Wearable Smart Orthosis System for Detection and Correction of Scoliosis Posture

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***Abstract*—Scoliosis is a spinal abnormality characterized by abnormal curvature and postural imbalance, requiring early detection and non-invasive correction, especially in adolescents. This paper proposes a Wearable Smart Orthosis system integrating digital quantum logic and IoT sensing for real-time detection and automated correction of scoliosis posture. The system employs six sensors (IMU, Accelerometer, FSR, sEMG, Flex Sensor, PPG) for comprehensive condition monitoring and six actuators (servo motor, vibration, air pump, LED, heating pad, EMS) for multi-level therapeutic response. A Finite State Machine (FSM) with five operational states (IDLE, MINOR ALERT, ACTIVE CORRECTION, INTENSIVE CORRECTION, SAFETY MODE) ensures deterministic, priority-based control with PPG-override safety mechanism. The control logic is validated through quantum gate representation (Pauli-X, CNOT, Toffoli) and dual-platform simulation: HDL (Verilog) for hardware validation and C# for microcontroller implementation. This work bridges classical digital design with quantum notation, providing a scalable framework for wearable biomedical device integration.**

***Index Terms*—scoliosis, wearable orthosis, IoT, quantum gates, FSM, Verilog, digital sensors**

I. INTRODUCTION

Scoliosis is a spinal disorder characterized by abnormal lateral curvature and postural imbalance. This condition affects body posture, causes muscle asymmetry, reduces comfort, and limits mobility. Early detection of scoliosis is crucial for gradual and non-invasive posture correction, particularly in adolescent patients.

In recent years, sensor-based electronic systems have rapidly developed for body posture analysis. Wearable technology enables real-time posture monitoring utilizing various physical quantities such as inclination angle, body pressure, muscle activity, and postural sway. To support the correction process, actuators such as vibration motors, heating pads, or automatic brace pressure systems can provide immediate feedback to patients.

This paper proposes a Wearable Smart Orthosis system that integrates digital quantum logic for detection and correction of scoliosis posture. The system combines multi-sensor inputs with intelligent actuator control through Finite State Machine (FSM) logic, validated using both HDL simulation and microcontroller implementation.

II. SYSTEM DESIGN

A. Sensors

The proposed system utilizes six digital sensors for comprehensive posture monitoring. Each sensor measures specific physical quantities and produces digital output (0 = normal, 1 = abnormal) based on research-validated thresholds.

1) IMU (Inertial Measurement Unit):

- **Physical Quantity:** Inclination angle (degrees)
- **Digital Threshold:**
  - 0 (Normal): Inclination angle $< 10°$
  - 1 (Abnormal): Inclination angle $\geq 10°$ [1]

2) Accelerometer:

- **Physical Quantity:** Pelvic and trunk inclination angle (degrees)
- **Digital Threshold:**
  - 0 (Normal): Pelvic/trunk tilt $< \pm 7°$
  - 1 (Abnormal): Pelvic/trunk tilt $\geq \pm 7°$ [2]

3) FSR (Force Sensing Resistor):

- **Physical Quantity:** Contact pressure between orthosis and body
- **Digital Threshold:**
  - 0 (Normal): Balanced pressure distribution
  - 1 (Abnormal): Unbalanced pressure [3]

4) sEMG (Surface Electromyography):

- **Physical Quantity:** Paravertebral muscle activity (mV)
- **Digital Threshold:**

- 0 (Normal): Stable/symmetric RMS EMG value
- 1 (Abnormal): RMS spike or significant asymmetry [4]

5) Flex Sensor:

- **Physical Quantity:** Spinal curvature through resistance (kΩ)
- **Digital Threshold:**
  - 0 (Normal): Resistance ≥ 220 kΩ
  - 1 (Abnormal): Resistance < 220 kΩ [5]

6) PPG (Photoplethysmography):

- **Physical Quantity:** Heart rate (bpm)
- **Digital Threshold:**
  - 0 (Normal): Heart rate 60–100 bpm
  - 1 (Abnormal): Heart rate < 60 or > 100 bpm [6]

B. Actuators

Six actuators provide multi-level therapeutic response. Each actuator performs specific physical actions controlled by digital signals (0 = off, 1 = on).

1) Servo Motor (DC/RC Servo):

- **Physical Action:** Mechanical angle/position correction
- **Digital Control:**
  - 0 (Idle): Servo at neutral position (90°)
  - 1 (Active): Servo moves to correction angle (0°–89° or 91°–180°) [7]

2) Vibration Motor (ERM/LRA):

- **Physical Action:** Haptic notification through vibration
- **Digital Control:**
  - 0 (Off): Motor not vibrating
  - 1 (On): Motor vibrating, warning active [8]

3) Air Pump (Pneumatic Compressor):

- **Physical Action:** Inflation/deflation of pneumatic cushion
- **Digital Control:**
  - 0 (Deflate): Pump off, pressure < 120 kPa
  - 1 (Inflate): Pump active, pressure ≥ 120 kPa [9]

4) LED Indicator (Status Light):

- **Physical Action:** Visual posture status indication
- **Digital Control:**
  - 0 (Green): Good posture, no alert
  - 1 (Red): Abnormal posture, correction needed [10]

5) Heating Pad (Thermal Therapy Element):

- **Physical Action:** Heat therapy for muscle relaxation
- **Digital Control:**
  - 0 (Off): Heating pad off, ambient temperature
  - 1 (On): Heating pad active, 40–45°C [11]

6) EMS (Electrical Muscle Stimulation):

- **Physical Action:** Electrical stimulation for muscle contraction
- **Digital Control:**
  - 0 (Off): EMS inactive, 0 Hz
  - 1 (On): EMS active, 20–50 Hz [12]

III. Digital Logic Design

A. Truth Table

The system maps 6 sensor inputs to 6 actuator outputs, resulting in $2^6 = 64$ possible combinations. Table I shows selected representative states covering all FSM conditions. Descriptions of each state condition follow the table.

TABLE I
Representative Truth Table Entries

No	Sn1	Sn2	Sn3	Sn4	Sn5	Sn6	A1	A2	A3	A4	A5	A6
1	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	1	1	0	1	0	0
3	1	1	0	0	0	0	1	1	0	1	0	0
4	1	1	1	0	0	0	1	1	1	1	0	1
5	1	1	1	1	0	0	1	1	1	1	1	1
6	1	1	1	1	1	0	1	1	1	1	1	1
7	0	0	0	0	0	1	0	1	0	1	1	0
8	1	1	1	1	1	1	0	1	0	1	1	0

Note: Sn1=IMU, Sn2=Accel, Sn3=FSR, Sn4=EMG, Sn5=Flex, Sn6=PPG; A1=Servo, A2=Vib, A3=Pump, A4=LED, A5=Heat, A6=EMS.

State descriptions:

- **No. 1 (IDLE):** All sensors normal (0); all actuators OFF (standby).
- **No. 2 (MINOR ALERT):** One sensor abnormal; system activates vibration/LED/actuator for minimal alert.
- **No. 3–4 (ACTIVE CORRECTION):** Two to three abnormal sensors; active multi-actuator correction mode.
- **No. 5–6 (INTENSIVE CORRECTION):** Four to five sensors abnormal; all actuators ON for maximum correction.
- **No. 7–8 (SAFETY MODE):** PPG abnormal or all sensors abnormal; mechanical actuators disabled, alert/comfort therapy active.

The complete truth table comprising all 64 input–output combinations can be found in the Appendix.

B. Finite State Machine (FSM)

A Finite State Machine (FSM) is a design model that consists of a finite number of states, transitions governed by input events (sensor readings), and actions mapped to each state. The FSM in this smart orthosis system ensures clear, deterministic behavior across all critical postural conditions.

1) **State Definitions**
   - **S0 – IDLE:** All sensors normal. System is in standby; all actuators OFF.
   - **S1 – MINOR ALERT:** One (non-PPG) sensor abnormal. Minimal correction and alert actuators ON.
   - **S2 – ACTIVE CORRECTION:** Two or three abnormal sensors (PPG normal). Multiple actuators for active correction ON.
   - **S3 – INTENSIVE CORRECTION:** Four or five abnormal sensors (PPG normal). All actuators are ON for maximum correction.

- **S4 – SAFETY MODE:** PPG abnormal (or all sensors abnormal). Only comfort/alert actuators ON; mechanical actuators are OFF.

2) **State Transitions**
   - S0 $\rightarrow$ S1: Any single abnormal sensor (PPG normal).
   - S1 $\rightarrow$ S2: Two or three abnormal sensors (PPG normal).
   - S2 $\rightarrow$ S3: Four or five abnormal sensors (PPG normal).
   - Any state $\rightarrow$ S4: PPG abnormal (safety override) or all sensors abnormal.
   - S4 $\rightarrow$ S0/S1/S2/S3: Return based on count and type of abnormal sensors as recovery occurs.
   - Any state $\rightarrow$ earlier state: Fewer abnormal sensors detected; system steps down accordingly.
3) **Outputs per State**
   - **IDLE (S0):** All actuators OFF.
   - **MINOR ALERT (S1):** Vibration/LED and one correction actuator ON.
   - **ACTIVE (S2):** Two to four actuators ON for active correction.
   - **INTENSIVE (S3):** All actuators ON for maximum response.
   - **SAFETY MODE (S4):** Mechanical actuators OFF; only comfort/alert actuators (LED, vibration, heat) ON.
4) **FSM Diagram**
   Figure 1 illustrates the FSM state transitions, with arrows triggered by specific sensor input combinations or a safety override (PPG).

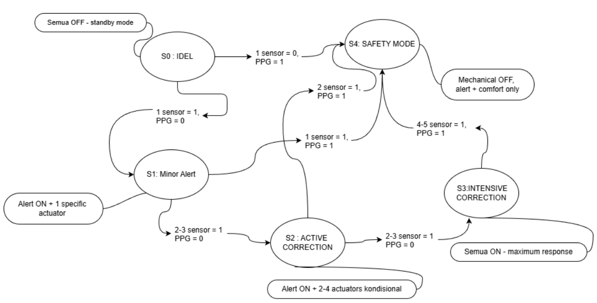

Fig. 1. FSM diagram of the smart orthosis system.

C. Flip-Flop and Matrix Implementation

The digital control logic of the smart orthosis is implemented using JK Flip-Flops, which serve as memory elements to store actuator states at each FSM cycle. The JK Flip-Flop is chosen for its flexibility—supporting Hold, Set, Reset, and Toggle operations that are ideal for multi-state digital designs.

1) **Scenario Selection**
   - The chosen scenario reflects the system responding to IMU, Accelerometer, and FSR sensors detecting abnormal conditions (each is set to 1); all other sensors are normal (value 0).
   - This scenario models a patient with simultaneous postural tilt, abnormal movement, and improper orthosis pressure.
   - The system classifies this as the ACTIVE CORRECTION state (S2) within the FSM, requiring coordinated actuator responses.
2) **Input and Output Mapping**
   - **Input vector:** $|1\,1\,1\,0\,0\,0\rangle$ (IMU, Accel, FSR = 1; others = 0)
   - **J inputs:** $|1\,0\,1\,1\,1\,1\rangle$ (logic to set Servo, Vib, Pump, LED, EMS)
   - **K inputs:** $|0\,0\,0\,0\,0\,0\rangle$ (no reset, all actuators maintain ON when required)
   - **Q (JK FF state):** $|1\,0\,1\,1\,1\,1\rangle$
   - **Output vector:** $|1\,1\,1\,1\,0\,1\rangle$ (Servo=ON, Vib=ON, Pump=ON, LED=ON, Heat=OFF, EMS=ON)
3) **Digital Output Logic (Explanation)**
   - **Servo Motor:** ON (IMU abnormal; posture tilt detected, needs correction)
   - **Vibration Motor:** ON (any abnormal detected; always signal user)
   - **Pump:** ON (FSR abnormal; pressure correction needed)
   - **LED:** ON (any abnormal; indicates system alert)
   - **Heating Pad:** OFF (no muscle asymmetry; no need for thermal therapy)
   - **EMS:** ON (multiple corrections active; EMS provides muscle support)
4) **JK Flip-Flop Selection Justification**
   - For this system, the JK flip-flop is chosen over other types (RS, D, T) because:
     – **No illegal state:** Unlike RS type, JK never enters an ambiguous or forbidden state—even if both J and K are high.
     – **Versatility:** JK supports all four logic functions—Hold, Set, Reset, and Toggle—determined by the combination of J, K, and clock edge input.
     – **Synchronized changes:** JK flip-flop only changes state on clock pulses, making actuator control reliable and preventing glitches.
     – **Direct mapping:** Sensors can directly drive J or K, so active corrections or resets are easily implemented.
   - Each main actuator requiring memory and control (Servo, Pump, EMS) is paired one-to-one with a JK flip-flop.
5) **Digital Matrix Representation**
   - Matrix logic is used to formally represent and structure the digital input-to-actuator mapping.
   - Table II summarizes the JK flip-flop configuration for this scenario:

For this scenario: when $J = 1$ and $K = 0$, the flip-flop sets its output to 1 (ON) at the clock pulse. Thus, Servo, Pump, and EMS switch ON together and remain

TABLE II
JK FLIP-FLOP MATRIX FOR SELECTED SCENARIO

	Servo	Pump	EMS
J input	1	1	1
K input	0	0	0
Q output	1	1	1

ON until the next relevant sensor-driven logic event. This matrix approach allows rapid expansion and modification for additional actuators or sensor combinations in future system development.

IV. QUANTUM REPRESENTATION

A. Bra-Ket Notation

Digital states (both sensors and actuators) are represented using Dirac's bra-ket notation:

- $|0\rangle$ = normal/off; $|1\rangle$ = abnormal/on
- The vector state is built with a tensor product ($\otimes$) of all relevant elements.

B. System State Representation

For the representative scenario (IMU=1, Accel=1, FSR=1, others=0), the states can be described as follows.

Sensor input state:

$$|\text{Input}\rangle = |1\rangle_{IMU} \otimes |1\rangle_{Accel} \otimes |1\rangle_{FSR} \otimes |0\rangle_{EMG} \otimes |0\rangle_{Flex} \otimes |0\rangle_{PPG} \tag{1}$$

Compact: $|\text{Input}\rangle = |111000\rangle$

Actuator output state:

$$|\text{Output}\rangle = |1\rangle_{Srv} \otimes |1\rangle_{Vib} \otimes |1\rangle_{Pump} \otimes |1\rangle_{LED} \otimes |0\rangle_{Heat} \otimes |1\rangle_{EMS} \tag{2}$$

Compact: $|\text{Output}\rangle = |111101\rangle$

Combined (system) state:

$$|\Psi_{\text{system}}\rangle = |\text{Input}\rangle \otimes |\text{Output}\rangle = |111000111101\rangle \tag{3}$$

Decimal: $|\Psi_{\text{system}}\rangle = |3965\rangle_{10}$, total state count $2^{12} = 4096$.

C. Quantum Gate Mapping

Digital logic operations in this system can be mapped to quantum gates:

- **Pauli-X Gate (Quantum NOT):** Flips single qubit; e.g., activating IMU sensor:
$$X_{IMU}|0\rangle = |1\rangle$$
- **CNOT Gate (Controlled-NOT):** Applies NOT to actuator if sensor is ON, e.g.,
$$\text{CNOT}_{IMU \to Servo} : |1\rangle_{IMU}|0\rangle_{Servo} = |1\rangle_{IMU}|1\rangle_{Servo}$$
- **Toffoli Gate (CCNOT):** Multi-sensor logic; e.g., activate EMS only if IMU, Accel, FSR are all abnormal:
$$\text{Toffoli}(|111\rangle_{sensors}|0\rangle_{EMS}) = |111\rangle_{sensors}|1\rangle_{EMS}$$

For the chosen scenario, the mapping uses three Pauli-X gates (sensor activation), four CNOT gates (conditional sensor-actuator coupling), and one Toffoli gate (AND logic for EMS).

This quantum modeling unifies digital logic design (truth tables, JK flip-flop control) with quantum notation, offering an alternative, scalable perspective to describe all possible postural correction scenarios in the smart orthosis system.

V. SIMULATION AND VALIDATION

A. HDL Simulation Results

The HDL (Verilog) simulation validates the digital logic for all major FSM states. Each figure below represents a specific system condition.

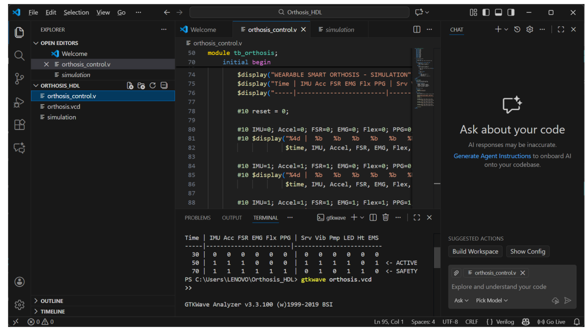

Fig. 2. HDL simulation code — Part 1.

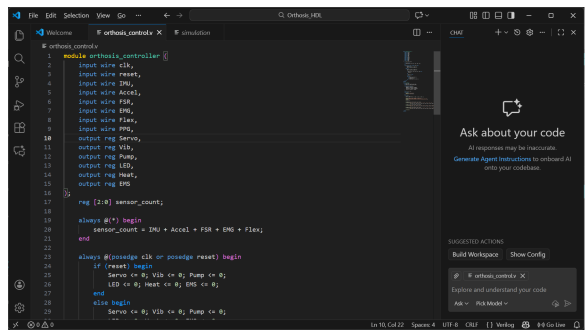

Fig. 3. HDL simulation code — Part 2.

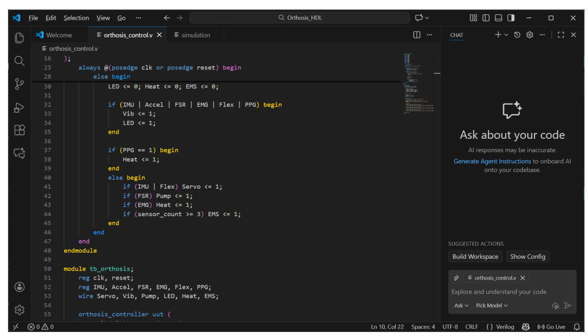

Fig. 4. HDL simulation code — Part 3.

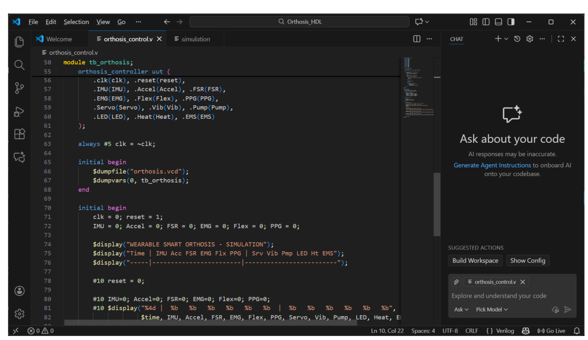

Fig. 5. HDL simulation code — Part 4.

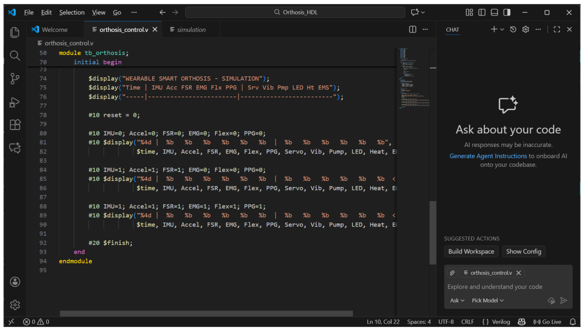

Fig. 6. HDL simulation code — Part 5.

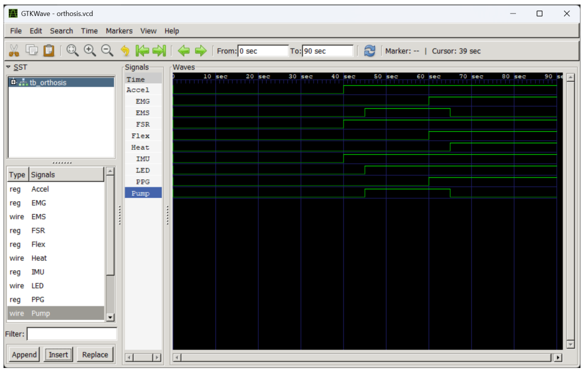

Fig. 7. HDL simulation waveform output.

B. C# Simulation Results

Microcontroller-level logic is validated by simulating the FSM system in a C# console application. Each figure below presents a distinct actuator response for specific input scenarios.

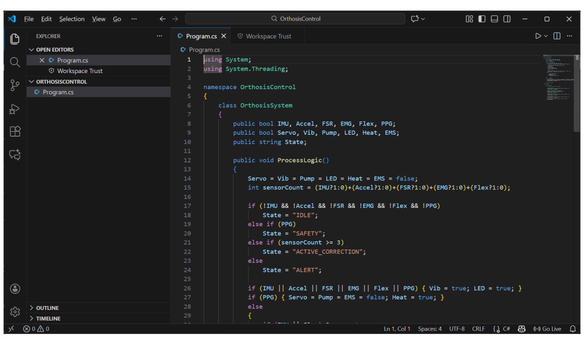

Fig. 8. C# simulation code

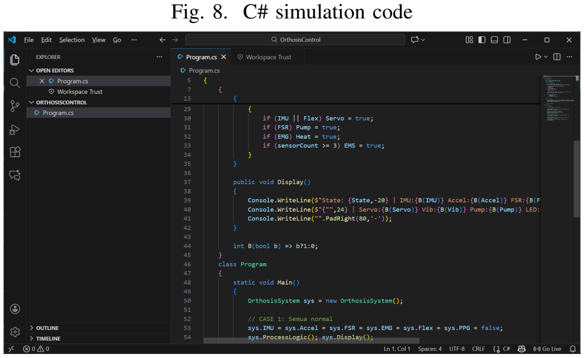

Fig. 9. C# simulation code

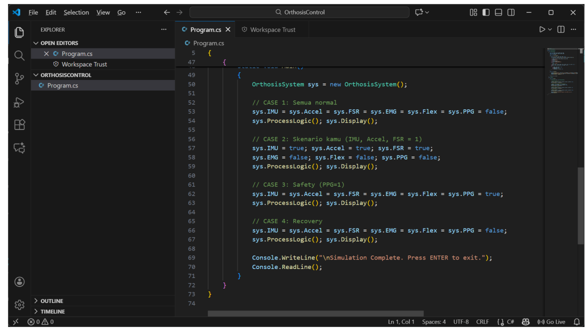

Fig. 10. C# simulation code

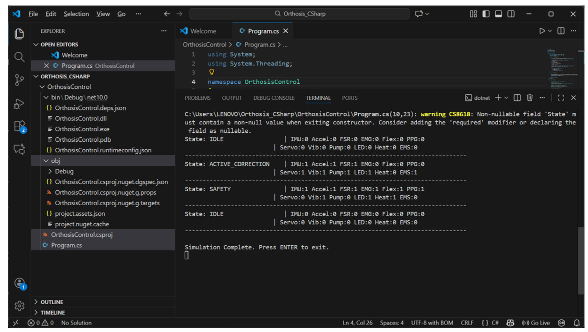

Fig. 11. C# simulation result

VI. Conclusion

This paper presents a Wearable Smart Orthosis system for scoliosis posture detection and correction using digital quantum logic. The system integrates six sensors and six actuators controlled by a 5-state FSM with PPG safety override. Control logic is represented using quantum notation (Bra-Ket) and implemented through Pauli-X, CNOT, and Toffoli gates.

Dual-platform simulation (Verilog HDL and C#) validates the deterministic behavior and correct sensor-actuator mapping across all operational states. This work demonstrates the feasibility of bridging classical digital design with quantum notation for wearable biomedical device development.

Future work includes hardware prototype implementation, clinical validation with scoliosis patients, and integration with IoT cloud platforms for remote monitoring.

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APPENDIX

Table III shows all 64 input-output combinations of the Wearable Smart Orthosis system.

TABLE III
COMPLETE TRUTH TABLE (64 COMBINATIONS)

No	Sn1	Sn2	Sn3	Sn4	Sn5	Sn6	A1	A2	A3	A4	A5	A6	State/Keterangan
1	0	0	0	0	0	0	0	0	0	0	0	0	IDLE - All Normal
2	0	0	0	0	0	1	0	1	0	1	1	0	Heart Alert Only
3	0	0	0	0	1	0	1	1	0	1	0	0	Spine Bend - Servo Correction
4	0	0	0	0	1	1	0	1	0	1	1	0	Spine Bend + Stress
5	0	0	0	1	0	0	0	1	0	1	1	1	Muscle Asymmetry - Therapy
6	0	0	0	1	0	1	0	1	0	1	1	0	Muscle + Stress
7	0	0	0	1	1	0	1	1	0	1	1	1	Muscle + Spine Issue
8	0	0	0	1	1	1	0	1	0	1	1	0	Muscle + Spine + Stress
9	0	0	1	0	0	0	0	1	1	1	0	0	Pressure Issue - Adjust Brace
10	0	0	1	0	0	1	0	1	0	1	1	0	Pressure + Stress
11	0	0	1	0	1	0	1	1	1	1	0	0	Pressure + Spine
12	0	0	1	0	1	1	0	1	0	1	1	0	Pressure + Spine + Stress
13	0	0	1	1	0	0	0	1	1	1	1	1	Pressure + Muscle
14	0	0	1	1	0	1	0	1	0	1	1	0	Pressure + Muscle + Stress
15	0	0	1	1	1	0	1	1	1	1	1	1	Pressure + Muscle + Spine
16	0	0	1	1	1	1	0	1	0	1	1	0	3 Issues + Stress (safety)
17	0	1	0	0	0	0	0	1	0	1	0	0	Movement Alert
18	0	1	0	0	0	1	0	1	0	1	1	0	Movement + Stress
19	0	1	0	0	1	0	1	1	0	1	0	0	Movement + Spine
20	0	1	0	0	1	1	0	1	0	1	1	0	Movement + Spine + Stress
21	0	1	0	1	0	0	0	1	0	1	1	1	Movement + Muscle
22	0	1	0	1	0	1	0	1	0	1	1	0	Movement + Muscle + Stress
23	0	1	0	1	1	0	1	1	0	1	1	1	Movement + Muscle + Spine
24	0	1	0	1	1	1	0	1	0	1	1	0	3 Issues + Stress
25	0	1	1	0	0	0	0	1	1	1	0	0	Movement + Pressure
26	0	1	1	0	0	1	0	1	0	1	1	0	Movement + Pressure + Stress
27	0	1	1	0	1	0	1	1	1	1	0	0	Movement + Pressure + Spine
28	0	1	1	0	1	1	0	1	0	1	1	0	3 Issues + Stress
29	0	1	1	1	0	0	0	1	1	1	1	1	Movement + Pressure + Muscle
30	0	1	1	1	0	1	0	1	0	1	1	0	3 Issues + Stress
31	0	1	1	1	1	0	1	1	1	1	1	1	4 Issues - Intensive
32	0	1	1	1	1	1	0	1	0	1	1	0	4 Issues + Stress (SAFETY)
33	1	0	0	0	0	0	1	1	0	1	0	0	Posture Tilt - Correction
34	1	0	0	0	0	1	0	1	0	1	1	0	Tilt + Stress
35	1	0	0	0	1	0	1	1	0	1	0	0	Tilt + Spine
36	1	0	0	0	1	1	0	1	0	1	1	0	Tilt + Spine + Stress
37	1	0	0	1	0	0	1	1	0	1	1	1	Tilt + Muscle
38	1	0	0	1	0	1	0	1	0	1	1	0	Tilt + Muscle + Stress
39	1	0	0	1	1	0	1	1	0	1	1	1	Tilt + Muscle + Spine
40	1	0	0	1	1	1	0	1	0	1	1	0	3 Issues + Stress
41	1	0	1	0	0	0	1	1	1	1	0	0	Tilt + Pressure
42	1	0	1	0	0	1	0	1	0	1	1	0	Tilt + Pressure + Stress
43	1	0	1	0	1	0	1	1	1	1	0	0	Tilt + Pressure + Spine
44	1	0	1	0	1	1	0	1	0	1	1	0	3 Issues + Stress
45	1	0	1	1	0	0	1	1	1	1	1	1	Tilt + Pressure + Muscle
46	1	0	1	1	0	1	0	1	0	1	1	0	3 Issues + Stress
47	1	0	1	1	1	0	1	1	1	1	1	1	4 Issues - High Intensity
48	1	0	1	1	1	1	0	1	0	1	1	0	4 Issues + Stress (SAFETY)
49	1	1	0	0	0	0	1	1	0	1	0	0	Tilt + Movement
50	1	1	0	0	0	1	0	1	0	1	1	0	Tilt + Movement + Stress
51	1	1	0	0	1	0	1	1	0	1	0	1	Tilt + Movement + Spine
52	1	1	0	0	1	1	0	1	0	1	1	0	3 Issues + Stress
53	1	1	0	1	0	0	1	1	0	1	1	1	Tilt + Movement + Muscle
54	1	1	0	1	0	1	0	1	0	1	1	0	3 Issues + Stress
55	1	1	0	1	1	0	1	1	1	1	1	1	4 Issues - Maximum Response
56	1	1	0	1	1	1	0	1	0	1	1	0	4 Issues + Stress (SAFETY)
57	1	1	1	0	0	0	1	1	1	1	0	1	Tilt + Movement + Pressure
58	1	1	1	0	0	1	0	1	0	1	1	0	3 Issues + Stress
59	1	1	1	0	1	0	1	1	1	1	1	1	4 Issues - Critical State
60	1	1	1	0	1	1	0	1	0	1	1	0	4 Issues + Stress (SAFETY)
61	1	1	1	1	0	0	1	1	1	1	1	1	4 Issues - Emergency Mode
62	1	1	1	1	0	1	0	1	0	1	1	0	4 Issues + Stress (SAFETY)
63	1	1	1	1	1	0	1	1	1	1	1	1	5 Issues - CRITICAL EMERGENCY
64	1	1	1	1	1	1	0	1	0	1	1	0	ALL ABNORMAL - SAFETY MODE

Sn1=IMU, Sn2=Accel, Sn3=FSR, Sn4=EMG, Sn5=Flex, Sn6=PPG; A1=Servo, A2=Vib, A3=Pump, A4=LED, A5=Heat, A6=EMS