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Article

Dynamic stability and load distribution in yoga physical education teaching: A stereoscopic analysis based on pressure plates

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Abstract: Effective stability and distribution of load are important in yoga practice. This is because it determines postural control, balance, and elimination of injuries. The current training and coaching strategies are based on visual observation and verbal cues without the means for quantifying biomechanics. This cross-sectional study utilized pressure platform system and 3D motion capture system to measure plantar pressure, *COP* aperture and mediolateral balance shift during different yoga postures. To investigate the effect of the skill level on stability, candidates with different levels of experience were also targeted for inclusion in the study. The findings show that balancing postures are more asymmetrical and associated with larger *COP* displacement, which demands better NMC. Comparing the results of *COP* variability (SD = 0.63 cm) and weight distribution, it can be stated that experienced practitioners exhibit less variability and accurate balance, proving the idea that expertise positively affects stability. The Symmetry Index results revealed significantly greater variability for single-leg stance postures, suggesting that balance unevenness is an important factor during these asanas. These findings are particularly relevant to teaching yoga sessions, physiotherapy, and rehabilitation that can implement evidenced-based balance training. The study presents biomechanical feedback techniques as valuable for enhancing the approaches used in teaching yoga and improving stability training.

Keywords: biomechanics; center of pressure; load distribution; stability training; yoga postures; motion analysis

1. Introduction

Stability is an important aspect that helps to control one's posture and maintain an upright position. Imbalance leads to a high probability of developing certain injuries and reduced mobility. Weight distribution is the manner in which the body weight is supported across the supports on which they rely on or rest. Imbalanced weight distribution affects the pressure or stress applied by muscles and joints in the body. Proper weight management will also enable one to maintain a better Al posture and eliminate much pressure on the several body parts. Weight distribution varies from one pose to another in yoga [1]. Standing poses require equal distribution of body weight on both the feet. In balance poses, there is delicate coordination ability and abdominal muscles strength required. Dynamic postures challenge overall stability. Knowing these mechanics facilitates yoga training. Stability patterns can also be examined through biomechanical analysis. It assists in determining impact forces have on the body. In this case, instability undermines the efficacy of the yoga poses. The distribution of weights directly impacts the angle and center of pressure. Studying these factors helps in enhancing the efficiency of posture. The various ideas and assumptions put forward about weight shifts can lay the ground for improving the technique for practitioners [1]. The purpose of this work will be to investigate postural stability in yoga poses by employing pressure plates. It focuses on the distribution of weight in different positions. The study will compare the differences in sheer forces with balancing and standing postures. Yoga postural control is maintained by three basic feedback mechanisms that are proprioceptive, visual and vestibular feedback systems. Stability is a measure of *COP* displacement, which is an integral part of NMC. Higher *COP* variability implies increased postural sway and reduced *COP* displacement, therefore balance control. *COP* fluctuations generally, and especially significant in single-limb postures as weight-bearing put more demand on core and lower limbs. The results found in the present study, associated with higher *COP* displacement in Tree and Crow poses are in line with the previous research on dynamic balance control stressing the need for progressive stability training for enhanced regulation of weight. Neuromuscular control or stabilization refers to the prevention or minimization of unnecessary postural adjustments. Research indicates that regular training in balance improves the proprioceptive acuity, making it easier for the professional to detect and correct the postural distortions.

1.1. Biomechanics of yoga and stability

Balance is important in yoga practice. This includes either holding a pose for an extended time or moving from one pose to another. Proper positioning minimizes stress and enhances biomechanical motion patterns. Stability is based on three primary somatosensory feedback mechanisms, muscle co-contraction and joint stabilization. Standing or sitting in the correct manner is important as it helps avoid putting certain pressure on bones and muscles that may later cause pain. Weight-bearing mechanics influence yoga performance. In standing poses, you should make sure that your weight is evenly distributed. Disparities have problematic implications and may lead to instability [3]. Certain poses may involve moving the body mass from one part of the body to another limb. Others involve single-limb support. These variations challenge balance and coordination. Postures are greatly determined by core strength. Lordosis results from weak anterior core muscles. To a notable extent, balance is influenced by feet positioning and grip as well.

Dynamic transitions demand precise control. A change in the weight distribution can cause instability. Motions reduce risks of falling down and getting injured. Proper weight bearing provides better yoga execution. Such mechanics facilitate the enhancement of teaching methodologies by providing a structured framework to follow. The benefits of going to a chiropractic office include; it facilitates better correction and alignment. Sensory organization, postural sway, and other biomechanical factors offer an indication of balance in yoga. Locating the center of pressure (*COP*) mean a point where the body weight is evenly distributed. It shifts as a person moves. Use of *COP* can be utilized in measuring balance as an objective measure of postural stability. Yoga makes it possible to understand how weight is placed on the feet through *COP* analysis. This also reveals changes in the position of the body in different poses [3].

Stable *COP* means balance and a variable *COP* means fluctuations. High *COP* movement suggests instability. Higher *COP* volatility is observed among students with little initial experience even when the measured APIs are small. Weight shifts in the older and experienced practitioners appear smoother than in the younger ones. As has been noted previously, measuring *COP* aids in determining levels of proficiency as a way of facilitating learning [3]. It also helps in balancing because it can help identify when one muscle group has become too tight and the other has become too weak. There are certain asanas which involve very little *COP* displacement. Others include dynamic changes which enables controlled changes to occur. *COP* analysis helps refine training programs. It identifies weak stability patterns. It also helps in correcting mechanical deformities such as postural distortions. *COP* values can be accurately measured from pressure plates. This data enhances knowledge concerning biomechanics in yoga. With the help of the *COP*, the instructor can provide differentiated feedback. This it makes training more stable and reduce cases of injury [3,4].

1.2. Pressure plate technology in sports science

Pressure plates measure force distribution. They monitor pressure and weight distribution at the feet. In sports science they are used to evaluate balance and movement of objects and people. People use them to correct errors that their genes or bodies produce. They are used by rehabilitation experts in the analysis of movement patterns. As for the need for stability, pressure plates in yoga can measure this. It is able to detect variations in postural weight. Pressure data is at the core of motion studies. Scientists study the differentiation of force. It further looks at how various surfaces impact the level of stability achieved. For yoga, pressure plates offer biofeedback in balance and works in real time. They reveal stasis in the intensity of the foot pressures they provide when in static motion and dynamicst [4,5].

Pressure plate feedback is very helpful for training programs. They have the flexibility of altering training in response to facts and statistics. Pressure plate technology is beneficial in the research of biomechanics. It enhances coordination and balance and helps to make postural evaluations. It is also helpful in identifying stability patterns related to processes, activities and interventions. Force plates and pressure plates both record the distribution of the pressure on the body. However, they differ in application. Force plates are devices that can quantify the forces exerted by the body on the supporting surface. They measure force produced on the ground. Pressure plates are pressure-sensitive devices which measure contact pressure. Some shoes offer pressure mapping of the foot and its activities [4,5].

Force plates are employed in dynamic analyses. It can quantify forces of impact during jumping and running activities. They are more suited for making balance studies which are static in nature. They also study how weight is distributed during standing asanas. For yoga, pressure plates are more beneficial. They capture subtle stability changes. They are transportable and easy to apply meaning that they can be used by anyone who has an interest in using them. Force plates require specialized setups. However, pressure plates provide detailed pressure distribution information. They offer clear view of load dispersion so that overly congested areas can be easily identified. This might make them ideal for yoga education. Their data can be useful in enhancing balance training. *P* they provide biomechanical feedback in physical education [5].

1.3. Stereoscopic analysis in movement studies

3D motion capture tracks body movements. It records the angles of movement of each joint and the position of limbs. The activity is recorded through some sort of sensors or cameras sampling views from different perspectives. This results in the formation of a three-dimensional model of motion. It is employed greatly in the field of sports science [5,6]. It helps analyze complex movements. Pressure plates, in contrast, works on the ground interaction. Some of the features include the minutiae of foot pressure and changes in body weight. They can only capture limited body movements and are unable to capture full body movements. Instead, they deliver force distribution information in more detail. Both methods offer valuable insights. However, they serve different purposes. In yoga, 3D motion capture is used to determine the proper positioning of bodies. It depicts how limbs change their positions during transitions. It helps detect improper positioning. Pressure plates show how loads are studied and distributed from the perspective of humans. They display stability patterns in various stances. The integration of both makes for a thorough assessment. It improves postural assessment accuracy [6].

Multiple perspectives give insights into movement than single assessments. The physical lordotic, kyphotic, flexed, extended, or swayed, or the muscular tightness or relaxation define different aspects of posture from different angles. The front, side, and top views are used to examine alignment. Pressure plates introduce another piece of information into the system. They depict force existence under feet. The integration of motion capture with pressure analysis has advantages. It provides a comprehensive perspective concerning stability. It also aids in identifying discrepancies in stability and balance. This data may be useful to fine-tune techniques for yoga teachers. They can provide targeted corrections. This improves learning outcomes. This is good news for biomechanics research because the methods provide data from multiple angles. They help in understanding of movement patterns. It also comes in handy in establishing better training modalities. Advanced assessments improve yoga education. They also develop better balance training interventions. The use of these methods helps to implement scientific-based approaches to teaching [6].

2. Methodology

2.1. Study design

This study employs an experimental design with a focus on quantitative biomechanical data collection. The first aim is to identify dynamic stability and load distribution in Yoga postures by pressure plate technology, and Stereoscopic analysis [7]. The methodology also utilizes real time data acquisition which helps to measure the force exerted during various yoga poses by practitioners. In order to minimize any variability in the results obtained due to individual's performance, the current study uses within-subject methodology where the participant performs the task for several trials. In postural stability, biomechanical values like center of pressure; load; and force symmetry are measured. From a mathematical point of view, stability in yoga asanas can be described by the center of pressure displacement function in Equation (1).

$$COP_x = \frac{\sum(F_i \cdot x_i)}{\sum F_i}, COP_y = \frac{\sum(F_i \cdot y_i)}{\sum F_i} \tag{1}$$

F_i represents the force at a given pressure sensor, and x_i, y_i denote the respective coordinates of the force application. By tracking COP_x and COP_y over time, variations in balance and stability can be evaluated across different postures.

2.2. Participants and sampling

The study recruited 45 participants from various yoga studios, university wellness programs, and community fitness centers. To ensure a diverse and representative sample, participants were classified into three skill levels. First, novice (15 participants, less than one year of practice), intermediate (15 participants, one to three years of practice), and advanced (15 participants, more than three years of practice). This classification enables an in-depth analysis of how expertise influences motor control, balance, and postural execution. A stratified random sampling approach was used to achieve a balanced distribution across different experience levels. Recruitment was conducted through online sign-ups, direct invitations at yoga studios, and referrals from instructors. Efforts were made to ensure diversity in age, gender, and body composition to enhance generalizability. The inclusion criteria required participants to be between 18 and 50 years old, non-smokers, and free from musculoskeletal injuries or neurological disorders. Participants were also required to have no prior history of lower limb biomechanical injuries, chronic joint pain, or balance disorders. Those with recent surgeries or conditions affecting balance were excluded from the study [8]. Before participation, all individuals underwent a preliminary screening involving a brief balance and flexibility assessment. They also provided written informed consent, ensuring compliance with ethical research guidelines.

2.3. Equipment and technology

Data acquisition includes pressure plates with high accurate resolution, stereoscopic cameras, and biomechanics specialized software. The pressure plates employed in this study are sensitive to force distribution; both spatially and temporally. These plates record ground reaction forces (*GRF*) in Newtons (*N*) and are described by the relation;

$$\sum F = m \cdot g \tag{2}$$

m is the participant's mass, and g is gravitational acceleration (9.81 m/s^2). By tracking real-time force distribution, the system evaluates asymmetries in weight-bearing patterns. Stereoscopic cameras record three-dimensional motion analysis through the use of reflective markers placed at the joints of the participants. The data is extracted from the pressure plates and cameras through a motion analysis program which synchronizes *COP* data together with the visual data. These technologies allow for quantifying post-standing balance, weight transfers, and stability changes that may occur in the various asana postures [8].

2.4. Experimental procedure

The experimental arrangement is such that all external variables including light, floor, and temperature are kept constant. Each participant is urged to do some yoga poses; these include Warrior Pose (Virabhadrasana), Tree Pose (Vrksasana), and Downward Dog (Adho Mukha Svanasana). Each posture falls into the stability category on the basis of the how much it challenges bilateral, single-leg support. Some of the preparations that are done before the trail include warming up of the muscles to avoid contraction or tightness. They then execute each posture on the pressure plate, holding the position for a specific amount of time that is usually 30 s. To complement experiments testing postures, 3 trials are carried out for each specific posture in an effort to minimize inter-subject variability [8,9]. They are integrated with the pressure platform and the stereoscopic camera to allow for continual recording of postural change. The groups are advised to master proper breathing and alignment of the body while in the poses. In cases of discrimination, adjustments are made, and other trials are made to check on changes or improvements.

2.5. Data collection and analysis

The methods used for data collection were carefully chosen and planned to facilitate high reliability and reproducibility of biomechanical measures. Specifically, prior to the test, subjects performed a standardized warm-up routine to reduce muscle rigidity and variability in balance. As for the reflective markers, electrodes were attached to hip, knee, and ankle joints to track motion during the experiment while keeping the external variables such as light, floor, and temperature consistent. They performed three sets of each yoga posture with each posture being held on the pressure plate platform for 30 s. Plantar pressure data was also registered in real time and included force distribution between the left and right foot. Center of pressure (*COP*) displacement was used to determine the degree of postural stability, while the Symmetry Index (*SI*) estimated the level of balance side dominance. The stereoscopic motion tracking system captured the joint motion trajectories of the patient and therapist synchronously, which enabled the analysis of postural and movement adaptations. The results of the ANOVA tests revealed the differences in the stability of subjects classified as beginners and advanced practitioners. Linear regression analysis was applied to detect the correlation between experience level and *COP* variance [9]. The relationship between *COP* displacement and posture complexity is modeled using Equation (5).

$$SD_{COP} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(COP_i - C\bar{O}P)^2} \tag{3}$$

$$SI = \left|\frac{F_L - F_R}{F_L + F_R}\right| \times 100 \tag{4}$$

$$COP_{disp} = \beta_0 + \beta_1(Experience) + \beta_2(Posture\ Type) + \varepsilon \quad (5)$$

β_1 and β_2 represent regression coefficients, and ε denotes the residual error term. The statistical significance threshold is set at $p < 0.05$.

3. Results and discussion

3.1. Load distribution across different yoga postures

Reflection on load distribution by various yoga poses uncovers information on the loading of weight over the left and right foot. For poses that require standing, they compared Warrior and Triangle poses which revealed a fairly split force distribution on both feet, then compared balancing poses Tree and Crow pose whereby they observed high force variance between the two feet [10]. In mathematical terms, force distribution on each foot can be defined as given in Equation (6) below;

$$F_{total} = F_L + F_R \quad (6)$$

where F_L and F_R are the forces on the left and right foot respectively. Ideally, in a symmetry the ratio of these forces should be a unity (see **Table 1**). Though in actual practice this ratio deviates very slightly from unity. Though, in the data it is seen that TREE pose has been having the force ratio from left to right ranging between 0.32 and 0.41 which shows that there is imbalance in the body weight due to some single leg exclusively supporting the body. The statistical analysis of the findings also reveals that balancing postures have larger *SD* values for load distribution (110.5 *N*, $p < 0.01$) as compared to the static standing postures [10,11]. These results can be further correlated to the biomechanics of performing yoga where dynamic balance entails more use of body weight control. The Symmetry Index (*SI*) was calculated as *SI* = No. of side chains with residues in both A and B positions/Total number of side chains with residues in A + B positions *SI* = 17/26 as given in Equation (4) above. The higher the value of *SI*, the higher the degree of asymmetry. Tree pose received the best rating of 42.5% for *SI*, and Downward Dog had the closest score distribution of 4.3%. These findings shown in **Table 1** are the complexity of various yoga positions in terms of their biomechanics.

Table 1. Yoga posture stability and load distribution data.

Yoga pose	Left foot pressure (*N*)	Right foot pressure (*N*)	*COP* Displacement (cm)	Symmetry Index (%)
Warrior	349.81	223.23	4.82	22.08
Tree	580.28	546.47	2.34	3.00
Downward dog	492.79	440.44	2.22	5.60
Triangle	439.46	483.22	2.23	4.74
Chair	262.40	208.23	2.71	11.51
Crow	262.39	587.96	3.59	38.28

3.2. Dynamic stability findings

The center of pressure (*COP*) displacement is reported to be a very useful variable to assess postural stability. *COP* trajectory variations allow for better understanding of the efficiency in postures' control [11,12]. The average *COP* displacement also showed considerable changes and was higher in Crow pose (3.59 cm) and Tree pose (4.82 cm).

Figure 1 is a 2D *COP* trajectory plot showing how the center of pressure moves over time for different yoga postures. This center of pressure (*COP*) Trajectory Plot visually compares postural stability between beginner and advanced yoga practitioners. The beginner trajectory (red) shows greater displacement and variation, indicating more instability, while the advanced trajectory (blue) remains more centralized and controlled, suggesting better balance and weight control.

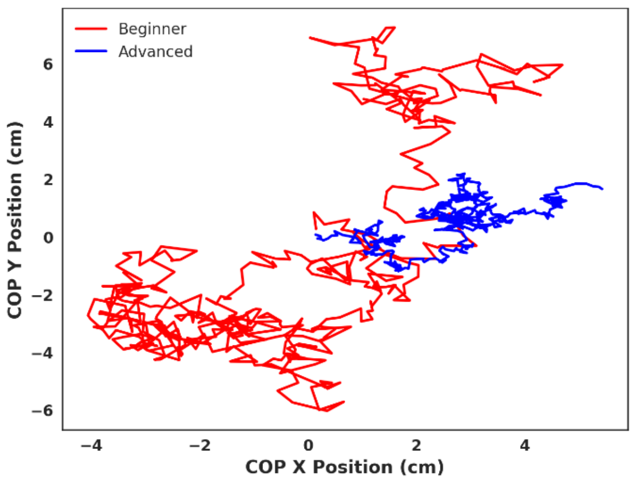

Figure 1. Center of pressure (*COP*) trajectory plot.

In this regard, Triangle and Chair poses yielded the smallest values of 2.23 cm and 2.71 cm respectively, an index of improved stability [12]. *COP* displacement was analyzed using Equation (3) above where SD_{COP} stands for the standard deviation of the *COP* values in relation to time. The SD_{COP} is higher when the degree of instability is higher. The novice's mean *SD_{COP}* was established as 1.15 cm, while the advanced mean *SD_{COP}* was 0.63 cm (t (14) = 4.42; $p < 0.05$) a finding that validates the idea that practice makes perfect when it comes to balance. A negative relationship was noted between experience level and *COP* displacement with a Pearson's correlation coefficient of −0.72 (p <0.001). This indicates that with more years of practice there is improved control of weight shift and reduction of movement that is unnecessary. Furthermore, the postural control efficiency was analyzed by calculating the coefficients of determination based on simple linear regression Equation (5) where β_1 and β_2 represent regression coefficients for experience and posture complexity, respectively. The model statistically explained 45.3% of the variation in *COP* displacement ($R^2 = 0.453$, $p < 0.001$). These results indicate that the efficiency of postural control depends on experience and pose difficulty [12].

3.3. Stereoscopic analysis insights

Stereoscopic motion capture differentiated weight shifts and helped in using 3D postural control. The motion trajectory demonstrations also displayed a significant variability in weight shifts between the novice group and the trained subject.

Figure 2 is a sequence of images from the stereoscopic camera system showing body alignment and joint movements in different poses. The Beginner Trajectory (Red) exhibits erratic and uncontrolled movements, indicating higher instability and larger shifts in posture adjustments. Advanced Trajectory (Blue) demonstrates smoother, more controlled movements, reflecting better balance and neuromuscular control [12,13]. It was observed that for beginners, the *COP* displacements that occur in a sudden manner during weight shifts were above 5 cm in postures such as Tree and Crow. The motion paths revealed more fluctuations, which could imply a higher variability in the lateral sense and the need for a reactive balance strategy. Amateurs, on the other hand, displayed more jerky motions during their weight transitions compared to advanced practitioners. We observed that their *COP* patterns were much more balanced, as the variations in their *COP*, in terms of distance, remained below 2 cm. This means that there is always a strong anticipation balance strategy among experienced practitioners to make minimal balance adjustments. Second feature that was highlighted involved the inclination of the torso and it was specific to novices and experts. In Warrior and Tree posture, beginners had a greater forward lean of the torso (mean = 9.5°) compared to advanced practitioners (mean = 3.2°) [12,13].

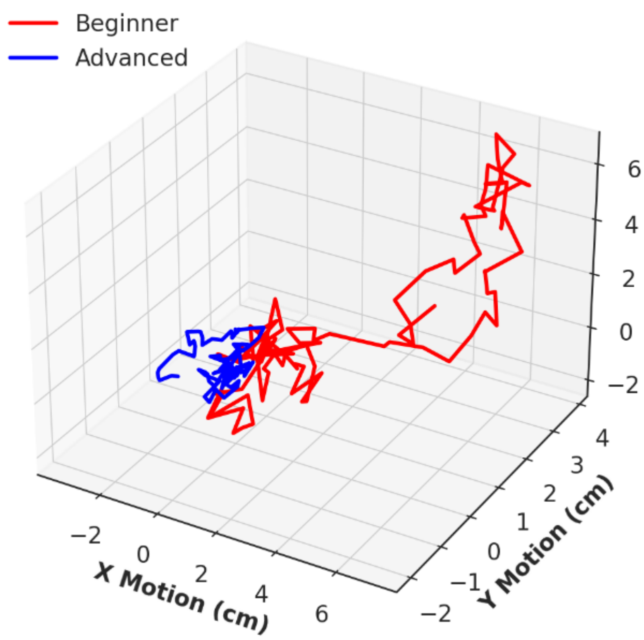

Figure 2. 3D motion analysis snapshots from stereoscopic tracking.

In **Figure 3** above, Tree and Crow Poses exhibit the highest asymmetry, confirming their demand for greater balance control. Warrior, Downward Dog, Triangle, and Chair Poses show lower *SI* values, indicating more even weight distribution. The distribution spread highlights variation among practitioners, reinforcing the need for individualized stability training strategies [14]. The

Symmetry Index (*SI*) measures the degree of weight-bearing asymmetry in yoga poses. Higher *SI* values indicate greater imbalance, requiring more neuromuscular control (NMC) to maintain posture.

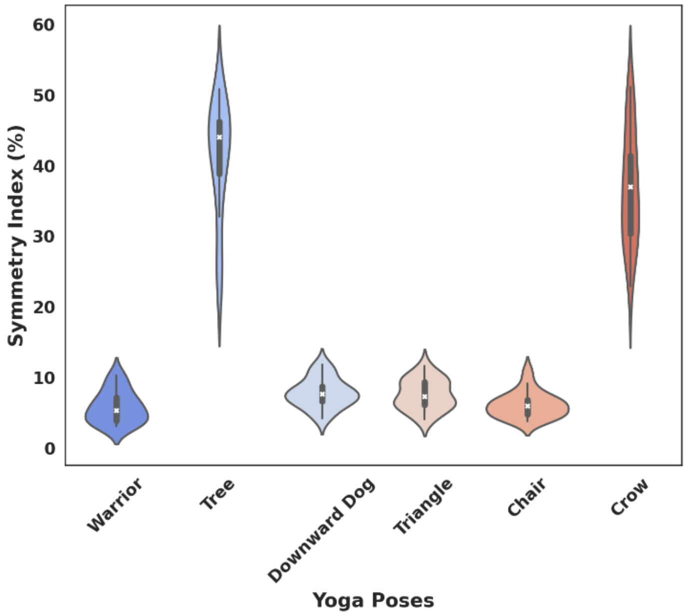

Figure 3. Symmetry Index (*SI*) comparison across yoga poses.

Figure 4 above is a time-series graph displaying how force changes as practitioners move from one pose to another. The Warrior to Tree Transition (Blue Line) shows a smoother force adjustment, indicating a more controlled weight shift. The Tree to Crow Transition (Red Dashed Line) exhibits greater fluctuations, suggesting higher instability and more abrupt force redistributions [14]. These findings confirm that dynamic transitions require greater postural control, making progressive stability training essential for improving transition smoothness.

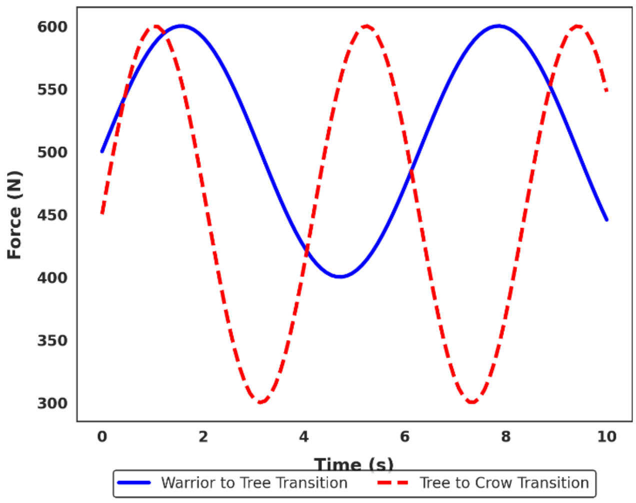

Figure 4. Force distribution over time in dynamic transitions.

Figure 5 is a contour plot displaying the stability zones of different experience levels (beginner, intermediate, advanced) based on *COP* displacement patterns. The

Beginner Stability Zone (Red) is wider and more dispersed, indicating larger *COP* fluctuations and reduced postural control. The Advanced Stability Zone (Blue) is more centralized, showing greater stability and refined balance control [15]. The data suggests that experience significantly improves postural stability, reinforcing the importance of skill-based yoga training progression.

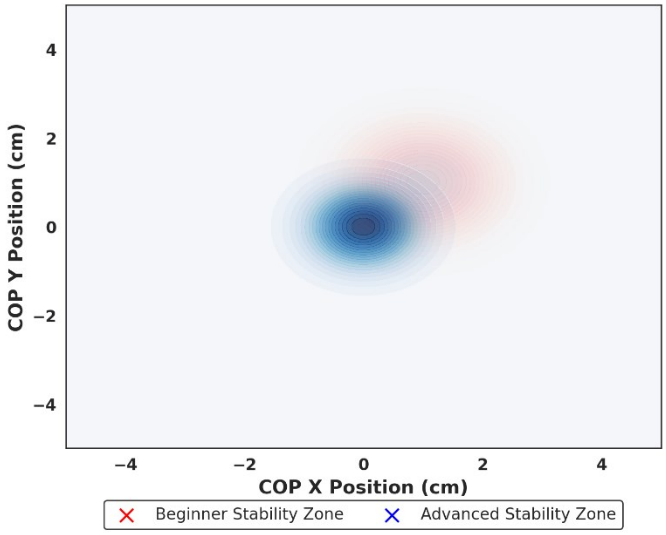

Figure 5. Comparative *COP* stability zones between experience levels.

4. Conclusion

In this paper the analysis of dynamic stability and load distribution in yoga postures was examined by pressure plate and stereoscopic motion capture. In view of this, it was found that foot pressure distribution affords a tangible impact on postural stability particularly balancing poses are distinctively more asymmetrical as opposed to standing postures. The study also showed that increased postural control meant that the advanced practitioners had a smaller sway area, lower *COP* displacement, and better weight distribution, which shows that experience improves balance control on the board. The data collected from pressure plates and 3D motion tracking produced stable outputs enabling a quantitative measurement that is not taken into consideration in conventional yoga teachings. Based on the force distribution and *COP* variability, it is demonstrated that using biomechanical tools may help improve the dissemination of yoga knowledge and enhance its applicability in postural disorders. The implication of the findings is that yoga training, physiotherapy, and other forms of rehabilitation should be evidence-based with a strong focus on balance implications. This study brings several innovations to the field of yoga biomechanics in comparison with other previous investigations. In contrast to previous qualitative approaches based on the naked eye examination, the present study employs the pressure plate and stereoscopic motion tracking in order to quantify stability, weight distribution, and postural control. This new set of biomechanical tools makes it possible to quantify, to a much higher degree, balance dysfunction and neuromuscular control. One of the major contributions of this study is in the examination of this relation based on skill level that translates into objective measures of postural control. This article's previous research primarily reflects on general balance mechanisms in yoga, whereas the present study offers more detailed *COP* variability measures, *SI* values, and force dispersion, which uncovers differentiations between comparatively inexperienced and experienced yoga practitioners.

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