

Original Article**Cyclical Force Generation for Triboelectric Nanogenerators: A Review of Mechatronic Approaches, Challenges and Future Perspectives**Amit Athanikar¹, Namdev Mote², S. R. Kumbhar³^{1,2} Research Scholar, Department of Electronics, Shivaji University, Kolhapur, India;³ Principal, Chintamanrao College of Commerce, Sangli, IndiaManuscript ID:
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**Abstract**

Triboelectric nanogenerators (TENGs) convert low-frequency and irregular mechanical energy into electrical energy for self-powered sensors, wearable electronics, Internet-of-Things devices and distributed energy systems. Although major advances have been made in triboelectric materials, surface engineering and device architectures, the mechanical excitation applied during TENG testing remains an important source of experimental variability. Manual tapping, pressing and sliding can introduce uncontrolled changes in force, displacement, velocity, frequency, contact area and waveform, making comparison between experiments difficult. This review examines cyclical force generation as a controllable subsystem for TENG characterization. Linear actuators, servo systems, electrodynamic shakers, cam-follower and crank-slider mechanisms, electromechanical testing machines and tribometers are compared in terms of force/displacement control, frequency, repeatability, cost and suitability. The review also summarizes the mechanical parameters that should be measured together with electrical output and presents a conceptual closed-loop cyclical force generator (CFG) incorporating an actuator, force sensor, displacement sensor, controller, driver, data-acquisition system and TENG fixture. Challenges involving force control, alignment, waveform fidelity, friction, wear, environmental conditions and standardization are discussed. Future CFG systems can incorporate real-world waveform reproduction, adaptive control, artificial intelligence and digital-twin modelling. A dedicated programmable CFG can therefore improve TENG repeatability, inter-laboratory comparison and the reliability of mechanical-to-electrical performance evaluation [1], [5], [10], [17].

Keywords: Triboelectric nanogenerator, TENG, cyclical force generator, mechanical excitation, mechatronics, force control, energy harvesting, standardization, closed-loop control.

Introduction

Triboelectric nanogenerators have attracted considerable attention as technologies for harvesting mechanical energy from human motion, vibration, rotation, wind, water movement and structural deformation. TENG operation is based primarily on contact electrification and electrostatic induction, and commonly discussed operating modes include vertical contact-separation, lateral sliding, single-electrode and freestanding triboelectric-layer modes [1], [2], [3]. Applications include self-powered sensing, wearable electronics, biomedical systems, IoT devices, environmental monitoring and mechanical-energy harvesting [4], [7], [10].

A TENG cannot, however, be evaluated independently of its mechanical input. Force, displacement, velocity, acceleration, frequency, contact area, waveform, alignment and environmental conditions can affect charge transfer and electrical output. Consequently, identical devices can show different electrical characteristics when tested under different mechanical conditions. Manual excitation is useful for demonstrations, but its force profile, frequency and displacement are difficult to reproduce accurately. Recent work on TENG testing and mechanical-structure design therefore emphasizes controlled excitation and better reporting of mechanical and environmental conditions [16], [17].

Rationale Of the Study

The central rationale for a cyclical force generator is to transform mechanical excitation from an operator-dependent test condition into a measurable and programmable experimental variable. For meaningful TENG comparison, the applied force and motion should be repeatable and, where possible, synchronized with electrical measurements. A dedicated CFG can provide controlled cyclic force or displacement, defined frequency and waveform, force feedback, position feedback and long-cycle operation. Such a platform is particularly relevant as TENG research moves from laboratory demonstrations toward practical harvesting and sensing systems [5], [16], [17].

Objectives

- To review the relationship between mechanical excitation and TENG output.
- To examine mechanical and mechatronic approaches for cyclic force generation.

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- To identify mechanical parameters required for repeatable TENG testing.
- To develop a conceptual architecture for a programmable cyclical force generator.
- To identify challenges and future opportunities involving intelligent and adaptive force-generation systems.

Hypothesis

Controlled and repeatable mechanical excitation using a programmable cyclical force generator has the potential to improve the reliability, repeatability and comparability of TENG characterization compared with uncontrolled manual mechanical excitation.

Methodology

This review uses a thematic and comparative literature-review approach. The selected literature in the supplied reference set was organized into five themes: (i) TENG operating principles and applications, (ii) mechanical excitation and testing, (iii) mechanical structures and force transmission, (iv) standardization, durability and power management, and (v) emerging intelligent and adaptive approaches.

The methods are compared using force control, displacement control, frequency control, waveform capability, repeatability, cost, integration complexity and TENG suitability as principal criteria. The synthesis is then used to define the requirements and conceptual architecture of a programmable CFG.

Analysis And Data Analysis

1. Mechanical Fundamentals and Testing Requirements

For a displacement $x(t)$, the velocity and acceleration are $v(t)=dx/dt$ and $a(t)=d^2x/dt^2$. The instantaneous mechanical input power is $P_m(t)=F(t)v(t)$, and the mechanical energy supplied during a cycle is $E_m=\int F(t)dx$. Electromechanical conversion efficiency can be expressed as $\eta=(E_e/E_m)\times 100\%$, where E_e is the useful electrical energy generated during the corresponding cycle. These relationships show that frequency and displacement alone do not fully characterize the mechanical energy supplied to a TENG. For CFG design, this distinction is important because two tests having the same nominal displacement and frequency may still apply different force profiles. The mechanical fixture, spring stiffness, friction and contact condition can change the actual force delivered to the TENG. Therefore, the measured rather than only commanded excitation should be retained in the experimental record. A useful test record should link each electrical waveform to its corresponding force and displacement waveforms.

For ideal sinusoidal excitation, $x(t)=X_0 \sin(2\pi ft)$, $v(t)=2\pi fX_0 \cos(2\pi ft)$, and $a(t)=-(2\pi f)^2X_0 \sin(2\pi ft)$. Thus, increasing frequency increases velocity and acceleration even when displacement amplitude is unchanged. The minimum mechanical information recommended for TENG testing is summarized below [17].

Parameter	Symbol	Importance
Force	F	Mechanical loading/contact condition
Displacement	x	Separation or sliding distance
Velocity	v	Rate of mechanical motion
Acceleration	a	Dynamic excitation
Frequency	f	Cycling rate
Contact area	A	Effective contact
Waveform	—	Temporal force/displacement profile
Temperature	Te	Environmental/material influence
Relative humidity	RH	Triboelectric influence
Alignment	—	Effective contact area
Cycle count	N	Durability

2. Mechanical Input and TENG Electrical Output

The electrical current of a TENG is related to transferred charge by $I(t)=dQ(t)/dt$. Under cyclic excitation, the generated electrical signal is related to the mechanical cycling rate, although the exact relationship depends on the TENG structure and operating mode. Reported testing guidance indicates that short-circuit current can increase with excitation frequency under some conditions, while transferred charge can be comparatively less dependent on frequency. Therefore, output current should not be interpreted without reporting the mechanical excitation conditions [10], [17].

3. Existing Cyclical Excitation Approaches

Manual tapping, pressing and sliding are low-cost and suitable for demonstrations but provide poor repeatability and an uncertain force profile. Linear motors provide programmable displacement and frequency with high repeatability, although they are relatively costly and may require closed-loop force control. Servo motors can generate reciprocating motion through crank-slider, eccentric cam, Scotch-yoke, lead-screw or similar mechanisms, providing an economical route to programmable cyclic motion. Electrodynamics shakers are suitable for vibration and higher-frequency excitation, whereas universal testing machines provide accurate force/displacement cycling at substantially higher cost. Tribometers are particularly useful for sliding TENGs because they can control normal force, sliding distance, velocity and friction [5], [10], [16], [17].

A cam-follower or crank-slider mechanism is attractive where a simple periodic displacement is sufficient. Its main advantage is mechanical simplicity and low cost, while its limitation is that the force waveform is strongly influenced by geometry, speed, inertia and load. Servo-based systems offer greater flexibility because the excitation frequency and commanded position can be changed electronically. Linear actuators provide direct reciprocating motion and are useful when a controlled stroke is required. For vibration-oriented TENGs, an electrodynamic shaker can reproduce higher-frequency acceleration profiles, while a tribometer is preferable when sliding distance, friction and wear are central variables. Thus, no single mechanism is universally optimal; the excitation system should be selected from the TENG operating mode and the variables that must be controlled.

4. Comparative Analysis

Method	Force	Displacement	Frequency	Cost	TENG suitability
Manual tapping	Low	Low	Low	Very low	Demonstration
Cam mechanism	Medium	Medium	High	Low	Good
Crank-slider	Medium	High	High	Low-medium	Very good
Servo motor	High	High	High	Medium	Excellent
Linear motor	Very high	Very high	Very high	High	Excellent
Electrodynamic shaker	Medium-high	High	Very high	High	Vibration TENG
Testing machine	Very high	Very high	High	Very high	Research testing
Tribometer	Very high	High	High	High	Sliding TENG

Overall, a servo- or linear-actuator-based closed-loop system provides an attractive compromise between controllability, flexibility and cost for a dedicated TENG CFG. The appropriate choice remains dependent on required force, displacement, frequency and operating mode [16], [17].

The comparison also suggests a practical development path for an academic research platform. A medium-cost servo motor can provide the primary cyclic motion, while a replaceable mechanical transmission can adapt the stroke and force range. Adding a load cell converts the system from open-loop motion generation to measurable force excitation. An encoder or linear displacement sensor then allows the actual motion to be compared with the commanded waveform. This modular arrangement can be upgraded later with environmental sensing, synchronized electrical acquisition and adaptive control without replacing the complete mechanical platform.

5. Proposed Mechatronic Cyclical Force Generator

The proposed CFG treats mechanical excitation as a controlled subsystem. The architecture consists of an actuator and force-transmission mechanism, force and position sensing, closed-loop control, motor driver, synchronized data acquisition and a replaceable TENG fixture. The platform should generate a specified force/displacement waveform while simultaneously recording the actual mechanical input and electrical response.

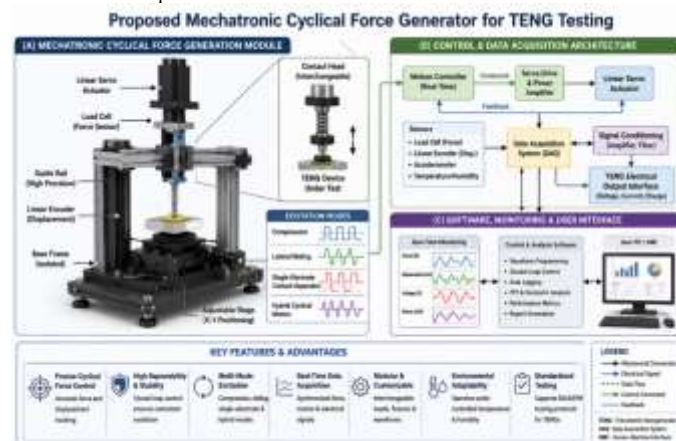


Figure 1. Proposed conceptual architecture of a mechatronic cyclical force generator for TENG testing.

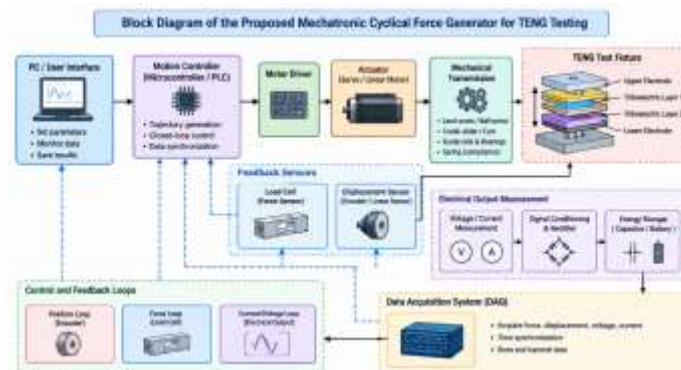


Figure 2. Block diagram of the proposed mechatronic cyclical force generator for TENG testing.

6. Functional Components and Closed-Loop Control

Possible actuators include a DC geared motor, BLDC motor, servo motor, stepper motor, linear actuator, voice-coil actuator and linear motor. For research-grade operation, a servo motor or linear actuator with feedback is preferred. A load cell measures the actual applied force, while an encoder or displacement sensor measures position. The measured force can be represented as $F_m(t) = S_f V_f(t)$, where S_f is the force-sensor calibration coefficient. The position error is $e_x(t) = x_d(t) - x_m(t)$. A PID controller can be expressed as $u(t) = K_p e(t) + K_i \int e(t) dt + K_d \frac{de(t)}{dt}$. Separate loops can be used for position, velocity and force according to the design requirement.

The actuator should be mechanically isolated from unwanted lateral motion and coupled to the TENG fixture through a rigid but serviceable transmission. The force sensor should be placed so that it measures the force actually reaching the triboelectric interface rather than only motor torque or an inferred load. Similarly, displacement should preferably be measured near the moving TENG member. These arrangements reduce errors caused by backlash, compliance and transmission losses. The controller can use the measured error to compensate for changes in load or operating conditions, while the data-acquisition system stores the commanded and measured signals for later analysis.

7. Waveform Generation and Standardization

A programmable CFG can generate sinusoidal, triangular, square, sawtooth, pulsed, random and recorded real-world force/displacement waveforms. Reproduction of measured human-motion or environmental vibration waveforms can bridge the difference between ideal laboratory testing and irregular real-world excitation [17], [21], [22].

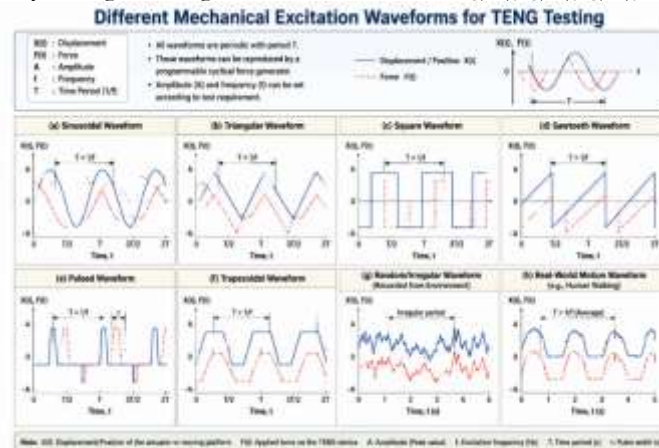


Figure 3. Representative mechanical excitation waveforms applicable to TENG testing.

Standardized testing should record, at minimum, force, displacement, velocity, frequency, contact area, cycle count, temperature, relative humidity and alignment. Standardization research has identified mechanical, electrical, fabrication and environmental testing as areas requiring more rigorous protocols [5], [17].

8. Mechanical Structure, Contact and Compliance

The mechanical structure determines how actuator energy reaches the triboelectric interface. Important elements include the base frame, guide rails, linear bearings, shafts, couplings, spring/damper elements, load cell, TENG holder, alignment mechanism, adjustable stops and the selected crank, linkage or screw mechanism. A spring can provide controlled compliance according to $F=kx$, reduce impact force, compensate for small alignment errors and improve repeatability. Excessive compliance, however, can introduce unwanted dynamic effects.

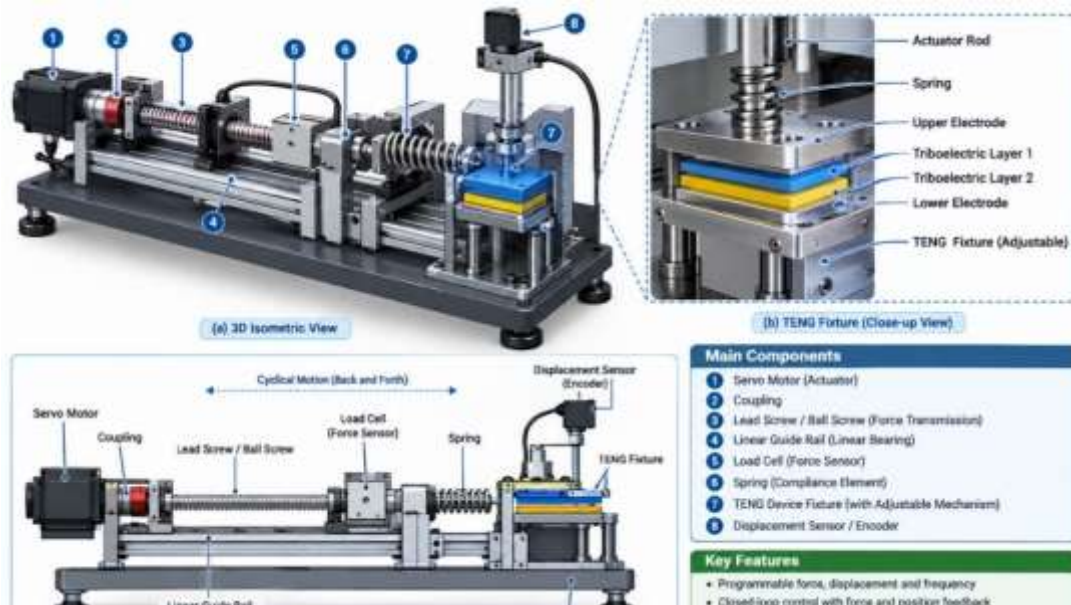


Figure 4. Mechanical structure of a proposed cyclical force generator showing actuator, guide mechanism, load cell, spring, TENG fixture and displacement sensor.

Actual contact area can differ from nominal area because of roughness, elasticity, pressure distribution, misalignment, deformation, contamination and wear. Therefore, accurate alignment and controlled normal load are important when comparing TENG devices. Different applied forces can otherwise make direct comparison of voltage or power misleading [16], [17].

9. Electrical Measurement, Durability and Performance Analysis

TENGs generally produce high voltage and low current with high internal impedance, so the electrical measurement chain should be selected accordingly. A representative system is TENG → voltage/current measurement → rectifier → capacitor → load. Load

power is $PL=VL^2/RL$ and stored capacitor energy is $EC=\frac{1}{2}CVC^2$. Mechanical and electrical measurements should be synchronized to permit evaluation of mechanical input energy, electrical energy, power and efficiency.

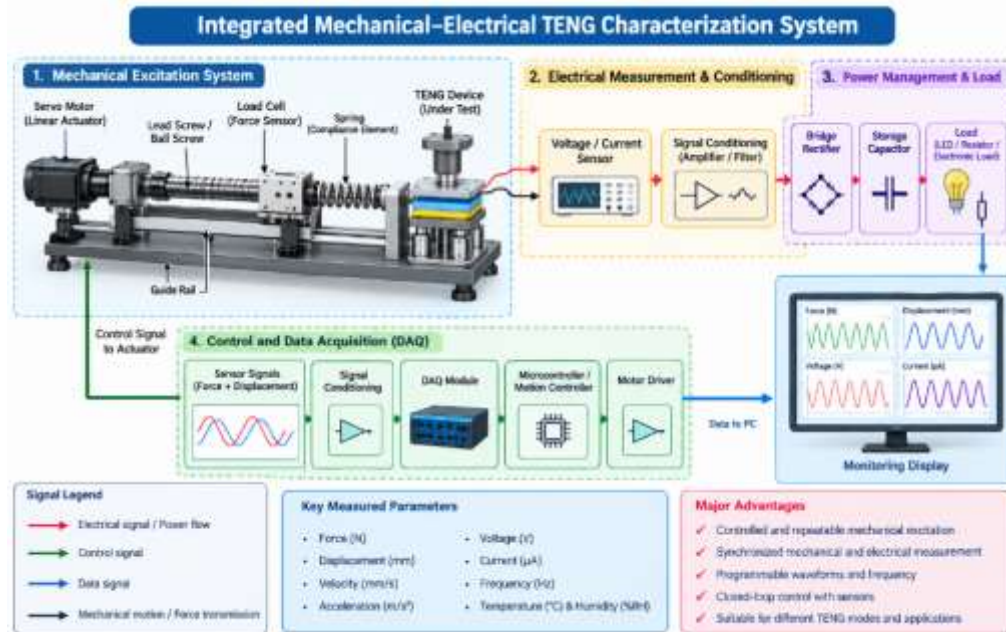


Figure 5. Integrated mechanical and electrical measurement system for TENG characterization.

Long-cycle operation is essential because repeated excitation can reveal surface wear, mechanical fatigue, loss of contact, triboelectric degradation, bearing wear, actuator heating and alignment changes. The number of cycles is $N=f \times t$; for example, 5 Hz operation for one hour produces 18,000 cycles. Recent work on low-wear TENG structures further highlights the importance of friction and wear in long-term reliability [23].

Challenges and Emerging Intelligent Approaches

Major CFG challenges are accurate force control, dynamic effects at higher frequency, surface alignment, friction, mechanical wear, environmental sensitivity, waveform reproduction, sensor synchronization, calibration and standardization. A future system can extend PID control through adaptive algorithms and AI-assisted optimization. If TENG output decreases during operation, measured force, displacement, alignment, humidity and surface condition can be examined to identify the likely cause and adjust excitation. AI has already been identified as an emerging direction for TENG-related systems [13].

Dynamic behaviour becomes increasingly important as frequency rises because inertia, damping and resonance can cause the actual force to differ from the commanded value. Friction can consume mechanical energy and alter the waveform, while repeated contact can change the triboelectric surface. Alignment errors can also change the effective contact area. These effects indicate that a CFG should be characterized as a complete electromechanical system rather than as a motor alone. Calibration of force and displacement sensors, verification of waveform fidelity and periodic inspection of the fixture are therefore essential for repeatable results.

Digital-twin modelling can further represent actuator behaviour, force transmission, displacement, resonance and energy input, while experimental data update the model for optimization. Mechanical regulation of irregular inputs is another emerging direction: rather than applying only constant cyclic motion, irregular environmental inputs can be converted into more stable mechanical excitation for TENG operation [19], [21], [22]. These concepts are retained here in concise form; their detailed conceptual diagrams are omitted to meet the conference page limit.

Research Gap and Proposed Design Framework

The reviewed literature indicates eight closely related gaps: mechanical excitation is often treated as a test condition rather than a controllable subsystem; force, displacement and waveform are not always simultaneously controlled; mechanical input energy is incompletely reported; standardized mechanical platforms are still developing; real-world irregular inputs are difficult to reproduce; mechanical and electrical measurements are not always fully synchronized; intelligent adaptive excitation remains underdeveloped; and there is an opportunity for a dedicated, modular and comparatively low-cost CFG for TENG characterization [16], [17], [21], [22].

A generalized design sequence is therefore: (1) define TENG mode, force, displacement, frequency and contact area; (2) select an actuator; (3) design force transmission using a crank, cam, lead screw, spring, linkage and guide; (4) integrate load-cell, encoder/displacement and environmental sensors; (5) implement a controller and motor driver; (6) provide an aligned, adjustable and replaceable TENG fixture; (7) synchronously acquire $F(t)$, $x(t)$, $V(t)$ and $I(t)$; and (8) calculate mechanical energy, electrical energy, power, efficiency, repeatability and degradation.

The proposed sequence also provides a practical experimental validation plan. First, the unloaded actuator motion should be characterized to verify displacement and frequency. Second, the force sensor should be calibrated over the intended operating range. Third, the mechanical fixture should be tested without the TENG to determine transmission losses, backlash and repeatability. Finally, TENG samples can be tested under repeated force levels and frequencies while mechanical and electrical signals are recorded synchronously. This staged procedure separates mechanical-system errors from TENG behaviour and provides a clearer basis for comparing device performance.

Future Perspectives

Future development can be viewed in five stages: programmable excitation; closed-loop force/displacement control; reproduction of real-world waveforms; AI-assisted optimization; and an intelligent standardized TENG test platform. The long-term objective is a modular system capable of testing different TENG modes under controlled and documented mechanical and environmental conditions [13], [17].

Conclusions

TENG performance is strongly coupled to the mechanical excitation used during characterization. Force, displacement, velocity, frequency, waveform, contact area, alignment and environmental conditions can alter electrical output. Manual excitation remains useful for demonstrations, but controlled actuators and feedback systems provide substantially better repeatability. Among the reviewed approaches, servo- and linear-actuator-based systems offer a practical route to programmable cyclical force generation, while testing machines and tribometers remain valuable for specialized high-accuracy and sliding applications.

A closed-loop CFG integrating an actuator, force sensor, displacement sensor, controller, driver, data acquisition and TENG fixture can convert operator-dependent testing into a measurable electromechanical experiment. Synchronized mechanical and electrical measurements also permit more meaningful assessment of mechanical input energy, efficiency and long-cycle degradation. Future integration of real-world waveform reproduction, adaptive control, AI and digital twins can further improve experimental reliability and automated optimization. A standardized and accessible CFG therefore has strong potential to improve TENG repeatability, comparison and transition toward practical systems [5], [17], [23].

Recommendations

- TENG experiments should report force, displacement, velocity and frequency together with electrical output.
- Controlled programmable excitation should be preferred for quantitative comparison over manual tapping or pressing.
- Force, displacement and electrical signals should be time synchronized through a common acquisition system.
- Temperature, relative humidity and alignment should be documented where they influence the experiment.
- TENG fixtures should provide repeatable contact area and controlled normal loading.
- Long-cycle tests should be included to evaluate wear, fatigue and output degradation.
- Common mechanical excitation and reporting protocols should be developed for inter-laboratory comparison.
- Future CFG platforms should support real-world waveform reproduction and adaptive/AI-assisted optimization.

AI Disclosure:

ChatGPT (OpenAI) was used as an AI-assisted tool for generating and refining selected conceptual diagrams/figures for visual presentation in this paper. The underlying scientific concepts, design decisions, technical content, interpretation, and final verification were performed by the authors. The authors take full responsibility for the accuracy and originality of the scientific content.

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