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# Intelligent Mechanical Characterization of Date Fruits for Automated Harvesting Grippers

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*Abstract*—**Robotic harvesting of date fruits requires precise grasping force control to prevent tissue damage, yet cultivar-specific biomechanical limits remain absent from the literature. This work presents the first continuous stress-strain characterization of three Saudi date cultivars (Ajwa, Barhi, Sagai) across three hydration states, translated into validated robotic grasping constraints. A custom parallel-plate compression system emulates two-finger robotic grasping, while a Mask R-CNN vision model provides non-contact geometric measurement with below $5\%$ relative error. Cyclic loading experiments establish elastic strain limits, with conservative operational thresholds of $7\%$ for Ajwa and Barhi and $5\%$ for Sagai. Validation with a UR10e manipulator confirms damage-free manipulation across all cultivars residual deformation below $1$ mm and strain tracking error below $1\%$. Future work will integrate vision and force feedback with machine learning models trained on these experimentally derived limits, enabling real-time geometry-based gripper control for fully autonomous harvesting.**

### *Introduction and Related Work*

Saudi Arabia leads global date exports ($390M USD annually, 30M palm trees) [1], yet manual harvesting exposes workers to serious hazards including falls, with an annual fatality rate of 3.4 per 1,000 workers [2]. Automated harvesting is therefore both an economic and safety imperative [3].

Vision-based ripeness detection [4], [5] and cluster-level robotic harvesters [6], [7] have been demonstrated, but none address safe manipulation of individual separated fruits. AI-driven systems for apples, and kiwi [8], [9] show that data-driven gripping can reduce damage when physically grounded force limits are available.

Force-aware gripper designs soft actuators [10], [11], force controllers [12], [13], and contact-pressure analyses [14]–[16], all depend on cultivar-specific mechanical limits that do not yet exist for date fruits. Prior date-fruit studies characterize physical dimensions [17], [18] and report discrete hardness or modulus values [19]–[22], but continuous stress-strain curves, cyclic elastic-recovery verification, and bioyield thresholds are absent from the literature. This work fills that gap.

### *Methodology*

A custom parallel-plate uniaxial horizontal apparatus (50 N capacity, $\pm 0.5\%$ tolerance, 100 Hz [23]) emulates two-finger grasping and resolves the low-strain elastic regime that standard UTMs cannot reliably capture in compliant tissue.

A Mask R-CNN (ResNet-50 FPN) model fine-tuned on a custom date dataset provides frame-by-frame segmentation during compression. Active-contour post-processing refines each mask to the true boundary; validation yields MAE of $0.991$ cm$^2$ in area ($4.58\%$, $R^2{>}0.96$) and $2.17$ mm in diameter ($2.19\%$), giving combined stress uncertainty $\approx 5\%$.

450 samples (50 per cultivar × hydration-state cell) at the Tamar ripeness stage were sized by SRS at $95\%$ confidence and $2.67\%$ relative margin of error ($\bar{y}{=}8.99$ N, $s{=}2.59$ N). Moistened fruits were immersed at $40°$C for 3-4 h; dried fruits were heated to $80°$C for 8-12 h [24].

Sequential load-unload cycles at $1, 3, 5, \ldots, 17\%$ strain were applied to three fruits per cultivar. Residual deformation $\delta_r{<}0.1$ cm (below visual detection, $\approx$3-4$\%$ of mean diameter) was classified as elastic; the bioyield point was the first strain level at which $\delta_r$ exceeded this threshold consistently.

Linear regression on gripper-gap vs. command data yielded $G_{\max}{=}77.59$ mm, $k{=}0.883$ mm/%. The robot command to impose strain $\epsilon$ on a fruit of initial diameter $L_0$ is

$$\text{per} = \left\lceil \frac{77.59 - L_0(1-\epsilon)}{0.883} \right\rceil .$$

### *Results and Discussion*

Two-way ANOVA showed cultivar and hydration state significantly affected all dimensions ($p{<}0.001$). Barhi had the highest moisture sensitivity (54.9% volumetric reduction, normal to dried); Ajwa was most stable (9.6% diameter change); Sagai was intermediate [25].

Dried samples were stiffest in all cultivars. Ajwa dried specimens reached $20.50{\pm}2.50$ kPa at $39\%$ strain versus $12.20{\pm}0.74$ kPa moistened ($68\%$ difference). Ajwa showed a stress plateau at 15-23% strain, supporting predictable-force grasping. Barhi had the highest variability (SE 10.3% of mean at 23% strain).

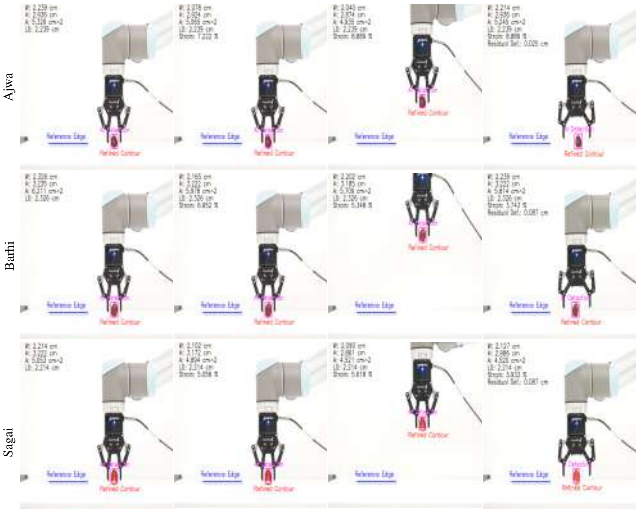
Cyclic tests gave bioyield points of $\approx 9\%$ for Ajwa (CV $6.96\%$) and Barhi (CV $32.96\%$), and $7\%$ for Sagai (CV $11.90\%$). Barhi's high variability necessitates a conservative $7\%$ operational limit (Table I).

TABLE I: Mechanical properties at the bioyield point (mean ± SE).

| **Property** | **Ajwa** | **Barhi** | **Sagai** |
|---|---|---|---|
| Force (N) | $1.70{\pm}0.11$ | $1.19{\pm}0.09$ | $0.82{\pm}0.05$ |
| Stress (kPa) | $3.29{\pm}0.20$ | $2.16{\pm}0.15$ | $1.72{\pm}0.11$ |
| Safe strain | $7\%$ | $7\%$ | $5\%$ |
| Young's mod. (kPa) | $47.0{\pm}2.79$ | $30.8{\pm}2.20$ | $34.5{\pm}2.26$ |

A supervised experimental validation using robotic manipulator completed pick-lift-release cycles for all cultivars with no bruising, puncture, or flesh compression (Fig. 1).

Residual deformation was $0.25$ mm (Ajwa), $0.87$ mm (Barhi), $0.87$ mm (Sagai), all below the $1$ mm constraint, and strain tracking error was within $0.8\%$, validating the calibration model.



(a) $\epsilon\!=\!0$ (b) Target $\epsilon$ (c) Lifting (d) Release

Fig. 1: Grasping sequences for Ajwa ($7\%$), Barhi ($7\%$), Sagai ($5\%$): (a) zero-strain contact, (b) bioyield strain, (c) $30\,$cm vertical lift, (d) post-release recovery. All fruits returned to original geometry with $\delta_r\!<\!1$ mm.

### *Conclusion*

We presented the first continuous stress-strain characterization of Saudi date fruits and validated cultivar-specific bioyield thresholds ($7\%$ Ajwa/Barhi, $5\%$ Sagai) as robotic grasping constraints on a two finger manipulator. All cultivars were manipulated damage-free with residual deformation below $1$ mm and strain error within $0.8\%$. These physically grounded limits provide a foundation for future work integrating vision and force feedback with machine learning models trained on the derived force limits, enabling real time geometry-based gripper control for fully autonomous, damage-free harvesting.

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