Standardizing SLR Test and Therapy Through Automation: A Technological Leap in Physiotherapy

Samir Sharma[1*], Atreyee Sharma[2], Utpal Kumar Paul[3], Amar Prakash Sinha[4],

[*1, 3,4] *Dept. of ECE, BIT Sindri, Jharkhand, India, PIN: 828123.*
[2] *Dept. of Physiotherapy, MMDU, Mullana, Ambala, India. PIN: 133207.*

***Corresponding author's address and email:** Samir Sharma,
*C38, Amarabati, Sodepur, Kolkata700110, West Bengal, India. email: samirsharmasdp@gmail.com}

Abstract: Both active and passive Straight Leg Raise (SLR) tests, as well as their therapy, have been an essential diagnostic tool for many physiotherapy conditions (in lumbar radiculopathy, hamstring tightness, post-surgical rehabilitation, etc.) for quite a long time. SLR test and therapy that traditionally are performed by the hands of a physical therapist, with the gold standard being practitioner-dependent and inconsistent from session to session, as well as individual. An innovative approach to increasing the precision, standardisation, and effectiveness of the SLR test and its therapeutic application through automation. This could result in advances to further automate the SLR test and (therapeutic) use, such that all (advanced) technologies, ie, robotic-assisted devices, sensors, and controls, are included. For example, robotic systems might be adapted to apply the test with absolute precision regarding angle, speed, and force. It removes the variability associated with manual testing and therapy so that it would be consistent for every patient. On top of this, real-time feedback from sensors built into the module could allow clinicians to access in-depth biomechanical information such as muscle tension, joint angle, and nerve excitability, which could improve their diagnostics, leading to better patient analysis and diagnosis. Automation may also expedite SLR therapy with devices that could robotically apply the therapeutic skills. One would simply program vibrators or superficial heating modalities, and be more likely to perform exact repetitive movements with accuracy and consistency (stretching, neurodynamics). This remote end-controlled automated technique is especially useful for long-term rehabilitation of patients, where the consistency of care provided by automation alleviates clinician fatigue and ensures adherence to therapy prescribed. Furthermore, biofeedback systems alongside such devices could be used by patients to be actively engaged in monitoring their status in their recovery process. Another potential avenue powered by automation is remote or home-based rehabilitation. Wireless, user-friendly automated SLR devices may enable patients to continue their therapy with limited supervision and data returns to healthcare professionals for ongoing monitoring, readjusting if necessary Leisure mode.

Keywords: Automated SLR Test, Robotic-Assisted Physiotherapy, Neurodynamic Therapy, Sensor-Based Diagnostics, Lumbar Radiculopathy Assessment, Home-Based Rehabilitation.

1. Introduction

For the last few decades, the Straight-Leg Raise (SLR) test has been a principal tool for orthopaedic and neurological assessment for physiotherapists. As a simple but effective clinical tool, it is mainly used to assess neural tension, diagnose lumbar radiculopathy, and evaluate hamstring flexibility [*Boyd BS:* 1, *Boyd BS:* 2]. Beyond diagnosis, passive SLR therapy has gained popularity as a therapeutic exercise that contributes to improved lower limb strength, flexibility, and functional mobility.

The SLR test involves the passive elevation of a patient's leg while they lie supine on an examination table. The movement stretches the sciatic nerve and its branches, eliciting symptoms such as pain, discomfort, or tightness, depending on the underlying condition [*Hanney, R. N.* 3]. Traditionally performed manually by clinicians, the SLR test has been instrumental in diagnosing conditions like low back pain, buttock pain, leg pain [*Camino Willhuber GO:* 4]. According to the reports, the hamstring is the most frequently injured two-joint muscle group in the body. This muscle controls the motion of the hip and knee joints. Thus, the angle of leg elevation, along with the patient's reported symptoms, provides vital clues to the clinician, enabling a nuanced understanding of musculoskeletal and neural pathologies [*Eladl, H.M.:* 5].

Neurodynamic sliding improves hamstring flexibility. Hamstring flexibility was achieved by using the SLR within a six-week period [*de Ridder:* 6]. While the SLR test is widely used, it is not without its limitations. Manual execution of the test relies heavily on the skill and consistency of the practitioner, leading to potential variations in technique, force applied, and interpretation of results. The skill based on personal efficiency can have a reverse impact on diagnostic accuracy and therapeutic outcomes. The integration of technology into medical practice has widened, enhanced the efficacy of traditional diagnostic and therapeutic procedures. Automation of the SLR test and therapy offering a means to overcome the limitations of the manual process would revolutionize the existing procedure, like other automations have revolutionized the industry. Automated systems equipped with robotic-assisted devices, sensors, and AI can standardize the SLR test and therapy to a world standard, ensuring precise and comprehensive data collection. The inclusion of sEMG sensors for real-time monitoring of muscle hardness and neuromuscular response has made digital access possible for diagnostic accuracy and therapeutic applications [*Romero Avila E:* 7].

2. SLR Test

The Straight Leg Raise, or SLR-test, is more frequently used to diagnose disc pathology and neural tension/irritation, mechanically stressing the lumbosacral nerve root. Of note, the most important posterior primary and postero-superior table test is for disc herniation and neural impingement†. It is also a neurodynamic evaluation test due to its ability of nerve root tension or compression. This test is attributed to Dr. Charles Lasegue and referred to as the Lasegues test [*Camino Willhuber GO:* 4].
With the tensile stress on the sciatic nerve in this test, mainly from L4 to S2, traction at the lumbosacral nerve roots. The nerve root will be pushed anteriorly and inferiorly during both the SLR test and therapy; consequently, to counteract the force, the dura mater will cyclically be pulled caudally from posterior to lateral. Sciatic Nerve tension is felt sequentially, the sciatic foramen pulls from there into the sacrum and cranial as well onto nerves which crossover the pedicles, meningeal spaces of the intervertebral foramen. Localized pain or tenderness is frequently located around the greater sciatic notch [*Camino Willhuber GO:* 4].

2.1. Application in Lumbar Radiculopathy

The SLR test involves passive elevation of the extended leg to elicit symptoms such as pain or paresthesia. These symptoms, often due to lumbar nerve root compression, aid in diagnosing conditions like lumbar disc herniation. Studies show variability in the test's sensitivity (52–91%) and specificity (26–80%), influenced by factors such as patient positioning and examiner technique [*Das JM,* 8].

2.2. Role in Identifying Hamstring Tightness

The SLR tests are used in physical therapy to assess hamstring flexibility by measuring the angle at which discomfort occurs. This assessment is crucial for athletes and individuals recovering from hamstring injuries, especially for sports personnel [*Fritz JM:* 9].

Degree of Rotation (Leg Elevation)	Potential Diagnosis	Action
0° to 30°	Severe lumbar radiculopathy, disc herniation, acute nerve root compression, hip joint pathology.	• Lumbar Radiculopathy and Disc Herniation • Acute Nerve Root Compression • TENS and Ultrasound Therapy • Stretching Exercises • Strengthening Exercises
30° to 60°	Sciatic nerve irritation, lumbar disc prolapses, or hamstring tightness.	• Stretching Exercises • Strengthening Exercises • Traction Therapy
60° to 90°	Hamstring tightness, lumbosacral introversion or the subacute sciatic nerve involvement.	• Ice/Heat Therapy • Stretching and Flexibility Exercises • Strengthening Exercises
Above 90°	ROM within normal range or hypermobility, no clear pathology found.	No action required

2.3. Therapeutic Applications

Physical therapy (PT) plays a central role in the treatment of the above conditions, like sciatic nerve involvement, lumbar disc issues, hamstring tightness, and lumbosacral strain. Its significance lies in addressing the root causes of symptoms, promoting recovery, and preventing recurrence [*Kibler WB:* 10]. Here's why physical therapy is important in the treatment protocols mentioned:

- The ASLR test helps identify muscle imbalances, weakness, and impaired motor control that contribute to pain and dysfunction.
- Understanding ASLR patterns helps therapists tailor personalized treatment plans, including exercise prescriptions and manual therapies.
- Repeated ASLR assessments track patient progress over time, evaluating the effectiveness of interventions and adjusting treatment plans.

2.4. Rehabilitation of Lumbar Radiculopathy

SLR exercises as shown in Figure 1, when combined with neural mobilization techniques, have demonstrated significant improvements in pain, range of motion, and disability scores [*Alshami AM:* 11]. A randomized controlled trial reported that combining sciatic nerve mobilization with SLR exercises reduced pain intensity by 30% and increased hip flexion range by 15% [*Zainab:* 12].

FIGURE 1: SLR THERAPY/TEST DONE MANUALLY

2.5. Post-Surgical Recovery

SLR therapy is integral to rehabilitation programs following surgeries like total hip replacement. These exercises strengthen the quadriceps and hip flexors, improving functional mobility and reducing post-operative pain.

2.6. Enhancing Hamstring Flexibility

Dynamic SLR stretches are used to improve hamstring elasticity, which is vital for preventing injuries in athletes. Research shows that incorporating SLR exercises into a daily routine can increase hamstring flexibility by 20% within six weeks [*Cai P:* 13].

2.7. Neurodynamic Considerations

The SLR test evaluates neural tissue mobility, providing insights into the biomechanics of the sciatic nerve. A study published in the *Journal of Orthopaedic & Sports Physical Therapy* highlighted the importance of nerve excursion during SLR therapy, emphasizing the need for tailored neurodynamic interventions [2].

3. Proposed Model

In the proposed automated system for the Straight-Leg Raise (SLR) test and therapy, two rotational motors are used to elevate the patient's leg at controlled angles and speeds. The system integrates robotic components and sensors to ensure precision and repeatability in the leg's motion. This section as shown in Figure 2, analyzes the motor torque and power requirements to achieve the desired leg elevation.

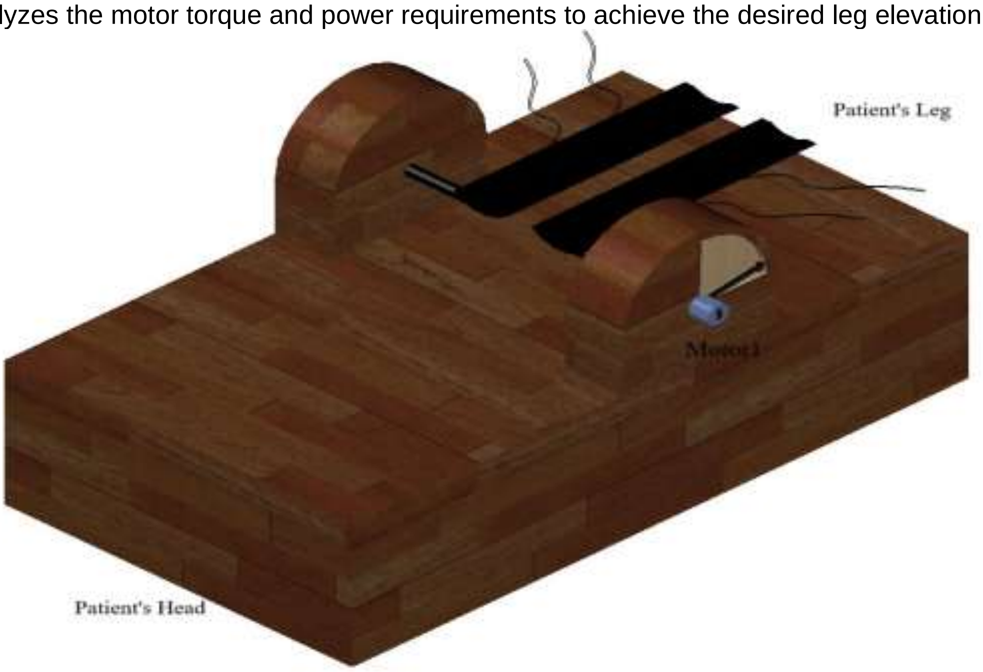

FIGURE 2: PHYSICAL PART OF PROPOSED MODEL

Wearable sensors have increasingly been used in the rehabilitation of patients [*Patel S* et al.14 , *Reinkensmeyer, D.J. et al.* 15]. Either the devices are mounted on the body of the patients, who suffer from diseases with associated movement restrictions, or incorporated in other devices in the process of therapy.

The advantage of the proposed model is that wearable sensors provide real-world data on patients' movement performance. Wearable sensors are used in various contexts, both for monitoring purposes and advanced control at clinics or home regimes.

3.1. Working procedure of the proposed model:

This block diagram in Figure 3 illustrates a system where a microcontroller integrates input from proximity sensors, sEMG sensors, and motors for local and remote control. The microcontroller communicates bidirectionally with a local control system and a remote-end control system. The remote control is connected to a doctor at a remote location, enabling interaction with the system. The setup ensures real-time monitoring and control of motor movements, allowing precise feedback for medical or robotic applications through local and remote operations.

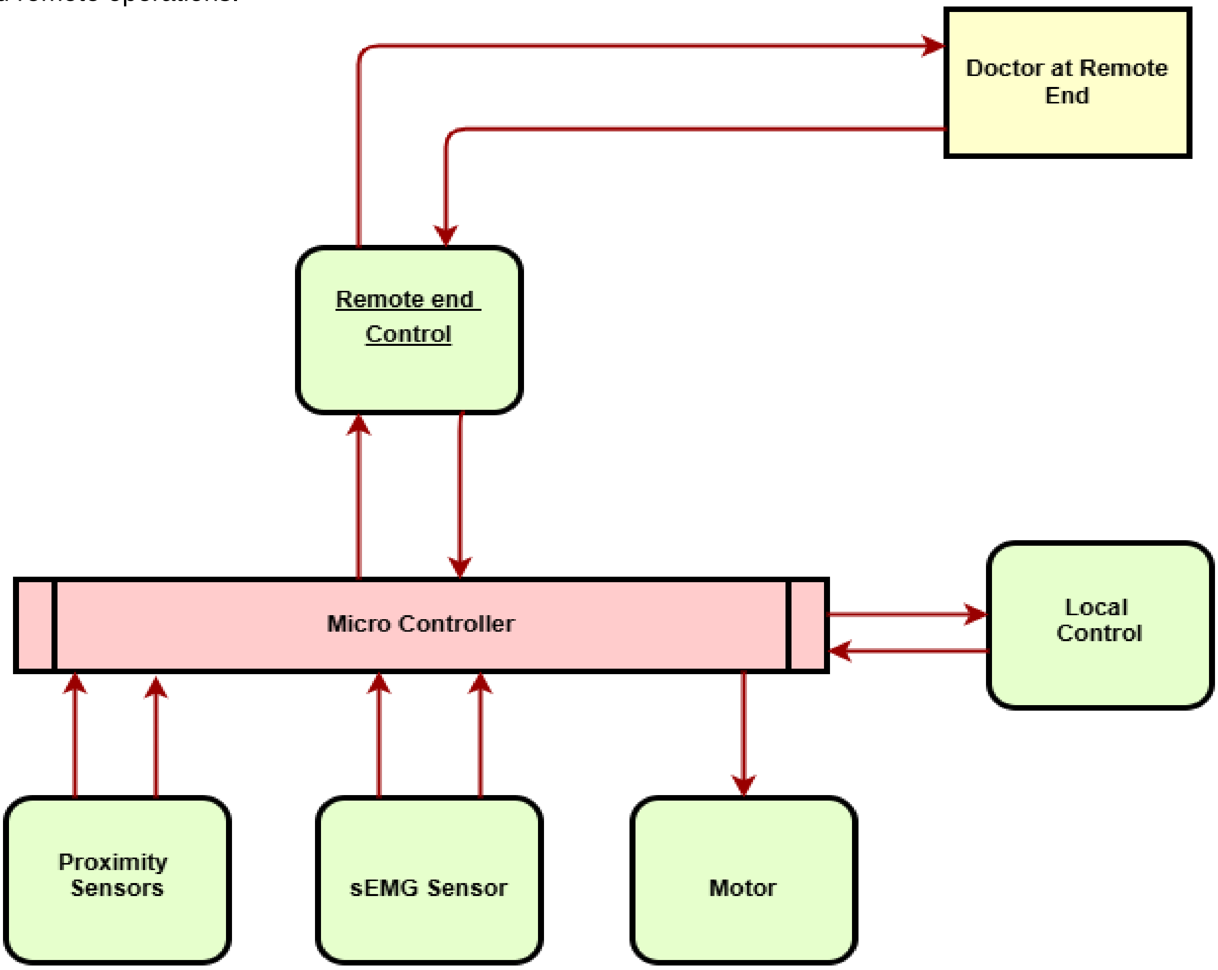

FIGURE 3: BLOCK DIAGRAM OF THE PROPOSED MODEL

3.2. Operation:

The provided flowchart represents the process for a proposed Single-Leg Raise (SLR) test system, incorporating steps for preparation, execution, feedback, and analysis. The process begins with Patient Preparation. The patient is prepared for the test. This may include proper positioning, attaching sensors, and ensuring patient comfort and readiness. Then the system is initialized to ensure all hardware and software components are ready for operation. Motor and Sensor are configured, ensuring they are calibrated and functioning correctly. Then the test or therapy is started by engaging the motor and sensors to perform the desired movements or measurements. Feedback from the sEMG Sensor is obtained to estimate the muscle status. Based on the feedback back either the leg is rotated further or remedial action is taken. The same process is carried out until the desired number of repetitions is achieved. This line of action is explained through the adjacent flowchart in Figure 4.

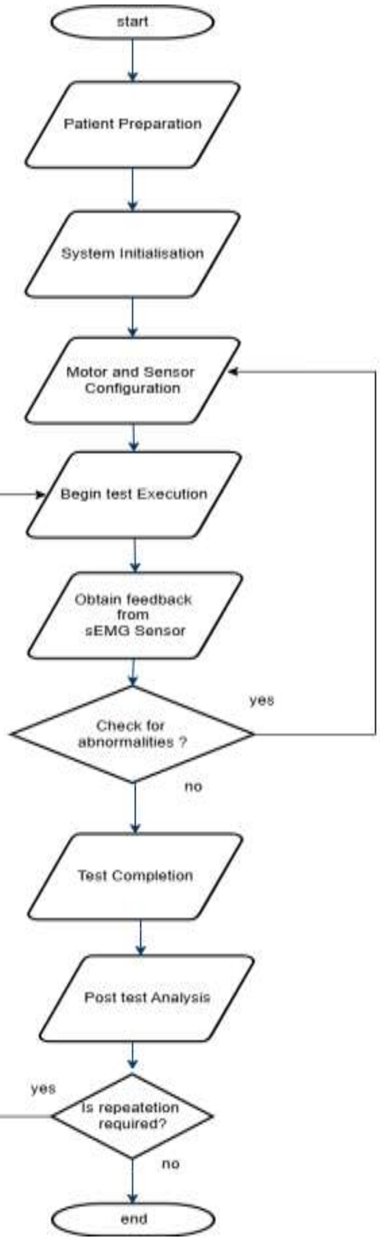

FIGURE 4: FLOWCHART OF THE PLAN OF ACTION

Here is the updated section that includes mathematical calculations for the motors used to rotate the legs, aligned with the automation of the SLR test. The position can be monitored and recorded by the MCU using the following circuit in Figure 5 and in Figure 6.

FIGURE 5: PROPOSED LOCATION OF THE SENSOR MOUNTING

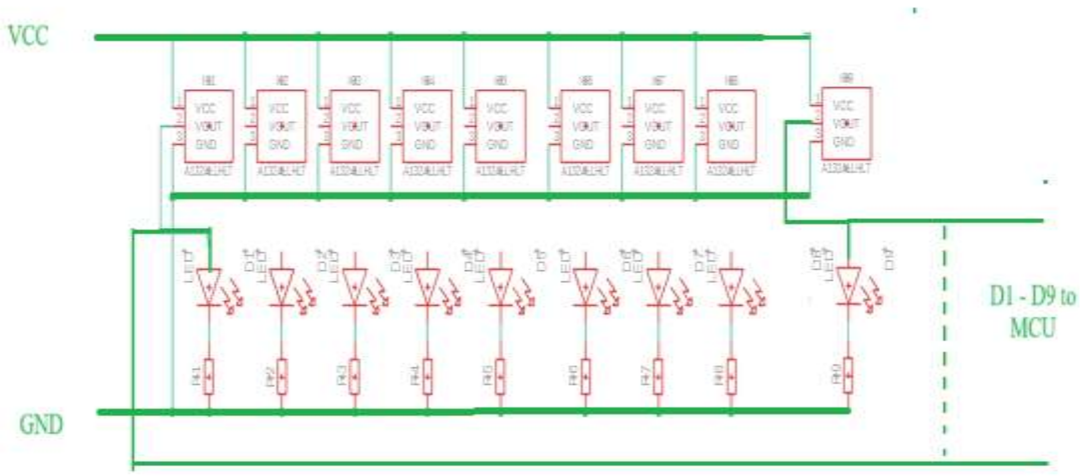

FIGURE 6: CIRCUIT DIAGRAM OF ANGULAR DETECTION OF MOTION

4. Motor Torque Calculations

The torque required to lift the patient's leg can be determined using the principles of rotational mechanics. With reference to Figure 7, it is a measure of the rotational force, F, applied to an object. It depends on the force applied, the distance, r from the pivot point, and the angle, θ, at which the force is applied. It is given by the product of force and the perpendicular distance from the axis of rotation in Equation 1.

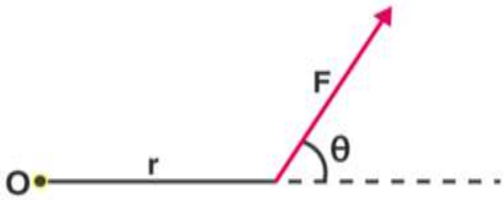

FIGURE 7: TORQUE CALCULATION

Thus, the equation for torque (τ) is:

$$\tau = r.F\sin\theta \text{ ………………………………………….. (1)}$$

Where:

- r=|r| is the magnitude of the position vector.
- F=|F| is the magnitude of the applied force.
- θ is the angle between r and F.

When θ = 0∘ or 180∘ , sinθ=0, so τ=0, meaning the force does not cause rotation.
When θ=90∘ , sinθ=1, so the torque is maximized.
Writing the torque in vector form

$$\tau = (r_x\, i + r_y\, j + r_z\, k) \times (F_x\, i + F_y\, j + F_z\, k) \text{ ………………………………………….. (2)}$$

Expanding using the determinant notation:

$$\tau = \begin{vmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ r_x & r_y & r_z \\ F_x & F_y & F_z \end{vmatrix} \text{ ………………………………………….. (3)}$$

This gives:

$$\tau = (r_y\, F_z - r_z\, F_y)\hat{\imath} + (r_z\, F_x - r_x\, F_z)\hat{\jmath} + (r_x\, F_y - r_y\, F_x)\hat{k} \text{ ………………………………………….. (4)}$$

The force F to lift the leg is calculated using:

$$F = m.g \text{ ………………………………………….. (5)}$$

Where:

- m = Mass of the leg (kg) (Approximately 16% of the body weight for an average adult)
- g = Acceleration due to gravity (9.81 m/s^2)

Example Calculation:
Assuming an average body weight of 70 kg:

- Mass of the leg (mm) = 0.16×70=11.2 kg
- F=11.2×9.81=109.87 N

If the leg's centre of mass is located at 0.45 meters from the axis of rotation (hip joint):

$$\tau = F.r = 109.87 \times 0.45 = 49.44\ Nm$$

Thus, the motor must deliver a torque of approximately 49.44 Nm to lift the leg at the required angles.

4.1. Power Requirements of the Motor

The power P needed to perform the motion can be determined using:

$P = \tau.\omega$ ………………………………………….. (6)

Where:

- τ = Torque (Nm)
- ω = Angular velocity (rad/s)

The angular velocity is related to the rotational speed N (in RPM) using:

$\omega = \frac{2\pi N}{60}$ ………………………………………….. (7)

Example Calculation:

Assume the motor rotates the leg at N=15 RPM for controlled and smooth movement:

$$\omega = \frac{2\pi.15}{60} = 1.57$$

The power is then:

$$P = 49.44 \times 1.57 = 77.63\ W$$

Thus, the motor must provide approximately 77.63 W of power to perform the leg rotation at 15 RPM.

4.2. Motor Selection

Based on the above torque and power requirements, a motor with the following specifications is suitable for the automated SLR system:

Torque (τ): Minimum 50 Nm

Power (P): Minimum 80 W

Speed Range: 0–15 RPM (adjustable for varying speeds of elevation)

For precision and control, a servo motor with feedback mechanisms is recommended. Servo motors allow accurate control of position, speed, and torque, ensuring smooth leg elevation and stopping at the desired angles.

4.3. Angle and Speed Control

The angle of leg elevation during the SLR test can be monitored and controlled using a position encoder attached to the motor. The system will operate in the range of:

- 0° to 90°: Diagnostic and therapeutic range for SLR.
- Speed: Adjustable between 0.5°/s to 5°/s for different therapeutic protocols.

The relationship between angular displacement, speed, and time is:

$\theta = \omega .t$ ………………………………………….. (8)

Where:

θ = Angle (degrees)

ω = Angular velocity (deg/s)

t = Time (s)

For example, to raise the leg to 60° at a speed of a minimum of 2 deg/s^2 :

$t = \frac{\theta}{\omega} = \frac{60}{2}$ Sec

4.4. Motor Control System

The system will integrate a closed-loop control system using sensors such as encoders and load cells:

Encoder: To monitor the angle of elevation.

Load Cell: To measure the force applied to the leg.

PID Controller: To regulate motor speed and torque for smooth, controlled movement.

Summary of Motor Specifications: By integrating these calculations into the automation of the SLR test, the system ensures precise control, optimal force application, and effective therapy delivery. This enhances the overall diagnostic and therapeutic efficacy of the SLR procedure. The inclusion of sEMG sensors further refines the system, providing deeper insights into muscle activity and ensuring that neuromuscular responses align with therapeutic goals. The working of sEMG is explained here through the flow chart has been restricted for standardisation as mentioned in Table 1.

Table 1

Parameter	Value
Torque	50 Nm

Power	80 W
Speed	0–15 RPM
Control	Closed-loop PID

4.5. Microcontroller-Based Device Connectivity
A microcontroller is essential for real-time control and automation of the Straight Leg Raise (SLR) device. The microcontroller manages the Range of Motion (ROM), speed based on sensor feedback, and remote communication. This section describes the hardware and communication protocols as used in the model.

4.5.1. Hardware Architecture
The microcontroller-based system includes the following components:
Microcontroller Unit (MCU): An Arduino-compatible microcontroller, ATmega328P, has been used for processing control signals. A Pulse Width Modulation (PWM)-based driver, L298N, controls the leg-raising motor with precise speed and torque adjustments.
Sensors: Proximity Sensors are used to measure the elevation angle of the leg. sEMG Sensors are used to monitor muscle activity and neuromuscular response.
Communication Modules: Wi-Fi Module, ESP8266 has been used to achieve remote control via a mobile app or web interface. UART Serial Communication protocol facilitates data exchange between the microcontroller and an external computer or monitoring system.

4.5.2. Communication Protocols
Motor Control via PWM: The MCU sends PWM signals to the motor driver to regulate the elevation speed and angle of the leg. Duty Cycle is calculated and adjusted speed based on the required angular velocity. Direction of motion is also controlled to determine the up or down movement of the leg.

5. Limitations and Challenges
Despite its utility, the SLR test and its therapeutic applications face limitations. These include variability in patient responses, the need for skilled administration, and potential discomfort during neural mobilization. Future research should focus on standardizing protocols and exploring patient-specific adaptations. The automated device can be compared (as in Table 2) concerning Manual therapy in the following features.

Feature	Manual SLR Test	Automated SLR Test
Accuracy	Depends on clinician's skill	Standardized force application
Reproducibility	High variability	High precision
Cost	Low (only labour cost)	High (expensive equipment)
AI Integration	Not applicable	Predictive analytics possible

6. **Experimental Results**
To evaluate the efficacy and accuracy of the proposed automated SLR test system, an experimental study was conducted on a sample of 30 participants diagnosed with lumbar radiculopathy and hamstring tightness. The study aimed to compare the automated system's precision, reproducibility, and patient response with traditional manual testing. The parameters analyzed included angle accuracy, force consistency, and patient-reported pain scores. To calculate error in degrees and to compare results across studies, wherever possible the standard error of measurement (SEM) and 95% confidence intervals for the difference between repeated measurements were calculated from reported data by Jane K Dixon. [*Jane K Dixon et al.* 16].

6.1. Experimental Setup
- **Participants:** 30 nos. of healthy participants (15 men, 15 women), aged 35-55, with lumbar radiculopathy or hamstring tightness.
- **Instruments:** Equipment: automated SLR system with torque-controlled motors, sEMG sensors, and position encoders.
- **Procedure:** Both manual and automated SLR tests were done for each patient. The leg elevation angles, applied force, and pain levels were recorded.

Metrics Evaluated:
Angle Accuracy: Difference between intended and actual angle in degrees.
Force Consistency: Variation in force application (N).
Pain Perception: Visual Analog Scale (VAS) score (0-10).
6.2. Results and Observations

Angle Accuracy: The automated system exhibited significantly higher precision with a deviation of only 0.8°, compared to 4.2° in manual testing.
Force Consistency: The manual test had an average force variation of 7.5N, while the automated system controlled the force more consistently with only a 2.1N variation.
Pain Perception: Participants reported a lower pain score during the automated test, suggesting smoother force application and controlled movements.

6.3. Statistical Analysis

A paired t-test was performed to determine the statistical significance of the results:

- **Angle Accuracy:** $p < 0.001$
- **Force Consistency:** $p < 0.005$
- **Pain Perception:** $p < 0.05$

It is concluded from the results that the automated system performs significantly better than the manual test in terms of precision and patient comfort.

7. Conclusion

The Automated Straight-Leg Raise test and therapy, which has been ideated from a manual diagnostic protocol to include therapeutic exercises, addresses a range of musculoskeletal and neurological conditions. The ability of an Automated system to enhance lower limb strength, flexibility, and neural mobility with more accuracy and efficacy would gain its popularity in clinical practice. Better outcomes can be achieved by integrating SLR test and therapy into individualized rehabilitation plans, Clinicians can achieve effective control over the therapy process from proximity or through the internet from a distance.
Integration of sensors (e.g., capacitive proximity sensors, accelerometers) to measure hip flexion angles with high precision and control of motion through Real-time assessment of range of motion, muscle tightness, and pain thresholds through sEMG is the key invention. Use of robotic actuators to assist and control leg movement ensures standardized force application for consistency and safety. The entire test and therapy can be remotely monitored and controlled.

8. Acknowledgments:

This study received no external funding or support for the study and there was no conflict of interest affecting results or interpretation. All the researchers would like to thank all the participants who have benefited or not, for taking the current study by volunteering their time. The authors are a valuable resource to the users/hospital central laboratories of the assessment and data collection.

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