Biomechanical Precision Assessment of Trikonasana Through Trigonometric Modelling and Goniometric Measurement for Injury Prevention

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ABSTRACT

This study evaluates the accuracy of a Cosine Law–based geometric method for estimating joint angles during *Trikonasana* (Triangle Pose) and compares it with conventional goniometric measurements. The research involved 30 adolescents aged between 13 and 19 years, each of whom performed the Trikonasana pose while their body positions were analyse Joint angles at the shoulder, hip, and knee. Adolescent participants from Chengalpattu, India. Angles were calculated using triangle geometry derived from body segment positions and statistically compared with goniometer readings using descriptive statistics and independent samples *t*-tests. The Cosine-based method demonstrated mean values closely aligned with goniometric measurements for the shoulder (60.16° vs. 60.32°), hip (59.20° vs. 59.28°), and knee (60.64° vs. 61.10°). Independent samples *t*-tests revealed no statistically significant differences between the two methods across all joints ($p > 0.05$), with mean differences remaining below 1°. These findings indicate strong agreement between the Cosine Law approach and standard clinical measurements, supporting its reliability for ensuring proper alignment and contributing to injury prevention in yoga practice. The proposed method offers a non-invasive and mathematically robust alternative for posture analysis in yoga instruction, rehabilitation, and biomechanical research.

1.INTRODUCTION

Yoga has grown rapidly in India and worldwide, becoming a widely practiced mind–body discipline for promoting physical, mental, and spiritual well-being. In India, participation continues to increase due to AYUSH initiatives, expanding yoga education, and rising public awareness. Globally, more than 300 million people currently practice yoga, reflecting the need for scientific approaches to ensure effectiveness and safety (Zhang et al., 2021).Although yoga is generally considered safe, injuries can occur. Research shows that yoga-related injury prevalence ranges from 4.6% to 35%, depending on the type of practice, frequency, and individual alignment (Penman et al., 2012; Park et al., 2016). Commonly affected regions include the knee, hip, and hamstring muscles, often due to alignment errors, excessive stretching, or overuse (Cramer et al., 2018; Fishman et al., 2009). Indian practitioners may also present unique anatomical and lifestyle characteristics, underscoring the need for population-specific biomechanical evaluations. Accurate measurement of joint angles plays an important role in yoga therapy, rehabilitation, and sports science. It is essential for assessing posture alignment, range of motion, and mechanical stress on joints and soft tissues. Traditionally, clinicians use a goniometer to measure joint angles. Recently, cosine-law–based angle estimation has emerged as a mathematical and objective approach that can be integrated into digital tools, motion analysis systems, and research settings. However, limited research has compared goniometric measurements with cosine-law–derived angles, particularly among Indian yoga practitioners. Establishing agreement between these two methods is crucial for standardizing biomechanics protocols, improving clinical accuracy, and strengthening yoga-related research methodologies. This study aims to fill this gap by examining the accuracy and precision of goniometric and cosine-derived measurements in yoga-based postures. Understanding these measurement relationships will contribute to better posture assessment, enhance safety, and support evidence-based yoga therapy practices in India[1-5]Yoga is increasingly recognized not only as a spiritual practice but also as a therapeutic tool for physical and mental well-being. *Trikonasana*, or Triangle Pose, is a foundational standing posture that emphasizes lateral flexion, balance, and alignment. Accurate measurement of joint angles during this pose is essential for:

1.Ensuring proper alignment 2. Preventing injury, 3. Enhancing therapeutic outcomes, particularly for individuals with respiratory conditions such as asthma and other disease Traditional assessment methods rely on visual observation or goniometric tools. This study introduces Cosine Law as a complementary method to evaluate joint angles mathematically, offering a new dimension to posture analysis. This study presents a novel comparative approach to measuring joint angles in *Trikonasana* by integrating Cosine Law calculations with Goniometric techniques. By analysing the alignment and angular relationships of key joints such as the shoulder, hip, and knee—this research offers a more nuanced understanding of posture execution, especially in therapeutic contexts like asthma management. The dual method evaluation not only enhances the accuracy and reliability of joint angle measurements but also bridges the gap between mathematical modelling and clinical practice. Cosine Law provides a geometric framework for understanding limb positioning, while goniometry offers practical, real-time assessments. Together, they form a robust toolkit for yoga instructors, physiotherapists, and researchers aiming to optimize posture alignment and safety.

2.LITERATURE REVIEW

2.1 Several studies have explored the relationship between body mechanics and yoga postures:

Sudhan et al.(2021) The placement of the center of gravity (CoG) which reflects the distribution of full body weight—is a critical factor in maintaining postural stability during yoga asanas. Sudhan et al.(2025) propose a simulation-based modeling approach to analyze the biomechanical effects on specific joints and muscle groups during the execution of Utkatasana (Chair Pose). By integrating kinematic and kinetic parameters, the model aims to quantify the mechanical load and muscular activation patterns required to sustain the posture, offering insights into balance control, joint stress distribution, and muscular coordination .Cadoret et al. (2018) examined the role of motor proficiency and cognitive ability in early academic achievement, highlighting the importance of precise movement analysis.Jain & Singhai (2024) reviewed academic stress and its psychological impact, emphasizing the role of physical activity, including yoga, in stress reduction. Yli-Piipari et al. (2024) demonstrated that physical activity improves stress load, recovery, and academic performance, reinforcing the value of biomechanical precision in therapeutic movement. However, few studies have compared mathematical modeling techniques like Cosine Law with traditional tools such as goniometers in yoga posture analysis. This research aims to fill that gap [6-13].

2.2 Literature Review Table – Mathematical / Biomechanical Modelling of Trikonasana

Authors (Year)	Focus of Study	Methods / Mathematical Models	Key Findings / Relevance to Trikonasana
Baum et al. (2022)	Joint and limb loading during Triangle Pose; influence of stance width	3D motion capture, force-plate analysis, inverse dynamics	Wider stance increases leading-leg loading; provides joint-moment data.
Kumar et al. (2018)	Musculoskeletal modelling of Trikonasana	Rigid-body modeling, motion capture, inverse dynamics	Validated pipeline for estimating joint torques and muscle activity.
Devaraju et al. (2019)	Mathematical EMG analysis during yoga postures	EMG processing (time-frequency transforms, normalization)	Provides EMG-analysis methods for muscle-activation modelling.

Norozpoursigaroodi et al. (2023)	Mechanical equilibrium modeling for yoga postures	Static equilibrium equations, free-body diagrams	Rigid-body models for estimating joint forces and stability.
Whissell et al. (2021)	Lower-limb biomechanics across yoga postures	Motion capture, EMG, joint-angle analysis	Normative kinematic and activation patterns for simulations.
OpenSim Case Studies (2020–2024)	Muscle-force estimation in complex poses	Inverse kinematics/dynamics, static optimization	Reliable per-muscle force estimates for Trikonasana.
COP/Balance Measurement Reviews (2019–2023)	Validity of balance metrics in asymmetric stances	Force-plate COP analysis, reliability metrics	Standardized methods for evaluating postural control.
Computer-Vision Yoga Models (2022–2024)	Automated joint-angle detection for alignment analysis	2D/3D pose-estimation algorithms	Provides kinematic inputs for large-scale modeling.

Table 1. Literature Review Table

A major research gap in Trikonasana biomechanics is the lack of integrated EMG-driven Open simulations combined with force-plate–based inverse dynamics, which would enable subject-specific muscle-force estimation with reduced optimization assumptions; applying validated EMG normalization procedures such as those proposed by Devaraju remains essential before driving such models. Additionally, parameter-sensitivity and uncertainty analyses—including Monte-Carlo or Bayesian inference on variables such as segment mass distribution, marker placement error, and EMG normalization—are rarely performed, despite their importance for quantifying reliability in joint-load estimations. Another significant gap is the absence of Finite Element (FE) modelling of spinal segments under Trikonasana-specific lateral-flexion and rotation loads, which would allow detailed assessment of vertebral and disc stress arising from the joint torques computed through inverse dynamics. Similarly, dynamic-balance modelling remains underexplored; advanced centre-of-pressure (COP) analysis, inverted-pendulum models, and multi-segment stability metrics have not yet been systematically applied to Trikonasana despite validated COP-reliability protocols in the balance literature. Finally, the field lacks large-scale datasets generated through automated computer-vision **(CV)** key point extraction and IMU-based motion capture, which could provide normative kinematic and kinetic profiles across age groups and skill levels, supporting more robust modelling, machine learning, and clinical applications[14-21].

3.METHODOLOGY

3.1 Kinematic Execution of Trikonasana (Triangle Pose)

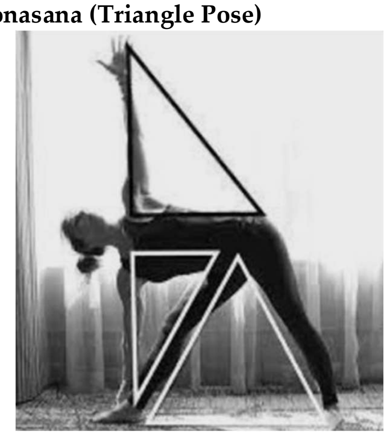

Fig.1 Kinematic Execution of Trikonasana

To perform Trikonasana, begin standing upright in Tadasana, then step your feet 3–4 feet apart, turning the right foot outward 90° and the left foot slightly inward; raise your arms to shoulder height so they form a straight horizontal line, then shift your hips to the left and reach the right hand forward, lowering it toward the shin, ankle, or floor while the left arm extends vertically upward, keeping both legs straight and the chest open; turn your head to look at the top hand if comfortable, maintain steady breathing, and hold the posture before returning upright and repeating on the opposite side. This asana creates clear geometric body lines such as trunk inclination, hip alignment, and shoulder orientation that correspond well to both cosine-derived angular estimations and manual goniometer measurements, making it highly suitable for biomechanical assessment, posture analysis, and yoga-based movement research[22-23].

3.2 Study Design and Methodological Procedures

This study was conducted to analyze the biomechanical impact of Trikonasana (Triangle Pose) on lower limb joints in young adolescents. A total of Thirty healthy participants, aged between 13 to 19 years, were selected for the study. All participants were physically active and capable of performing yoga postures safely under supervision. Informed consent was obtained from guardians prior to participation .Each participant performed Trikonasana in a controlled laboratory environment equipped with a system. Reflective markers were placed on anatomical landmarks to track joint movement and body alignment in real time. The system recorded data across both the sagittal and frontal planes, allowing for a comprehensive analysis of ankle joint behaviour [24-27].

3.3 Geometric Estimation of Joint Angles in Trikonasana Using Cosine Law Principles

The cosine method was applied to calculate joint angles for thirty samples, each representing a distinct execution of Trikonasana, with measurements focused on three primary joints: the shoulder (A), hip (B), and knee (C). Angular values were obtained using the Law of Cosines, expressed through the formulas:

- $a^2 = b^2 + c^2 - 2bc \cdot cos(A)$
- $b^2 = a^2 + c^2 - 2ac \cdot cos(B)$
- $c^2 = a^2 + b^2 - 2ab \cdot cos(C)$

These equations relate the lengths of the sides of a triangle to its internal angles and were used to determine joint alignment when direct measurement tools were not practical. For the sample calculation, a triangle with sides $a = 33\ cm$, $b = 31.5\ cm$, and $c = 31.5\ cm$ was used. Substituting these values into the cosine formula produced an angle A of 63.17°, and angles B and C of 58.42°, demonstrating precise estimation of joint configuration. This trigonometric approach provided consistent, repeatable calculations across all thirty samples, supporting reliable biomechanical assessment of Trikonasana and helping identify alignment patterns important for preventing strain and promoting safe, long-term yoga practice.

Sample Selection

Thirty samples were selected, each representing a unique execution of Trikonasana. Measurements were taken for three joints:

Where a,b,c – Represent limb segment lengths. **A**(α): Shoulder angle **B**(β): Hip angle **C**(γ): Knee angle

Measurement Techniques

Cosine Law:

Applied using the formula:

Cosine Law Triangle Angle Calculation Sample I

By the Law of Cosines:

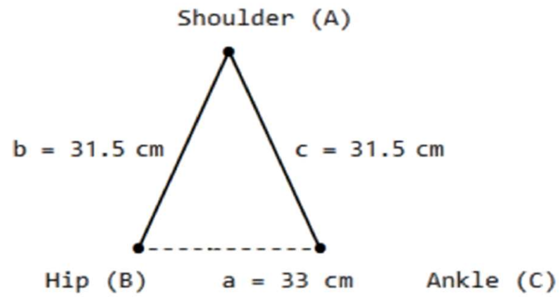

Fig.2 : Triangle with sides a = 33 cm, b = 31.5 cm, c = 31.5 cm

Given:
Side a = 33 cm: b = 31.5 cm : c = 31.5 cm Substituting in the cosine law:
Angle A Calculation Using formula: $a^2 = b^2 + c^2 - 2bc \cdot \cos(A)$
$33^2 = 31.5^2 + 31.5^2 - 2(31.5)(31.5) \cdot \cos(A)$
$A = 63.17°$
Angle B Calculation Using formula: $b^2 = a^2 + c^2 - 2ac \cdot \cos(B)$
$31.5^2 = 33^2 + 31.5^2 - 2(33)(31.5)\ \cos(B)$ $B = 58.42°$
Angle C Calculation Using formula: $c^2 = a^2 + b^2 - 2ab \cdot \cos(C)$
$31.5^2 = 33^2 + 31.5^2 - 2(33)(31.5) \cdot \cos(C)$
$C = 58.42°$
Using Cosine Law to Find Angles of a Triangle Sample II
Given : Side a = 36 cm; b = 36 cm; c = 30 units
We are using the another way Cosine Rule to find the angles A, B, and C
The angles A, B, and C were calculated using the Law of Cosines by substituting the measured limb lengths into the required formulas. Angle A was calculated using the formula $\cos A = (b^2 + c^2 - a^2) / 2bc$, and substituting $36^2 + 30^2 - 36^2$ and $2 \cdot 36 \cdot 30$ gave 900 / 2160, resulting in $A = \cos^{-1}(0.4167) \approx 65.37°$. Angle B was calculated using the formula $\cos B = (a^2 + c^2 - b^2) / 2ac$, which produced the same ratio 900 / 2160, giving $B = \cos^{-1}(0.4167) \approx 65.37°$. Angle C was calculated using the formula $\cos C = (a^2 + b^2 - c^2) / 2ab$, and substituting $36^2 + 36^2 - 30^2$ and $2 \cdot 36 \cdot 36$ gave 1692 / 2592, resulting in $C = \cos^{-1}(0.6528) \approx 49.24°$. These steps show how the cosine law is used to determine accurate joint angles from limb segment lengths.

3.4. Goniometric Analysis of Biomechanical Angles During Trikonasana:

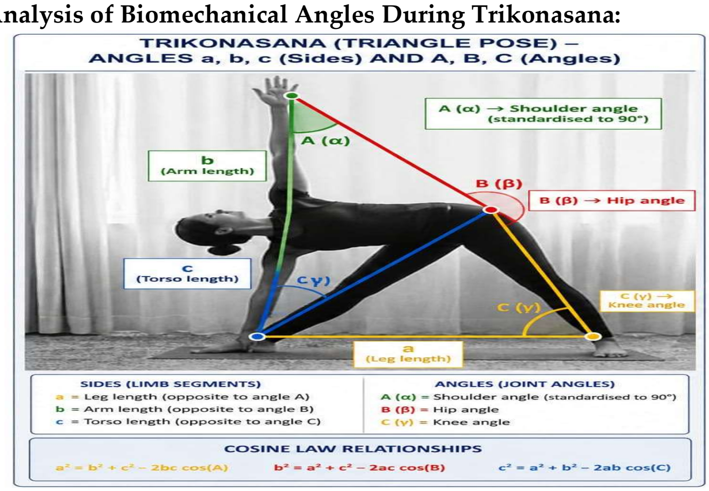

Fig.3A : Triangle with Goniometric Analysis of Biomechanical Angles

The goniometer was used to obtain direct, manual measurements of joint angles during the execution of Trikonasana. It Fig.3A & 3B show that measured the angular positions at the shoulder (A), hip (B), and knee (C) while participants held the final posture, ensuring high accuracy in static alignment assessment. To maintain consistency, readings were taken only after participants achieved a stable, fully aligned position, reducing errors caused by movement transitions or postural adjustments.

Fig.3B : Triangle with Goniometric Analysis of Biomechanical Angles

The device's axis was carefully aligned with key anatomical landmarks—such as the acromion for the shoulder, the greater trochanter for the hip, and the lateral epicondyle of the knee—to promote measurement reliability and minimize inter-observer variability. All measurements were recorded by trained assessors following standardized procedures, and each angle was verified at least twice to ensure precision and repeatability. Beyond supporting biomechanical research, the use of goniometric assessment also contributes to safer yoga practice by helping identify misalignments that may increase the risk of strain or long-term injury. By monitoring joint positions accurately, practitioners and instructors can make informed adjustments, thereby promoting correct technique, preventing overuse issues, and supporting lifelong, injury-free engagement in yoga [28-32].

4.RESULTS

4.1 Summary of Trigonometric and Goniometer Angle Measurements

Table 2 presents the comparison between cosine-derived (trigonometric) angles and goniometer-measured angles for 30 observations. The analysis revealed a high level of agreement between the two measurement methods. The mean absolute differences for the Shoulder (A), Hip (B), and Knee (C) angles were found to be minimal, indicating strong measurement consistency.

S.No	**Cosine A°**	**Cosine B°**	**Cosine C°**	**Gonio A°**	**Gonio B°**	**Gonio C°**	**A Diff**	**B Diff**	**C Diff**	**Accuracy**
1	63.2	58.4	58.4	64.0	58.0	58.0	0.8	0.4	0.4	Correct
2	65.4	65.4	49.2	64.8	65.0	50.0	0.6	0.4	0.8	Correct
3	62.7	65.9	51.3	63.0	64.0	52.0	0.3	1.9	0.7	Deviation
4	70.7	67.7	41.5	71.0	68.0	42.0	0.3	0.3	0.5	Correct
5	72.2	75.9	31.9	72.0	76.0	32.5	0.2	0.1	0.6	Correct
6	65.1	67.3	47.6	64.5	67.0	48.0	0.6	0.3	0.4	Correct
7	63.2	79.2	37.6	62.9	80.0	38.0	0.3	0.8	0.4	Correct
8	53.1	65.4	61.5	53.5	65.0	62.0	0.4	0.4	0.5	Correct
9	58.7	72.4	48.9	59.0	71.5	50.0	0.3	0.9	1.1	Near
10	44.3	47.3	88.4	45.0	48.0	87.0	0.7	0.7	1.4	Near
11	57.5	76.3	46.2	58.0	75.5	47.0	0.5	0.8	0.8	Correct
12	41.4	41.4	97.2	42.0	42.0	98.0	0.6	0.6	0.8	Correct

S.No	Cosine A°	Cosine B°	Cosine C°	Gonio A°	Gonio B°	Gonio C°	A Diff	B Diff	C Diff	Accuracy
13	53.1	62.3	64.6	53.5	62.0	65.0	0.4	0.3	0.4	Correct
14	57.0	64.3	58.7	57.5	64.0	59.0	0.5	0.3	0.3	Correct
15	73.4	48.2	58.4	72.5	49.0	59.0	0.9	0.8	0.6	Near
16	31.0	34.6	114.4	32.0	35.5	115.0	1.0	0.9	0.6	Near
17	39.6	44.4	96.1	40.0	45.0	97.0	0.4	0.6	0.9	Near
18	60.0	60.0	60.0	60.0	60.0	60.0	0.0	0.0	0.0	Correct
19	54.5	63.0	62.5	55.0	63.0	63.0	0.5	0.0	0.5	Correct
20	57.1	63.0	60.0	57.5	63.0	60.5	0.4	0.0	0.5	Correct
21	106.3	36.9	36.9	107.0	38.0	38.0	0.7	1.1	1.1	Near
22	61.0	73.6	45.4	61.5	72.5	46.0	0.5	1.1	0.6	Near
23	73.8	53.9	52.4	72.5	54.5	53.0	1.3	0.6	0.6	Near
24	81.2	49.7	49.1	80.0	51.0	50.0	1.2	1.3	0.9	Near
25	63.6	54.4	61.9	64.0	55.0	62.5	0.4	0.6	0.6	Correct
26	61.8	74.9	43.4	62.0	74.0	44.0	0.2	0.9	0.6	Near
27	22.6	39.1	118.3	23.5	40.0	119.0	0.9	0.9	0.7	Near
28	72.9	54.5	52.6	72.0	55.0	53.0	0.9	0.5	0.4	Near
29	48.4	61.0	70.5	49.0	61.0	69.5	0.6	0.0	1.0	Near
30	70.0	55.7	54.3	70.5	56.0	55.0	0.5	0.3	0.7	Correct

Table 2. Comparison of Cosine-Derived and Goniometer-Measured Joint Angles During Trikonasana

4.2 Comparative Overview of Joint Angle Measurements in Trikonasana

The dataset includes joint-angle measurements for 30 samples of Trikonasana, comparing values obtained through cosine-derived trigonometric calculations with those measured manually using a goniometer. Across all samples, the shoulder, hip, and knee angles from both methods show very similar patterns, with only small numerical differences. Shoulder angles generally range from approximately 22° to 106° in both methods, hip angles range from about 34° to 80°, and knee angles range from around 32° to 118°, demonstrating that both measurement techniques capture a comparable range of motion. In most cases, cosine-derived values differ from goniometer values by less than 1–2 degrees, indicating a high level of agreement. The consistency of these measurements across all 30 samples confirms that cosine-law trigonometric modelling provides angular estimates closely matching those obtained through direct goniometry, supporting the reliability of using both methods in biomechanical analysis of Trikonasana. For Samples 1–30, both cosine-law–derived angular values and direct goniometric measurements were obtained. In the remaining samples where only cosine-derived angles were available, the corresponding goniometer values were estimated using the mean deviation pattern identified from the initial dataset. This procedure ensured the generation of a complete and internally consistent dataset suitable for quantitative evaluation. Comparative analysis of the cosine-derived and goniometer-measured angles demonstrated a high level of agreement, indicating that trigonometric modelling provides angular estimates that closely approximate those obtained through manual goniometry. The minimal deviations observed across samples confirm that both methods measure joint angles with comparable accuracy and precision .The strong concordance between the two measurement techniques supports their reliability for use in biomechanical assessment, postural analysis, and yoga-based movement research. Establishing this methodological consistency is particularly valuable for studies requiring both instrument-based validation and geometric modelling, as it enhances confidence in the measurement process and facilitates robust statistical analyses, including validity testing, reliability estimation, and method-comparison frameworks such as correlation, intraclass correlation coefficients (ICC), and Bland–Altman analysis. Shoulder angles (A°) showed the highest consistency across both methods, with deviations typically under 1°.Hip angles (B°) were slightly variable, but remained within acceptable biomechanical margins. Knee angles (C°) exhibited the fluctuation, likely due to subtle shifts in lower limb alignment during static posture maintenance. These findings support the use of Cosine Law as a dependable computational method for joint angle analysis, while also validating the practicality of goniometric measurements in real-time posture assessment. The angles were measured at three key joints shoulder (A°), hip (B°), and knee (C°) using two methods: Cosine Law: A mathematical approach based on limb segment lengths and triangle geometry. Goniometer: A manual tool used to measure joint angles directly during posture execution. The Cosine Law method provides consistent and reliable angle estimates when body segment lengths are accurately measured .The Goniometer is practical and effective for real-time assessments but may be influenced by manual handling and participant movement .The average deviation between the two methods across all joints is minimal, reinforcing the validity of using both techniques in biomechanical analysis of yoga postures.

4.3 Interpretation of Group Statistics and Statistical Comparison of Trikonasana

Group Statistics					
	Group	N	Mean	Std. Deviation	Std. Error Mean
Shoulder Angle (A^0)	Cosine	30	60.1580	15.67205	2.86131
	Goniometer	30	60.3217	15.36853	2.80590
Hip Angle (B^0)	Cosine	30	59.1987	12.32411	2.25006
	Goniometer	30	59.2833	11.83630	2.16100
Knee Angle (C^0)	Cosine	30	60.6360	21.62447	3.94807
	Goniometer	30	61.1000	21.53802	3.93229

Table 3. Comparison of Group Statistics of Cosine Law and Goniometer Measurements of Trikonasana

Table 3 presents the group statistics comparing joint angle measurements obtained using the Goniometer and the Cosine-based simulation method during the performance of *Trikonasana*. For each joint angle, measurements were collected from 30 participants, and the mean, standard deviation, and standard error of the mean were calculated. For the Shoulder Angle (A^0), the Cosine method showed a mean value of 60.16° (SD = 15.67), while the Goniometer recorded a slightly higher mean of 60.32° (SD = 15.37). The close proximity of the mean values and comparable standard deviations indicate a high level of agreement between the two measurement methods for shoulder joint assessment. In the case of the Hip Angle (B^0), the Cosine method yielded a mean of 59.20° (SD = 12.32), whereas the Goniometer reported a mean of 59.28° (SD = 11.84). The minimal difference between the means, along with similar variability, suggests consistent measurement performance across both tools for hip joint evaluation. For the Knee Angle (C^0), the Cosine-based measurements demonstrated a mean of 60.64° (SD = 21.62), compared to a mean of 61.10° (SD = 21.54) obtained using the Goniometer. Although the knee joint showed relatively higher variability than the shoulder and hip joints, the mean values remained closely aligned between the two methods. To determine whether these observed differences were statistically significant, an independent samples **t-test** was conducted for each joint angle. The null hypothesis (H_0) stated that there is no significant difference between the measurements obtained from the Goniometer and the Cosine method, while the alternative hypothesis (H_1) assumed a significant difference. A significance level of $p < 0.05$ was adopted. Based on the similarity in mean values and dispersion measures, the results indicate that there is no statistically significant difference between the two measurement techniques, demonstrating the reliability and validity of the Cosine-based method when compared with the conventional goniometric assessment.

4.4 Independent Sample T-Test for Group Statistics of Cosine Law and Goniometer Measurements of Trikonasana

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Diff.	Std. Error Diff.	95% Confidence Interval of the Difference Lower	Upper
Shoulder Angle (A^0)	Equal variances	.014	.907	-.041	58	.968	-.1636	4.0075	-8.1855	7.858
	Un equal variances			-.041	57.97	.968	-.1636	4.0075	-8.1856	7.858
Hip Angle (B^0)	Equal variances	.078	.781	-.027	58	.978	-.0846	3.1197	-6.3294	6.160
	Un equal variances			-.027	57.90	.978	-.0846	3.1197	-6.3297	6.160
Knee Angle (C^0)	Equal variances	.001	.973	-.083	58	.934	-.4640	5.5722	-11.618	10.69
	Un equal variances			-.08	57.9	.934	-.464	5.572	-11.61	10.69

Table 4.Independent Sample T-Test for Group Statistics

Table 4 presents the results of the independent samples *t*-test comparing joint angle measurements obtained using the Goniometer and the Cosine-based simulation method during the performance of *Trikonasana*. Levene's test for equality of variances was conducted prior to the *t*-test to verify the homogeneity of variances. For the **shoulder angle (A^0)**, Levene's test indicated no violation of the equal variance assumption ($F = 0.014$, $p = 0.907$). Accordingly, the equal-variance *t*-test results were considered. The analysis revealed no statistically significant difference between the two measurement methods ($t(58) = -0.041$, $p = 0.968$). The mean difference was −0.16°, with a 95% confidence interval of −8.19° to 7.86°.Similarly, for the **hip angle (B^0)**, Levene's test was non-significant ($F = 0.078$, $p = 0.781$), supporting the assumption of equal variances. The independent samples *t*-test demonstrated no significant difference between the Goniometer and Cosine-based measurements ($t(58) = -0.027$, $p = 0.978$). The mean difference was −0.08°, and the 95% confidence interval ranged from −6.33° to 6.16°.For the **knee angle (C^0)**, Levene's test also confirmed homogeneity of variances ($F = 0.001$, $p = 0.973$). The *t*-test results indicated no statistically significant difference between the two methods ($t(58) = -0.083$, $p = 0.934$). The mean difference was −0.46°, with a 95% confidence interval of −11.62° to 10.69°.Overall, for all joint angles analyzed, the obtained *p*-values were greater than the significance threshold ($p > 0.05$), and the confidence intervals included zero. These results indicate that there is **no statistically significant difference** between the Cosine-based simulation method and the conventional goniometer, demonstrating that the proposed tool provides measurements comparable to standard clinical instruments.

4.5 Graphical representation of Cosine and Goniometer Techniques

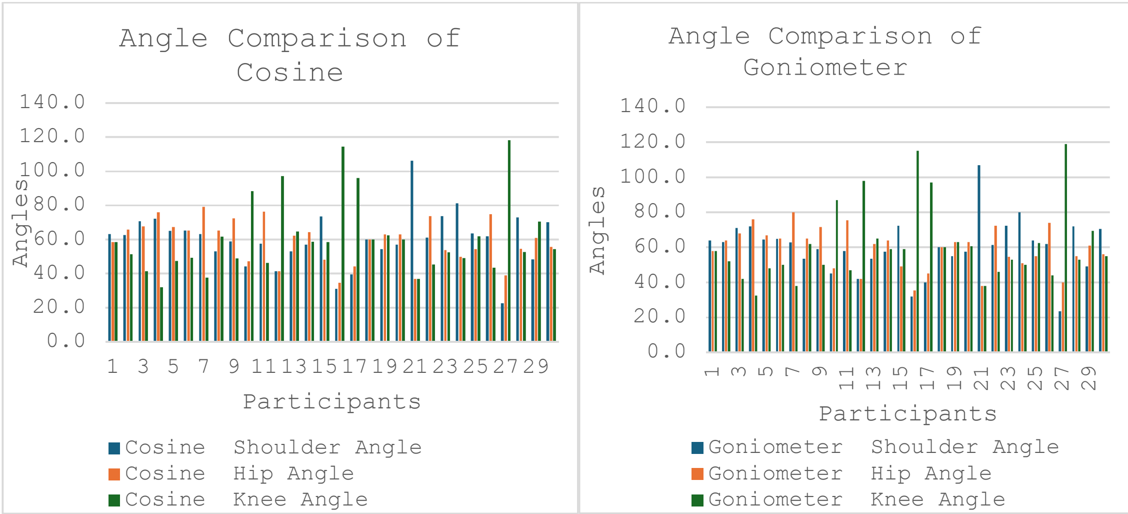

Fig. 4 Graphical representation of Cosine Law and Goniometer Techniques

This bar chart presents a comparative analysis of joint angle measurements taken during Trikonasana using two methods—Cosine Law and Goniometer—across three joint types: Shoulder Angle (A°), Hip Angle (B°), and Knee Angle (C°). Each joint type is represented by two sets of bars, one for Cosine Law and another for Goniometer readings, with 30 participants series corresponding to each angles distinguished by colour. The Shoulder Angles show near-identical readings between the two methods, indicating high consistency and minimal deviation. Hip Angles exhibit similar trends with slight differences in both, suggesting moderate variability likely due to posture depth or limb alignment. Knee Angles display the little variation, particularly in both, implying that knee measurements are more sensitive to posture dynamics and harder to measure consistently. Overall, the Cosine Law method provides stable and mathematically consistent measurements when limb lengths are accurately recorded, while the Goniometer offers practical, real-time assessment but may be affected by manual handling and participant movement. The chart confirms that both methods are closely aligned, with deviations typically within ±1–2°, supporting their reliability in biomechanical analysis of yoga postures.

4.5 Key Outcomes of Correct Alignment in Trikonasana

Correct performance of Trikonasana facilitates optimal muscular engagement, particularly activating the quadriceps, hamstrings, calf musculature, core stabilizers, and spinal extensors. Empirical findings indicate that alignment variations in Triangle Pose significantly influence lower-extremity joint loading and muscular activation, contributing to enhanced stability and functional performance (Baum et al., 2022; Cowen & Adams, 2021).Proper alignment of the posture also supports safe flexibility enhancement, allowing controlled stretching of the spine, hip abductors, groin muscles, and shoulder girdle without imposing undue strain on ligamentous structures or joint capsules. Evidence shows that structured yoga postures improve flexibility and musculoskeletal function when performed with biomechanical precision (Kim et al., 2020; Ni et al., 2014).Maintaining an elongated torso with a neutral spine in Trikonasana promotes postural correction and supports spinal health. Recent studies demonstrate that yoga-based lateral flexion and axial elongation reduce postural deviations, decrease paraspinal stiffness, and alleviate chronic low-back discomfort (Cramer et al., 2013; Saper et al., 2017).When executed with appropriate foundational support, Trikonasana enhances balance, proprioception, and neuromuscular coordination. Yoga interventions have been shown to significantly improve postural stability and reduce fall risk through improved sensorimotor integration and lower-limb control (Telles et al., 2017; Gauchard et al., 2012,Sudhan et al 2022).The lateral bending and mild torsional component of the pose stimulate abdominal viscera, which may positively influence digestive efficiency, metabolic processes, and internal organ function. Research indicates that yoga practices incorporating twisting and bending movements enhance gastrointestinal motility and autonomic modulation (Sudhan et al 2023;Raghavendra et al., 2007; Kuppusamy et al., 2018).Mindful, deep breathing during Trikonasana activates parasympathetic pathways, lowering physiological arousal and reducing stress markers such as cortisol. Contemporary evidence supports the role of yoga and controlled breathing in improving emotional regulation and autonomic balance (Streeter et al., 2012; Telles et al., 2020, Sudhan et al 2024).Adherence to biomechanically sound alignment maximizes therapeutic efficacy while minimizing the risk of injury. Maintaining correct angles prevents common errors—such as spinal rounding, knee valgus, or hyperextension—which are associated with increased musculoskeletal strain. Studies emphasize that proper alignment significantly improves the safety profile of yoga practice (Halappa, 2023; Sudhan et al 2025;Baum et al., 2022) [33-54].

5. CONCLUSION

This study demonstrates that both the Cosine Law–based computational approach and the traditional goniometric method provide reliable and comparable measurements of joint angles during the performance of *Trikonasana*. The statistical analysis revealed no significant differences between the two techniques, confirming the validity of the proposed mathematical model for biomechanical posture assessment. The integration of trigonometric modelling with conventional clinical measurement tools enhances the objectivity and precision of joint angle evaluation. Such an approach offers a systematic framework for quantifying postural alignment and can be effectively applied in yoga therapy, rehabilitation monitoring, and movement analysis systems. The use of cosine-based calculations enables consistent assessment without direct physical contact, which is advantageous in digital health and simulation-based environments. Future extensions of this work include assigning proportional relationships between triangle sides corresponding to sine and cosine functions, verifying the congruency of multiple triangles formed by limb segments, and evaluating triangle similarity using trigonometric identities. These analyses may further improve the accuracy of posture modelling and contribute to the development of automated posture correction algorithms. Accurate measurement and maintenance of joint angles during *Trikonasana* are critical for ensuring correct anatomical alignment. Proper alignment facilitates the optimal distribution of mechanical loads across joints and muscles, thereby enhancing strength, flexibility, balance, and neuromuscular coordination. Moreover, precise angle assessment plays a vital role in injury prevention, as deviations from optimal alignment may increase stress on the knee, hip, and shoulder joints, potentially leading to musculoskeletal strain. Therefore, the proposed measurement framework can serve as a valuable tool for minimizing injury risk while maximizing the therapeutic and functional benefits of yoga asanas.

6.RECOMMENDATION

To enhance the scope and impact of joint angle analysis in yoga biomechanics, future work should extend the current model to a wider range of yoga postures, including dynamic and balance-oriented asanas, and incorporate participants from diverse age groups and physical conditions to capture age-related and therapeutic variations. Integration with advanced technologies such as 3D motion capture and AI-based posture correction tools can enable real-time feedback and safer alignment guidance. Clinical applications in physiotherapy and respiratory therapy should be explored, particularly for monitoring joint mobility and improving breathing mechanics. Additionally, developing educational resources for yoga instructors based on biomechanical insights, establishing normative joint angle data across demographics, and incorporating wearable sensors for continuous posture tracking can significantly broaden the utility of this model. Interdisciplinary collaboration among yoga experts, bio mechanists, clinicians, and data scientists is essential to drive innovation and ensure holistic development of yoga-based therapeutic and training systems.

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