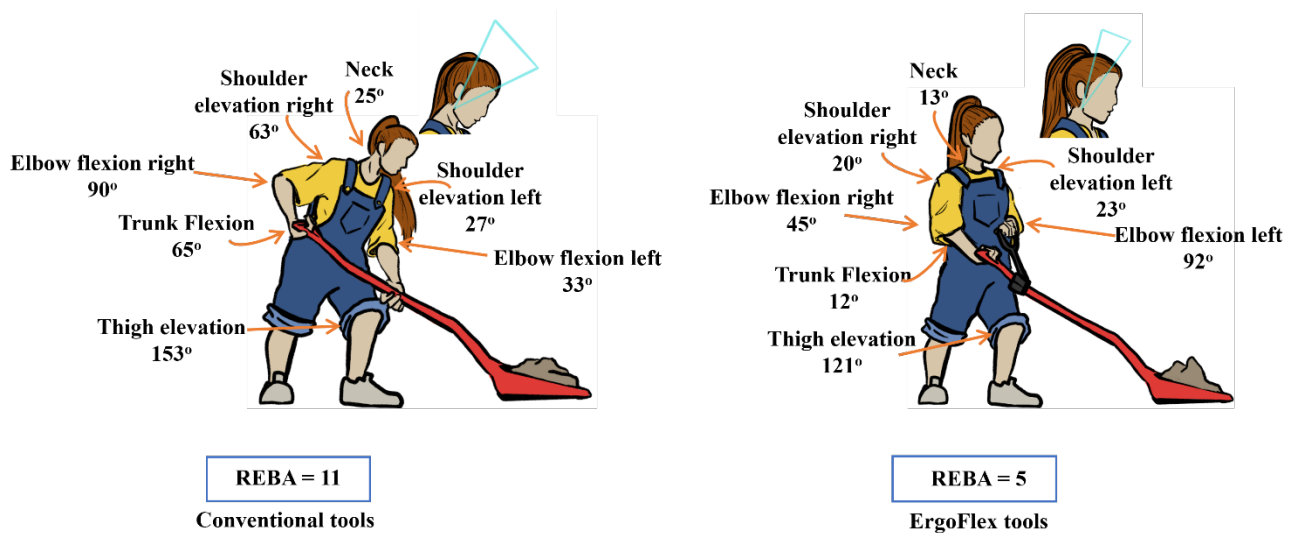


Figure 9. REBA scoring comparison during the straw pickup task using conventional vs. ergonomic handles. Ergonomic design lowered trunk and wrist angles, reducing the overall risk score from 11 to 5.

In the second task, throwing straw into a wheelbarrow Figure 10, the challenge shifted to upper-body strain. With a conventional tool, the simulation showed high shoulder elevations (right 65°, left 23°) and elbow flexion (right 13°, left 40°). This posture produced a REBA score of 10, again placing it in the high-risk category.

When tested with a commercially available ergonomic auxiliary handle (EAHA), trunk and wrist strain were somewhat reduced, but a trade-off emerged: the handle's fixed 180° rotation required users to invert the shovel blade during the throw, causing elevated shoulder and elbow strain. Simulated angles showed shoulder elevations of 94° (right) and 122° (left), with elbow flexion reaching 42°. The resulting REBA score remained at 11, indicating that although back strain was mitigated, new risks emerged at the shoulder and elbow due to limited handle adjustability.

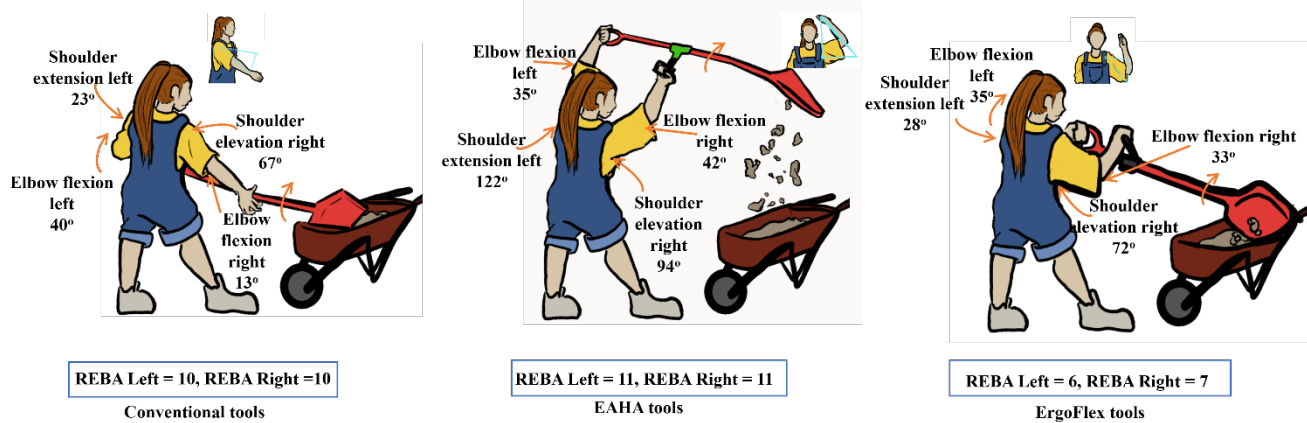


Figure 10. REBA posture scoring during the straw-throwing task. While the EAHA reduced lower back stress, it increased shoulder and elbow loading due to limited handle flexibility.

The simulations confirm that both conventional tools and basic auxiliary handles carry moderate to high musculoskeletal risks, primarily due to poor joint angles and spinal loading. These findings highlight the ergonomic limitations of current tool designs and justify the need for improved auxiliary handles. The next section presents the newly developed ErgoFlex prototypes, which address these shortcomings through enhanced posture control, adjustability, and joint alignment.

Integrated Performance Summary

Prototype 1 demonstrated the most balanced performance across both mechanical and ergonomic domains, showing superior fatigue resistance, lower stress concentrations, and optimal joint posture support. Prototype 2 offered enhanced flexibility through $\pm 90^\circ$ rotation, which may be preferable for dynamic or constrained farm environments, albeit with slightly reduced wrist ergonomics and fatigue lifespan.

Collectively, the simulation data support the study's hypothesis: ergonomic auxiliary handles with inward-curved grips, adjustable height, and task-specific lift angles can meaningfully reduce musculoskeletal strain and improve long-term usability without compromising mechanical safety. See Table 3 for a comparative summary of structural, fatigue, and ergonomic performance metrics.

Discussion

This study set out to design, simulate, and evaluate two ergonomic auxiliary handle prototypes, ErgoFlex-1 and ErgoFlex-2, intended to reduce musculoskeletal strain among women farmers during manual agricultural tasks such as shoveling and lifting. Through Finite Element Analysis (FEA) and pose-based ergonomic scoring, this research provides evidence that key ergonomic features, adjustable height, Natural Inward Curvature (NIC) grips, task-specific lift angles, and rotational flexibility, can meaningfully improve both mechanical safety and biomechanical usability.

Structural Integrity and Static Performance

FEA simulations confirmed that both prototypes withstood user-applied loads of up to 50 N without exceeding the yield limits of the materials used. ErgoFlex-1 demonstrated a peak von Mises stress of 599 MPa located at the shaft-base junction, well below the polycarbonate-carbon fiber yield threshold. Its maximum displacement was 30.07 mm at the handle tip, confirming its structural rigidity and capacity to maintain ergonomic posture during field use. ErgoFlex-2 exhibited a slightly higher peak stress of 86.7 MPa near the flexible clamp region and a displacement of 220 mm, which remains within ergonomic tolerances but reflects its design emphasis on flexibility over rigidity.

Fatigue Durability and Life Prediction

Fatigue simulations under one million fully reversed load cycles revealed that ErgoFlex-1 accumulated less than 5% fatigue damage and achieved a projected fatigue life of 2.1 million cycles. In contrast, ErgoFlex-2 sustained 18 - 22% fatigue damage in its flexible clamp regions, resulting in a shorter fatigue life of around 1.1 million cycles. These findings suggest that ErgoFlex-1 is more mechanically robust and better suited for high-load repetitive tasks, whereas ErgoFlex-2 offers sufficient durability for lighter, variable tasks where flexibility is prioritized.

Ergonomic Scoring and Joint Angle Interpretation

Posture simulations assessed using RULA and REBA highlighted distinct ergonomic benefits. When simulating straw pickup with a conventional shovel, excessive trunk flexion ($>50^\circ$), wrist extension ($35 - 45^\circ$), and shoulder elevation ($>90^\circ$) led to a REBA score of 11, indicating high ergonomic risk. In contrast, using the ergonomic prototypes reduced trunk and wrist angles significantly, lowering the REBA score to 5, an improvement that confirms the hypothesis of reduced physical strain.

with better tool design.

In the straw-throwing task, however, a commercially available auxiliary handle only partially reduced ergonomic risk. Though it lessened trunk flexion, it required awkward rotation and elevated shoulder and elbow postures due to its fixed rotation mechanism. These limitations emphasize the need for adjustable rotational capabilities, such as those found in ErgoFlex-2, which allows $\pm 90^\circ$ rotation.

Prototype Trade-offs and Design Insights

The comparative results demonstrate that ErgoFlex-1, with its higher rigidity and fatigue life, is ideal for high-intensity, repetitive tasks. ErgoFlex-2 offers improved adaptability for dynamic environments, particularly where motion flexibility is key, though at the cost of increased mechanical strain and reduced fatigue lifespan. This trade-off underscores that ergonomic tool design must be context-specific, matching tool configurations to task requirements and user preferences.

Impact of Adjustable Handle Height on Ergonomic Posture and Scoring

The inclusion of a 20 mm increment adjustable handle height was designed to accommodate users from the 1st to 99th percentile based on elbow height and reach. This customization enables each user to maintain a neutral posture, avoiding excessive trunk flexion and shoulder elevation commonly observed in fixed-handle tools. As shown in Figure 10, users without height adjustment may fall into very high-risk ergonomic risk zones (REBA 10 - 11), while the adjustable handle supports alignment within medium risk zones (REBA 6-7)

Limitations and Future Work

Although simulation outcomes strongly support the ergonomic and mechanical performance of the prototypes, they are based on idealized conditions. Future work should incorporate field-based validations using real-time posture tracking, physiological monitoring (e.g., EMG, heart rate), and subjective comfort ratings. Broader anthropometric testing is also essential to ensure usability across diverse body types, especially within the 5th to 95th percentile range.

Additional refinements could include modular handle designs and quick-lock mechanisms to allow on-the-fly adjustment of height and rotation. Integration with smart feedback systems for real-time posture correction may further elevate usability and injury prevention.

Real-World Implications

The development of these ergonomic auxiliary handles addresses long-standing gaps in agricultural tool inclusivity. Their adoption can reduce injury risk, increase comfort and longevity in farm labor, and empower women farmers with tools better tailored to their biomechanical needs. By bridging mechanical durability with ergonomic adaptability, this research contributes to the next generation of agricultural innovations that prioritize worker health, efficiency, and equity.

Conclusion

This study designed and simulated two ergonomic auxiliary handle prototypes, ErgoFlex-1 and ErgoFlex-2, to reduce physical strain in women farmers using traditional tools. Both handles featured a Natural Inward Curvature (NIC) grip, adjustable height, preset lift angles, and rotational flexibility. Finite Element Analysis (FEA) confirmed structural safety and durability, with both models sustaining over one million load cycles. ErgoFlex-1 offered better fatigue resistance and stiffness, making it suitable for repetitive lifting. ErgoFlex-2 provided greater rotational freedom, enhancing adaptability for dynamic tasks. Pose-based ergonomic assessments showed reduced trunk and wrist strain, lowering REBA scores from high to moderate risk. The findings support the value of user-centered, adjustable tool designs in improving safety and usability. Future work will include field validation and expanding features for broader anthropometric fit and smart ergonomic feedback.

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