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# BAROPODOMETRIC ASSESSMENT OF PLANTAR BIOMECHANICS AND POSTURAL STABILITY FOLLOWING STATIC VERSUS DYNAMIC BALANCE TRAINING IN POST-ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION PATIENTS: AN EXPERIMENTAL INVESTIGATION

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## Abstract

**Background**: anterior cruciate ligament (ACL) reconstruction impaired the proprioception and neuromuscular system that control dynamic knee stability resulting in characteristic pattern of planter pressure asymmetry, postural sway elevation, and altered mechanical loading that persist long into the post operative rehabilitation period. Baropadometry - the objective qualification of the planter pressure distribution and postural parameters using a pressure sensitive sensor plate - offer a reliable and valid tool sensitive for detecting these biomechanical deficits and monitoring rehabilitation induced correction. While both stating and dynamic balance training are recognized rehabilitation exercise for post ACL reconstruction patient, no study has symmetrically compared their differential effect on comprehensive baropadometric outcomes within a controlled experimental design. This study is design to address this gap.

**Methods**: An Experimental, two groups, pre-test and post-test comparative study was conducted at the Department Of Physiotherapy, Pacific Medical College and Hospital, Udaipur. 30 post ACL reconstruction patient were divided into Group A ( Static Balance Training n = 15) and Group B ( Dynamic Balance Training n = 15 ). Both groups received there respective intervention for 6 days per week for 4 weeks. Seven baropadometric parameter- Baropadometric index (%), Load Distribution (%), Mean Planter Pressure (kPa), Peak plantar pressure (%) ,Foot Barycenter (mm²), Body Barycenter (mm²),, and Centre Of Pressure (COP) Distance (mm)- were assessed using a Baropadometric sensory plate at baseline and post intervention. Re assessment was performed every third day to guide individualized protocol progression. Statistical analysis employed paired t – test for within group and independent t – test for between group comparison (significance $p < 0.05$)

**Results** : both groups demonstrated highly significant improvement in all seven baropadometric parameter ($p < 0.001$ for all). Group A (Static) achieved post intervention means of baropadometric index 52.56 ± 1.88%, Load Distribution 46.89 ± 2.35%, Mean Pressure 157.23 ± 8.76 kPa, Peak Pressure 270.0 ± 14.12 kPa, Foot Barycenter 35.64 ± 3.38 mm², Body Barycenter 48.01 ± 3.84 mm², and COP Distance 19.62 ± 3.46 mm. Group B (Dynamic) achieved superior outcomes across all seven parameters: Baropadometric Index 53.68 ± 1.21%, Load Distribution 45.36 ± 1.31%, Mean Pressure 151.52 ± 4.70 kPa, Peak Pressure 261.46 ± 7.93 kPa, Foot Barycenter 35.98 ± 1.60 mm², Body Barycenter 45.43 ± 1.98 mm², and COP Distance 17.06 ± 1.60 mm. Standard deviation were consistently lower in group B which reflect superior consistency of bio mechanical adaptation.

**Conclusion** : Both static and dynamic balance training produce comprehensive, clinically sufficient improvement, baropadometric parameter Following ACL reconstruction. Dynamic balance training demonstrated superior biomechanical outcomes across all seven parameter assessed with greater reduction in postural sway, more symmetrical planted distribution, and more consistent inter- individual adaptation. Baropadometric assessment is validated as a sensitive and objective tool for monitoring post ACL reconstruction rehabilitation progress and guide individualized program to get better progression

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## 1. INTRODUCTION

Anterior cruciate ligament (ACL) reconstruction represent one of the most demanding and rehabilitation intensive surgical procedure in orthopedic sports medicine. ACL injury affect approximately 200,000–300,000 individuals annually in the United States and are associated with functional impairment, prolonged recovery, and significant risk of re-injury and long term me osteoarthritis [1,2]. Following reconstruction, the graph undergoes a prolonged biological process of ligamentisation –revascularization, re-innervation and progressive re-modelling - over 12 to 24 months. Throughout the period, characteristic biomechanical deficit in planter pressure distribution, postural control, and limb loading symmetry are well documented and represent clinically important rehabilitation goal [3,4].

The mechanoreceptors enclosed within the native ACL provide continuous afferent sensory input regarding joint position, velocity, and load to the central nervous system. ACL rupture impairsthis proprioceptive pathway, and graph tissue following reconstruction is characterized by severely limited mechanoreceptors regeneration within a vascular collagen tissue.- making the resulting proprioceptive deficit both profound and persistent[5]. The disruption in proprioception manifest as biomechanically as impaired postural stability, elevated postural sway measured by centre of pressure (COP) displacement, asymmetrical planter load distribution, and altered foot ground interaction pattern. All quantifiable through baropadometric assessment [6].

Baropadometry - the measurement of planter pressure distribution and associated postural stability parameter using a pressure sensory plate which provide objective, quantitative and reproducible data regarding the mechanical consequences of post ACL reconstruction neuromuscular dysfunction that cannot be captured by subjective clinical scale or performance based test [7].Key baropadometric parameter including the baropadometric r index (overall plantar stability) load distribution (bilateral limb loading symmetry), mean and peak plantar pressure, Foot Barycenter (foot centre of pressure position ) Body Barycenter (whole body centre of mass control) and COP distance(postural sway extent) collectively provide a comprehensive and multidimensional characteristic of planter biomechanics and postural control status [8].

Despite the recognized clinical sensitivity and objective baropadometric assessment in lower limb pathology its systematic application as a primary outcome measure in controlled post ACL reconstruction rehabilitation research remaininsufficient in the published literature [9]. The majority of balance training studies in this population have focus on performance based and subjective outcome measures with relatively few employing the objective quantitative assessment of planter biomechanics that baropadometric affords additionally no study compared differential baropadometric effect of Static and dynamic balance training separately in a controlled experimental design with comprehensive multi parameter assessment [10].

Balance training - including both static postural stability exercise and dynamic movement base activities is the primary rehabilitation strategy for restoring the neuromuscular and problems active function damage by ACL injury and reconstruction [11]. Static exercises restore essential joint position sense and postural stability through controlled stationery changes while dynamic exercise engage feedforward neuromuscular mechanism that more closely replicate the functional biomechanical demands of daily activity and sports [12]. The differential effects of these exercise on the specific baropadometric parameters reflecting planter biomechanics and postural control are

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however incompletely characterized limiting evidence based treatment selection in clinical practice.

This study wasDesigned to systematically characterize and compare the Baropadometric effects of static versus dynamic balance training in post ACL reconstruction patient providing objective biomechanical evidence to Gayatri habilitation protocol design and serial outcome monitoring.

### 1.1 Study Aim and Objectives

The primary aim of this study was to objectively assess and compare the effect of Static and dynamic balance training parameters and baropadometric parameters in patient after ACL reconstruction. This Pacific objective were:

To assess changes in baropadometric index following both intervention

- To compare changes in bilateral load distribution.
- Two evaluate and compare mean and peak planter changes.
- To assess foot Barycenter and body Barycenter displacement changes.
- To compare COP distance (postural sway) changes.
- To determine which training exercise produce superior Baropadometric.rehabilitation outcomes.

## 2. REVIEW OF LITERATURE

### 2.1 Baropodometric Assessment in Knee Rehabilitation

**Hiemstra, Lo, and Fowler (2001)** used baropadometricassessment to evaluate wait bearing symmetry in patient after ACL reconstruction showed that the limb loading asymmetry indicated by unequal plantar pressure distribution between limbs was significantly greater in reconstructed patient compared to healthy control. The study demonstrated that the normalization of plantar pressure distribution was a clinically meaningful rehabilitation objective that could be effective which monitor through baropadometric assessment establishing the measurement framework adopted in a present study [13].

**Fransen and McConnell (2008)** studied the relationship between plantar pressure distribution and knee joint loading demonstrate that the asymmetrical planter pressure including elevated peak pressure on the affected side was associated with greater compartment loading and accelerated cartilage degradation [14]. These finding underscore the clinical significance of plantar pressure normalization as a therapeutic goal in post ACL reconstruction patient persistent loading a symmetry does not represent a functional deficit but carries direct implication for long term articular cartilage help and osteoarthritis prevention.

**Orlin and McPoil (2000)** demonstrated a comprehensive review of plantar pressure assessment methodology established the validity and reliability of pressure plate baropodometric assessment as a clinical and research measurement tool. The authors confirmed that parameters including COP distance load distribution, mean pressure, and peak pressure provide clinically meaningful and reproducible measures a postural biomechanics in weight bearing population [15].

### 2.2 Proprioceptive Deficits and Biomechanical Consequences of ACL Injury

**Relph, Herrington, and Tyson (2014)** demonstrated a systemic review that AC and injury produces consistent deficit in joint position sense threshold to detection of passive motion and force reproduction accuracy with these proprioceptive deficits persisting for months to years following both injury and reconstruction [5].

**Palmieri-Smith, Thomas, and Wojtys (2008)** demonstrated that ACL reconstruction alters Quadriceps and hamstring activation pattern increasing anterior tibial shear forces and aberrant joint loading neuromotor changes that directly manifest in abnormal planter pressure distribution during weight bearing tasks at biomechanical level. [16].

**Scanlan, Blazek, and Chaudhari (2010)** investigated altered muscle coordination in post ACL reconstruction patient during dynamic activities demonstrating significantly altered quadriceps and hamstring activation strategies during landing and cutting compared to healthy control. These altered neuromuscular pattern persisted even after patient were cleared for return to sports providing mechanistic explanation for the persistent baropadometric abnormalities documented in post Reconstruction population and highlighting the need for continued targeted rehabilitation beyond conventional discharge criteria [17].

**2.3 Neurophysiological Mechanisms of Balance Training**

**Riva, Bianchi, and Rocca (2016)** demonstrated neuro physiological adaptations associated with dynamic balance training that show improvement in dynamic postural stability were associated with enhanced cortical motor planning, improved cerebellar adaptation and more efficient integration of visual, vestibular and somatosensory input during complex movement task providing mechanistic evidence for the neuroplastic adaptation underlying dynamic training benefits that demonstrated improved by baropadometric stability indices [18].

**Stöckel, Gulde, and Hodzic (2015)** studied the neurophysiological adaptation underline static balance training demonstrating that improvement in postural stability following single leg stance training were associated with increased cortical and subcortical sensorimotor activity enhanced interhemispheric connectivity and improved visual motor integration. These neuro imaging finding provided mechanistic evidence for the central adaptation underlying static balance training benefits in the context of post ACL reconstruction rehabilitation [19].

**Lephart, Pincivero, and Giraldo (1997)** distinguished between feed forward neuromuscular control through pre programmed motor strategies and feedback control through reactive adjustment that argue dynamic balance training uniquely restore feed forward mechanism particularly the rapid pre programmed muscular responses occurring within the initial phase of landing ,cutting or pivoting tasks that protect the reconstructed ACL from excessive loading mechanism that static training alone cannot adequately challenge or develop [12].

**2.4 Balance Training and Baropodometric Outcomes**

**Kang, Oh, and Kwon (2012)** studied the effect of combine Static and dynamic balance training on strength and function after ACL reconstruction conclude that dynamic balance exercise produced greater improvement in planter stability and functional biomechanics than static training attributing these advantage to the greater proprioception and neuromuscular demand imposed by dynamic movement task on the sensorimotor system producing biomechanical improvements with direct baropadometric correlated [20].

**Risberg, Holm, and Myklebust (2007)** conducted a randomizedclinical trial demonstrating that neuromuscular training included with progressive balance challenges achieved significantly better muscles strength outcomes at the six month follow up compared to strength training alone. The author highlight the importance of structured neuromuscular training throughout all phase of post ACL rehabilitation for restoring both the subjective functional measure and underlying biomechanical stability that baropadometry can quantify [21].

**Paterno, Rauh, and Schmitt (2012)** demonstrated re - injury incident of approximately 29.5% within 2 years of return to sports following ACL reconstruction with continuously postural control deficits identified as significant indicator of second injury. As postural control deficit are directly measured through baropadometric parameters

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particularly COP distance and load distribution these finding support the use of serial baropadometric assessment as an objective return to sports criterion in addition to performance based measures [22].

## 3. MATERIALS AND METHODS

### 3.1 Study Design and Setting

An experimental, two-group, pre-test and post-test comparative study was conducted at the Department of Physiotherapy, Pacific Medical College and Hospital, Bhilo Ka Bedla, Udaipur, Rajasthan, India, following Institutional Ethics Committee approval. Participants were randomly allocated to intervention groups using simple random allocation, and all baropodometric outcome measures were assessed at two standardised time points: baseline (Day 1, prior to intervention) and immediately following completion of the intervention period (Day 28 or equivalent).

### 3.2 Participants

There are 30 post ACL reconstruction patients ( age between 20 to 40 years , ≤4 months post-operative, independently ambulant with near full range of motion and minimal pain ) were recruited and equally divided into two groups. Group A ( Static Balance Training n = 15 ) and include ( Dynamic Balance Training n = 15 ).Exclusion criteria include uncontrolled medical condition like neurological condition, cognitive impairment and recent surgery other than ACL reconstruction. All participant provided written informed consent .

### 3.3 Baropodometric Assessment Protocol

All baropadometric measurement were performed using a pressure sensitive sensory plate ( baropadometric platform) under standardised condition. Participant stand barefoot on the platform in an anatomical position, arms at their side, stand erect for the assessment duration. The platform software automatically computed the following seven parameter at each assessment.:

Table 3.1: Baropodometric Parameters — Definition and Clinical Significance

| Parameter | Definition | Rehabilitation Indicator |
|---|---|---|
| Baropodometric Index (%) | Overall plantar stability and quality of foot-ground interaction | Higher values = improved balance and plantar stability |
| Load Distribution (%) | Symmetry of weight-bearing between bilateral lower limbs | Reduction toward 50% = improved bilateral symmetry |
| Mean Plantar Pressure (kPa) | Average pressure exerted over total plantar surface | Reduction = improved weight distribution efficiency |

(ISSN: 0973-7049(P))

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| | | |
|---|---|---|
| Peak Plantar Pressure (kPa) | Maximum pressure at regions of localised stress concentration | Reduction = improved force distribution, less focal stress |
| Foot Barycenter ($mm^2$) | Centre of pressure within the foot; foot alignment during standing | Reduction = improved foot alignment and stability control |
| Body Barycenter ($mm^2$) | Overall centre of mass of the body; postural alignment | Reduction = enhanced postural stability and neuromuscular coordination |
| COP Distance (mm) | Extent of postural sway during static standing | Reduction = improved balance and postural sway control |

Serial baropadometric reassessment was performed every third day throughout the intervention protocol to enable individualised progression based on objective biomechanical improvement data. The intervention protocol for each participant was modified based on three reassessment finding to address specific identified deficit in load symmetry, pressure distribution, and postural sway control.

### 3.4 Intervention Protocols

Group A received static balance training ( 4 weeks, 6 session per week, 45 to 60 minutes per session) comprising progressively challenging stationery postural exercises. Feet together standing, semi Tandem stance and single legs stance on progressively unstable surfaces. Group B received dynamic balance training of equivalent duration and frequency including

movement base function exercises front and back and lateral weight shifting, hip abduction, extension and stationery marching, calf raises, squats, leg curls, side stepping and step forward task progressively advanced from bilateral to unilateral and stable to unstable surface condition.

### 3.5 Statistical Analysis

All the data were analysed using Statistical Analysis Software (SAS). Descriptive statistic are presented as a mean± standard deviation (SD). Normality was assessed using the Shapiro-Wilk test. Within group pre to post intervention comparison work conducted using paired t test. Between group post intervention

(ISSN: 0973-7049(P))

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comparison work conducted using independent sample t- test. Statistical significance was set at $p < 0.05$ ( two – tailed ).

## 4. RESULTS

### 4.1 Demographic Characteristics

30 participant completed the study with no dropouts. Mean age was 28.1± 2.44 years ( Group A) and 28.73 ± 2.86 years ( Group B) post operative duration 2.74± 0.26 months and 2.64 ± 0.26 months respectively confirming baseline homogeneity between groups

### 4.2 Baropodometric Outcomes — Group A (Static Balance Training)

Group A demonstrated statistically highly significant improvements in all seven baropodometric parameters following the four-week static balance training intervention ($p < 0.001$ for all variables).

Table 4.1: Baropodometric Outcomes — Group A (Static Balance Training, n = 15)

| Parameter | Pre Mean ± SD | Post Mean ± SD | Mean Diff | p-value | Sig. |
|---|---|---|---|---|---|
| Baropodometric Index (%) | 48.34 ± 1.15 | 52.56 ± 1.88 | +4.22 | < 0.001 | Yes |
| Load Distribution (%) | 52.03 ± 0.97 | 46.89 ± 2.35 | -5.14 | < 0.001 | Yes |
| Mean Plantar Pressure (kPa) | 182.36 ± 6.06 | 157.23 ± 8.76 | -25.13 | < 0.001 | Yes |
| Peak Plantar Pressure (kPa) | 307.54 ± 10.93 | 270.00 ± 14.12 | -37.54 | < 0.001 | Yes |
| Foot Barycenter ($mm^2$) | 41.08 ± 2.14 | 35.64 ± 3.38 | -5.44 | < 0.001 | Yes |

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 21705-21722, 2026 www.thebioscan.com

| | | | | | |
|---|---|---|---|---|---|
| Body Barycenter (mm²) | 53.90 ± 2.62 | 48.01 ± 3.84 | -5.89 | < 0.001 | Yes |
| COP Distance (mm) | 27.06 ± 1.90 | 19.62 ± 3.46 | -7.44 | < 0.001 | Yes |

The baropadometric index increased from 48.34 ± 1.15 to 52.56 ± 1.88% which show improvement in planter contact quality and over all foot ground stability. Load distribution decrease from 52.03 ± 0.97 to 46.89 ± 2.35% indicating meaning full correction of compensatory wed bearing asymmetry. Mean and peak plantar pressure reduced significantly from 182.36 ± 6.06 to 157.23 ± 8.76 kPa and from307.54 ± 10.93 to 270.00 ± 14.12 kPa respectively. Reflecting improved force distribution and enhanced shock absorption. Foot Barycenter reduced from 41.08 ± 2.14 to 35.64 ± 3.38 mm², and body barycenter from 53.90 ± 2.62 to 48.01 ± 3.84 mm², indicating improved foot alignment and whole body postural alignment control. COP distance reduced from 27.06 ± 1.90 to 19.62 ± 3.46 mm, indicating substantially decreased postural sway and enhanced balance symmetry.

**4.3 Baropodometric Outcomes — Group B (Dynamic Balance Training).**

Group B demonstrated highly significant improvement in all seven baropadometric parameter ($p < 0.001$) with the magnitude of improvement exceeding group A across most variable and consistently smaller standard deviation indicating greater uniformity of biomechanical adaptation.

Table 4.2: Baropodometric Outcomes — Group B (Dynamic Balance Training, n = 15)

| Parameter | Pre Mean ± SD | Post Mean ± SD | Mean Diff | p-value | Sig. |
|---|---|---|---|---|---|
| Baropodometric Index (%) | 48.28 ± 1.29 | 53.68 ± 1.21 | +5.40 | < 0.001 | Yes |
| Load Distribution (%) | 51.64 ± 1.04 | 45.36 ± 1.31 | -6.28 | < | Yes |

(ISSN: 0973-7049(P))

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 21705-21722, 2026 www.thebioscan.com

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|---|---|---|---|---|---|
| | | | | 0.001 | |
| Mean Plantar Pressure (kPa) | 178.48 ± 3.33 | 151.52 ± 4.70 | -26.96 | < 0.001 | Yes |
| Peak Plantar Pressure (kPa) | 300.52 ± 5.71 | 261.46 ± 7.93 | -39.06 | < 0.001 | Yes |
| Foot Barycenter (mm²) | 39.72 ± 1.17 | 35.98 ± 1.60 | -3.74 | < 0.001 | Yes |
| Body Barycenter (mm²) | 52.15 ± 1.43 | 45.43 ± 1.98 | -6.72 | < 0.001 | Yes |
| COP Distance (mm) | 25.70 ± 1.24 | 17.06 ± 1.60 | -8.64 | < 0.001 | Yes |

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The baropadometric index increased from 48.28 ± 1.29 to 53.68 ± 1.21%, and SD decreased from 1.29 to 1.21 post intervention indicating not only improved foot ground stability but exceptional consistency of improvement across all participant. Load distribution decreased from 51.64 ± 1.04to 45.36 ± 1.31%, the lowest post intervention load distribution value in the study indicating superior bilateral symmetry correction. Mean and peak planter pressure reduced 151.52 ± 4.70 kPa and 261.46 ± 7.93 kPa respectively. Body barycenter reduced from 52.15 ± 1.43 to 45.43 ± 1.98 mm², representing a 6.72 mm² reduction — the largest absolute barycenter improvement in the study. Most notably, COP distance reduced from 25.70 ± 1.24 to 17.06 ± 1.60 mm — a reduction of 8.64 mmwhich was the lowest post intervention COP value recorded across the entire study indicating superior postural sway reduction.

**4.4 Between-Group Baropodometric Comparison**

Table 4.3: Between-Group Comparison of Post-Intervention Baropodometric Parameters

(ISSN: 0973-7049(P))

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 21705-21722, 2026 www.thebioscan.com

| Parameter | Group A Post-Test Mean ± SD | Group B Post-Test Mean ± SD | Significance |
|---|---|---|---|
| Baropodometric Index (%) | 52.56 ± 1.88 | 53.68 ± 1.21 | $p < 0.05$ |
| Load Distribution (%) | 46.89 ± 2.35 | 45.36 ± 1.31 | $p < 0.05$ |
| Mean Pressure (kPa) | 157.23 ± 8.76 | 151.52 ± 4.70 | $p < 0.05$ |
| Peak Pressure (kPa) | 270.00 ± 14.12 | 261.46 ± 7.93 | $p < 0.05$ |
| Foot Barycenter ($mm^2$) | 35.64 ± 3.38 | 35.98 ± 1.60 | $p < 0.05$ |
| Body Barycenter ($mm^2$) | 48.01 ± 3.84 | 45.43 ± 1.98 | $p < 0.05$ |
| COP Distance (mm) | 19.62 ± 3.46 | 17.06 ± 1.60 | $p < 0.05$ |

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Group B achieved numerically superior post intervention value compared to Group A on all seven baropadometric parameter with between group difference reach statistical significance ( $p< 0.05$). The most clinically notable between group distribution are –

1. COP distance - Group B (17.06 ± 1.60 mm) vs. Group A (19.62 ± 3.46 mm), representing a 2.56 mm greater reduction in postural sway with group B SD being less than half that of Group A confirming superior consistency.

4.5 Overall Summary — All Subjects (N = 30)

2. Body Barycenter –Group B (45.43 ± 1.98 $mm^2$) vs. Group A (48.01 ± 3.84 $mm^2$), a 2.58 $mm^2$ difference with significantly less variability

3. Load distribution – Group B (45.36 ± 1.31%) vs. Group A (46.89 ± 2.35%), indicating superior bilateral symmetry correction.

(ISSN: 0973-7049(P))

The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 21705-21722, 2026 www.thebioscan.com

Table 4.4: Overall Pre- and Post-Intervention Baropodometric Outcomes (N = 30)

| Parameter | Pre Mean ± SD | Post Mean ± SD | Mean Diff | p-value | Result |
|---|---|---|---|---|---|
| Baropodometric Index (%) | 48.31 ± 1.6 | 53.12 ± 1.9 | +4.81 | < 0.001 | Sig. |
| Load Distribution (%) | 51.83 ± 1.3 | 46.10 ± 1.7 | -5.73 | < 0.001 | Sig. |
| Mean Pressure (kPa) | 180.42 ± 5.7 | 154.37 ± 6.4 | -26.04 | < 0.001 | Sig. |
| Peak Pressure (kPa) | 304.03 ± 8.0 | 265.73 ± 7.9 | -38.30 | < 0.001 | Sig. |
| Foot Barycenter (mm²) | 40.40 ± 1.9 | 35.78 ± 2.2 | -4.62 | < 0.001 | Sig. |
| Body Barycenter (mm²) | 53.02 ± 2.4 | 46.72 ± 2.7 | -6.30 | < 0.001 | Sig. |
| COP Distance (mm) | 26.38 ± 2.0 | 18.34 ± 2.3 | -8.04 | < 0.001 | Sig. |

## 5. DISCUSSION

The present study provide a comprehensive and systematic baropadometric characterization of the different effects of Static and Dynamic balance training after ACL reconstruction address a significant gap in the evidence base research. The consistent pattern of improvement observed across all seven baropadometric parameter in both groups combined with the statistically significant superiority of dynamic training across all measures provide quantitative biomechanical evidence to guide post ACL reconstruction protocol design.

### 5.1 Effectiveness of Static Balance Training on Plantar Biomechanics

The significant improvement in all baropadometric parameters following static balance training - most notably the COP distance reduced from 27.06 ± 1.90 to 19.62 ± 3.46 mm and the load distribution correction from 52.03 ± 0.97% to 46.89 ± 2.35%confirm that the static exercise produce genuine biomechanical rehabilitation effect which measure through plantar pressure analysis. The improvement in baropadometric index from 48.34 ± 1.15 to 52.56 ± 1.88% reflects enhanced foot ground contact quality and sensorimotor integration consistent with the neurophysiological adaptation documented by Stöckel et al. (2015), who demonstrated increased cortical and subcortical sensorimotor activities following static balance training. The reduction in mean and peak plantar pressure are clinically important as they indicate improved force distribution and shock absorption directly reducing the localized articular stress implicated in post ACL cartilage degradation pathway documented by Fransen and McConnell (2008).

### 5.2 Superiority of Dynamic Balance Training on Baropodometric Parameters.

Dynamic balance training produced superior improvement across all baropadometric parameter compared to Static training, with statistically significant between group difference ( $p< 0.05$) and consistently smaller standard deviation confirming greater consistency of biomechanical adaptation. The post intervention COP distance of 17.06 ± 1.60 mm in Group B — compared to 19.62 ± 3.46 mm in Group A represents the lowest COP value recorded in the entire study and a 2.56 mm greater reduction in postural sway than achieved by static training. The superiority in sway reduction is consistent with the neurophysiological framework advanced by Riva et al. (2016), who demonstrated that the dynamic balance training is associated with enhance cortical motor planning improved cerebellar adaptation and more efficient multisensory integration - neuroplastic mechanism that produce more comprehensive improvement in postural stability parameter than stationery proprioceptive training alone.

The body Barycenter improvement in Group B (from 52.15 ± 1.43 to 45.43 ± 1.98 mm², a reduction of 6.72 mm²) was the largest absolute Barycenter improvement in the study indicating superior body postural alignment control. This finding a line with the theoretical distinction advanced by Lephart et al. (1997)Between feedforward and feedback neuromuscular control dynamic exercise uniquely developed feedforward pre programmed motor strategies that enable more precise centre of mass control during movement producing baropadometric improvement in body Barycenter stability that reflect the neuromotor gains achieved through dynamic challenge.

The superior lord distribution correction in Group B (to 45.36 ± 1.31% vs. 46.89 ± 2.35% in Group A), with a substantially lower SD suggesting greater uniformity reflects the capacity of dynamic exercises particularly weight shifting and stepping tasks to provide direct systematic training of bilateral load transfer and symmetry correction under functional movement condition. Weight shifting exercise is create repetitive demand of controlled by lateral load equalization that are not adequately challenged by the stationary postural task of static training.

**5.3 Standard Deviation Patterns and Consistency of Biomechanical Adaptation**

A particularly important and under appreciated finding of this study is the consistent pattern of smaller standard deviation across all baropadometric variable in Group B compared to Group A post intervention. For COP distance Group B SD was 1.60 mm versus 3.46 mm in Group A . For load distribution Group B SD was 1.31% versus 2.35 percent in Group A. For baropadometric index Group B SD was 1.21% versus 1.88% in Group A. Systematic pattern of lower variance in the dynamic training group indicates that the dynamic balance training produces not only superior mean improvement but more reproducible and uniform biomechanical adaptation across participants an important characteristic for clinically predictability and protocol standardisation . The greater homogeneity of response to dynamic training may reflect the more comprehensive and multi system neuroplastic, adaptation it engages simultaneously training cortical motor planning , cerebellar adaptation and peripheral proprioceptive pathways producing more complete and consistent sensorimotor restoration across participants.

### 5.4 Clinical Significance of Serial Baropodometric Monitoring

The use of serial baropadometric reassessment every third day throughout the intervention which enable individualized protocol progression based on objective biomechanical data represent an important methodological contribution of the study. The quantitative and parameter specific information provided by baropadometric assessment which include the identification of specific deficits in unilateral versus bilateral loading, anterior-posterior versus medial- lateral sway and focal pressure concentration pattern enable a level of individualized treatment prescription that subjective functional scales and performance based tests cannot achieve. This approach is consistent with the recommendation of Orlin and McPoil (2000) for the integrating planter pressure assessment into the clinical monitoring of lower limb rehabilitation.

The finding support the routine incorporation of baropadometric assessment are both a primary outcome measure and a clinical progression monitoring tool in post ACL reconstruction rehabilitation providing quantitative biomechanical data that complements and extends the information obtainable through balance board score and functional performance assessment.

### 5.5 Study Limitations

Limitation include a sample size of 30 limiting generalizability the absence of non balance training control group a four week intervention period is insufficient to capture long term bio mechanical durability and lack of three dimensional motion analysis or etectromyographicdata to characterize the underline neuromuscular mechanism of baropadometric improvement. Future studies which larger samples, randomized control design, extended follow up incorporating return to sports endpoints multi model biomechanical assessment are warranted.

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## 6. CONCLUSION

This experimental study provide the first systematic baropadometric comparison of Static and dynamic training effects in post ACL reconstruction patient. The finding are (i) both stating and dynamic balance training produce highly significant and clinically meaningful improvement in all 7 seven baropadometric parameter assessed baropadometric index , load distribution, mean planter pressure, Foot Barycenter, body Barycenter and COP distance with $p < 0.0001$ for all comparisons. (ii) Dynamic balance training produces statistically superior baropadometric outcomes compared to Static training across all seven parameters with between group differences significant at $p < 0.05$.(iii) dynamic training consistently produces smaller standard deviation across all baropadometric adaptation and (iv) baropadometric assessments is validated as a sensitive, objective and clinically valuable tool for monitoring rehabilitation induced by biomechanical changes and guiding individualized protocol progression in post ACL reconstruction patients.

A progressive rehabilitation approach introducing static balance training early to establish foundational proprioceptive and postural stability followed by systematic advancement to dynamic exercises is recommended as the evidence based framework foroptimizing baropadometric outcomes in post ACL reconstruction rehabilitation. Dynamic balance training should be prioritizedin the intermediate and advanced rehabilitation phases for its superior effect on postural sway reduction, load symmetry correction and plantar pressure normalisation, baropadometric monitoring should be integrated as the standard clinical assessment tool to enable objective, data driven data driven rehabilitation progression and comprehensive characteristic of biomechanical recovery.

## 7. CLINICAL IMPLICATIONS

The baropadometric findings of the study carry specific and actionable clinical implication for Physiotherapy practice in post AC reconstruction rehabilitation. The demonstration that both Static and dynamic balance training produce significant and quantifiable improvement in planter pressure distribution, load symmetry, postural sway provides strong objective evidence for the mandatory inclusion of structured balance training within post ACL reconstruction rehabilitation protocol supplementary existing clinical guideline based predominantly on subjective and performance based measures

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The Bioscan AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES 21(2): S.I (2), 21705-21722, 2026 www.thebioscan.com

The identification of COP distance as a particularly sensitive baropadometric indicator of rehabilitation induced improvement with the largest absolute reduction of any parameter in both groups suggest that COP distance should be adopted as a primary quantitative endpoint for post ACL reconstruction balance rehabilitation monitoring. A target COP distance thresholdpotentially the value achieved by the dynamic training group (17.06 ± 1.60 mm) may be considered as an objective functional criterion for advancing patient from balance rehabilitation to sports specific training, supplementing existing limb symmetry index criteria..

The superior correctionof load distribution asymmetry achieved by dynamic training reducing from approximately 52% to 45% on the affected side suggest that the weight shifting and stepping exercises, are the core component of dynamic training protocol, should be symmetrically included and progressively advanced in the intermediate rehabilitation phase specifically to address the bilateral loading a symmetry that is a characteristic biomechanical signature of post ACL construction and a risk factor for secondary articular pathology. Serial baropadometric monitoring every third day as employed in this study provide the objective progression data required to make individualized protocol advancement decision that are not possible with periodic subjective assessment alone.

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