R&D Reference Report: Actuation & Micro-Scale Biomechanics (Robot Max)

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Executive Summary

Integrating life-like locomotion and organic facial expressions into a 12 cm micro-companion robot, while adhering to a strict weight budget of 80 g and maintaining absolute mechanical silence, rules out standard rotary actuators (miniature servomotors, which are noisy and rigid). This report formalizes the findings of our 2026 physical and technological research on shape memory alloy (SMA Nitinol) actuators, thermal dissipation using hexagonal Boron Nitride (h-BN) filled silicone, passive-walking kinematics driven by center-of-gravity transfer, and underactuated limb/neck architectures.

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1. Metallurgical and Physical Properties of Nitinol (Flexinol)

Nitinol is an intermetallic nickel-titanium (Ni-Ti) alloy exhibiting unique shape memory properties driven by a reversible crystallographic phase transition.

1.1 Martensite $\leftrightarrow$ Austenite Phase Transition

Electrical actuation of the Nitinol wire is achieved via Joule heating, triggering the transition from a low-temperature monoclinic structure (**Martensite**) to a high-temperature face-centered cubic structure (**Austenite**).

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          Heating (Active Contraction, 3.7V - 5V)
Martensite (Flexible) ——————————————————————————————————> Austenite (Rigid, 3-5% Contraction)
        <—————————————————————————————————— Cooling (Passive Return, h-BN)
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For the Max robot, the alloy is specified with an active austenite finish temperature (A_f) of **40°C to 45°C**: * **Lower Bound**: High enough to prevent accidental actuation from human body heat ($\approx 37^{\circ}\mathrm{C}$) or warm ambient environments. * **Upper Bound**: Low enough to minimize the thermal gradient required for passive cooling, thereby maximizing the actuation frequency.

1.2 Mechanical Dimensioning and Specific Power

Nitinol possesses an extraordinary power density ($\approx 100\ \mathrm{W/g}$), allowing it to develop mechanical stresses exceeding 100 MPa. In Max: * A **75 µm** diameter wire (legs and neck) develops an active blocking force of $1.8\ \mathrm{N}$ (capable of lifting 183 g, which is more than twice the robot's total weight). * A **50 µm** diameter wire (upper limbs) develops approximately $0.8\ \mathrm{N}$. * A **25 µm** wire (eye movement) develops $0.2\ \mathrm{N}$.

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2. Thermodynamics and Dissipation: h-BN vs. LMPE Assessment

Because Max's outer shell consists of an RTV silicone skin (a strong thermal insulator of $\approx 0.15\ \mathrm{W/m \cdot K}$), dissipating the heat lost through Joule heating represents a major technological bottleneck.

2.1 Failure Mode Analysis: The Non-Viability of LMPE

Liquid Metal Programmed Elastomers (LMPE), consisting of an eutectic gallium-indium alloy (EGaIn, $\approx 26\ \mathrm{W/m \cdot K}$) suspended in silicone, were evaluated and rejected due to two critical physical failure modes:

1. **Mechanical Sintering and Short-Circuits**: At rest, the EGaIn droplets are isolated by a nanometer-thick gallium oxide ($\mathrm{Ga_2O_3}$) shell. Under cyclic stress from Nitinol contractions and limb flexions, this oxide shell tears. The liquid droplets merge (sintering), forming a conductive path. This short-circuits the bare Nitinol wire, paralyzing the joint.
2. **Intergranular Gallium Corrosion**: Free gallium diffuses into standard metals via grain boundaries. Upon contact with copper (dissipation braids and Flex PCB) or brass (ball-joints), it forms brittle intermetallic compounds ($\mathrm{CuGa_2}$), crumbling electrical connections within days (liquid metal embrittlement).

2.2 Material Solution: Hexagonal Boron Nitride (h-BN) Filled Silicone

The selected alternative uses a nanostructured ceramic filler of **hexagonal Boron Nitride (h-BN)**, commonly referred to as "white graphite."

$$\text{Composite Thermal Conductivity } (\kappa_{\text{composite}}) \approx \kappa_{\text{matrix}} \left(\frac{1 + 2\phi\beta}{1 - \phi\beta} \right) \quad \text{where} \quad \beta = \frac{\kappa_{\text{filler}} - \kappa_{\text{matrix}}}{\kappa_{\text{filler}} + 2\kappa_{\text{matrix}}}$$

By dispersing the h-BN powder (5–15 µm average particle size) at a 60% mass fraction in Ecoflex 00-30 silicone: * The overall thermal conductivity increases from $0.15\ \mathrm{W/m \cdot K}$ to $2.0\ \mathrm{W/m \cdot K}$. * The material remains a **perfect electrical insulator** (dielectric strength $> 20\ \mathrm{kV/mm}$). * The cooling time for a 50 µm wire is reduced from $0.5\ \mathrm{s}$ to $0.15\ \mathrm{s}$, enabling stable oscillation cycles up to $5\ \mathrm{Hz}$ without thermal runaway.

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[Nitinol Wire] ——(Heat)——> [Silicone + 60% h-BN] ——> [Copper Braids] ——> [Titanium Skull]
 (Actuation Source)          (Electrical Insulator,     (Metallic Conduction)     (Passive Hea
                             Thermal Conductor)
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3. Passive Walking Kinematics and Energy Efficiency

Bipedal walking on a 12 cm scale is highly unstable under active classic servo regulation. Max relies on a **double inverted pendulum model coupled with damped pelvic roll**.

3.1 Inverted Pendulum Mechanics and Resonance

The effective length of Max's lower limbs ($L = 35 \text{ mm}$) governs its natural swing frequency:

$$T = 2\pi\sqrt{\frac{L}{g}} \approx 2\pi\sqrt{\frac{0.035 \text{ m}}{9.81 \text{ m/s}^2}} \approx 0.375 \text{ s} \quad \Rightarrow \quad f_{\text{natural}} \approx 2.66 \text{ Hz}$$

- **The Central Actuator (Roll)**: A silent 1.2 g ultrasonic rotary piezoelectric motor (operating at inaudible frequencies $> 40 \text{ kHz}$) drives an eccentric stainless steel camshaft (3 mm offset). This motion induces a gentle pelvic roll of $\pm 4^\circ$, shifting the center of gravity from side to side.
- **The Nitinol Swing**: The leg being lifted experiences zero vertical gravitational load. A 75 µm Nitinol wire of only 0.15 g swings the leg forward with minimal power consumption (a short $\approx 50 \text{ ms}$ pulse).
- **Electro-Permanent Micro-Clutches (MEP)**: As the foot strikes the ground, the knee and hip are immediately locked by a 10 ms pulse sent to a bistable magnetic micro-clutch (MEP). The robot remains upright on its rigid skeleton without drawing current during the stance phase (ZHP - Zero-Hold Power).

3.2 Comparative Energy Analysis

This model allows Max to achieve an outstanding theoretical Cost of Transport (CoT) for a micro-biped:

$$\text{CoT} = \frac{P_{\text{average}}}{M \cdot g \cdot v} \approx \frac{0.05 \text{ W}}{0.080 \text{ kg} \cdot 9.81 \text{ m/s}^2 \cdot 0.06 \text{ m/s}} \approx 0.10$$

In contrast, a classical bipedal robot of this scale using active servomotors requires a constant average power of $\approx 0.6 \text{ W}$ for active balance, which would reduce its battery life on a 1200 mAh Li-S cell from 6 hours to just 45 minutes.

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4. Organic Facial Architecture and Conjugate Linkages

To animate Max's face and upper limbs without adding weight to the skull, the robot uses underactivation and mechanical synergy.

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[Single Dyneema Tendon] ——> [Three-Finger Split] ——> [Passive RTV Springs]
           |
           ▼
[SMA Actuator in Trunk] (0.6g total per arm)
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4.1 Underactuated Upper Limbs

Object gripping relies on a single degree-of-freedom (DoF) mechanical synergy per arm: * The three fingers feature a 0.1 mm flexible carbon-fiber core acting as a return spring. * A single 0.1 mm Dyneema tendon runs through the arm, splitting in the hand to attach to the distal phalanges. * This tendon is pulled by an SMA wire in the trunk. The hand closes adaptively, conforming to the geometry of the gripped object.

4.2 The 3-DoF Helical Neck

To orient the head (pitch, roll, yaw), the neck features a central brass ball-joint and four SMA actuators arranged in a helical pattern (twisted at 15° around the vertical axis): * **Pitch & Roll**: Controlled by simple asymmetrical contraction. * **Yaw (Axial Rotation)**: Controlled by activating diagonal pairs. The helical arrangement converts vertical pull into pure torsional torque, allowing $\pm 15^\circ$ of rotation without any rotary motors.

4.3 Conjugate Eye Movements

Eye saccades require high angular speeds. * Two CMOS OV2640 cameras (eyes) are housed inside 12 mm 3D-printed spheres resting on spherical sockets in the titanium skull. * A Dyneema linkage ties both eyeballs at the back, forcing a synchronous movement (conjugate linkage). * A cross arrangement of four ultra-thin **25 µm** Nitinol wires drives the motion. Drawing only 80 mA, they cool in **30 ms** thanks to the h-BN thermal path, enabling rapid saccades mimicking biological eyes.

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5. Control Topology: CM824 & EIT Sensing

Joint control is achieved without physical encoders, which would add unacceptable weight to the micro-joints.

5.1 "Sensorless" Resistive Feedback

The electrical resistance R of Nitinol varies linearly with its length during transition. The **Cambridge Mechatronics CM824** driver tracks this resistance in real time:

$$R = \frac{V_{\text{measured}}}{I_{\text{measured}}} \quad \Rightarrow \quad \Delta R \propto \Delta L \quad (\text{Deformation})$$

This 100 Hz feedback loop allows the ESP32-S3 firmware to compute precise joint angles without adding physical encoders.

5.2 Electrical Impedance Tomography (EIT) Skin

To complete the proprioceptive loop, a 16-electrode flexible copper array is embedded in the silicone skin. An AD5933 impedance analyzer injects low-current high-frequency ($50\ \mathrm{kHz}$) signals. * **Resolution**: Real-time impedance reconstruction detects skin deformation (human touch, obstacles) with a spatial resolution of **2-3 mm**. * **Dual-use**: The skin acts both as a tactile interface and as a feedback loop to adjust Nitinol contraction force upon physical contact.

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6. Physical & Budget Specifications Summary

Mechanical Module	Actuators	Feedback Type	Mass (g)	Power
Pelvis & Roll	Piezo Cam (1.2g)	Sensorless (Speed)	2.2	<0.2 W (Active)
Legs & Feet	4× 75 µm Nitinol + 2× MEP	EIT + Sensorless	3.5	0.4 W (Pulsed)
Neck & Joints	4× 50 µm Nitinol	Sensorless (CM824)	1.2	0.3 W (Pulsed)
Eyes & Eyelids	4× 25 µm Nitinol + 2× SMA	Conjugate Linkage	0.9	0.15 W (Fast)
Arms & Hands	2× 50 µm Nitinol	EIT Tactile Skin	1.0	0.2 W (Pulsed)
Total Actuation	**17 integrated actuators**	**Zero physical encoders**	**8.8 g**	$\approx 0.45\ \mathrm{W}$ **avg**