COMPREHENSIVE JOINT FLEXIBILITY ASSESSMENT IN LOWER EXTREMITIES AND SPINAL COLUMN: A BIOMECHANICAL ANALYSIS USING DIGITAL GONIOMETRY

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Abstract

Background: *Spinal column and lower extremity flexibility are critical components of functional movement, athletic performance, and injury prevention. Digital goniometry offers objective, precise assessment capabilities superior to traditional measurement methods.*

Objective: *To comprehensively evaluate static flexibility of the cervical spine, thoracolumbar spine, coxofemoral joint, knee, and ankle using the Mobee Med digital goniometry system, establishing normative data and identifying clinical flexibility patterns.*

Methods: *Three healthy adult subjects underwent systematic flexibility assessment using Mobee Med (TGA-registered) with 142 standardized mobility tests. Evaluations included: cervical spine (flexion/extension, lateral bending, rotation), thoracolumbar spine (flexion/extension, lateral bending, rotation), coxofemoral joint (flexion/extension, abduction/adduction, rotations), knee (flexion/extension), and ankle (dorsiflexion/plantarflexion, eversion/inversion). Statistical analysis utilized descriptive statistics and one-sample t-tests comparing measured values against reference standards (α=0.05).*

Results: *Significant deficits were identified across multiple regions. Cervical spine: flexion 70.67°±3.06 (reference 80°, p=0.034), left rotation 77.67°±3.51 (reference 85°, p=0.026). Thoracolumbar spine: extension 15.00°±3.61 (reference 25°, p=0.041). Coxofemoral joint: left hip flexion 118.33°±2.52 (reference 125°, p=0.004), right abduction 55.33°±3.51 (reference 70°, p=0.010). Knee: left flexion 120.33°±5.51 (reference 135°, p=0.044). Ankle: dorsiflexion 15.00°±2.00 left, 14.33°±2.52 right (reference 20°); plantarflexion 42.67°±7.77 left, 43.33°±4.04 right (reference 55°). Statistical analysis revealed flexibility restrictions averaging 10-40% below reference values, with larger deficits in extension movements and rotational patterns.*

Conclusions: *Digital goniometry reveals systematic flexibility deficits in spinal and lower extremity joints even in healthy populations. Cervical and thoracolumbar extension limitations (26.67-66.67% deficits) reflect modern postural dysfunction from prolonged sitting and forward head positioning. Coxofemoral restrictions in flexion (5.63%), abduction (26.51%), and rotations (20-27%) indicate hip* *musculature tightness predisposing to low back pain and lower extremity pathology. Knee flexion deficits (10.89-12.19%) and ankle mobility restrictions (25-28.90%) compromise functional movement patterns essential for daily activities and athletic performance. The Mobee Med system provides precise, standardized assessment enabling early intervention before clinical symptom manifestation.*

Keywords: spinal flexibility, lower extremity mobility, hip joint assessment, digital goniometry, biomechanical evaluation, postural dysfunction.

1. INTRODUCTION

1.1 Spinal column biomechanics and flexibility

The vertebral column represents the axial skeleton's central structure, providing mechanical support, protecting neural elements, and enabling multi-planar trunk movement. Spinal flexibility varies substantially across regions: the cervical spine demonstrates the greatest mobility (80-90° rotation capability), the thoracic spine exhibits restricted motion due to rib cage attachments, and the lumbar spine provides intermediate mobility primarily in flexion-extension planes (Neumann, 2017; Oatis, 2017).

Modern lifestyles characterized by prolonged sitting, computer work, and smartphone use create chronic postural stresses promoting adaptive flexibility losses (Straker et al., 2018). Forward head posture, thoracic kyphosis, and lumbar flexion positioning induce length-tension relationship alterations in spinal musculature, potentially contributing to neck pain, thoracic dysfunction, and low back pathology (Harrison et al., 2018; Kim et al., 2015).

1.2 Lower extremity joint mobility significance

The coxofemoral, knee, and ankle joints constitute the lower kinetic chain essential for locomotion, balance, and functional activities. Hip joint mobility restrictions correlate strongly with low back pain incidence through compensatory lumbar spine motion (Ellison et al., 1990; Van Dillen et al., 2000). Reduced hip flexion, extension, and rotation associate with altered gait mechanics, increased fall risk in elderly populations, and sport-specific injury patterns (Winters et al., 2004; Cibulka et al., 2009).

Knee joint flexibility, while primarily limited to sagittal plane motion, influences functional activities from stair climbing to athletic performance. Ankle dorsiflexion restrictions represent well-established risk factors for lower extremity injuries including ankle sprains, Achilles tendinopathy, and plantar fasciitis (Hoch & McKeon, 2011; Kaufman et al., 1999).

1.3 Digital assessment advantages

Traditional spinal and lower extremity flexibility assessment relies on inclinometry, goniometry, or functional tests (sit-and-reach, fingertip-to-floor distance) demonstrating variable reliability and validity (Williams et al., 2013). The Mobee Med digital goniometry system addresses these limitations through three-axis gyroscopic sensors capturing complex multi-planar movements with ±0.5° precision, real-time visualization, and standardized neutral-zero methodology (Mobee Med, n.d.).

1.4 Study objectives

This investigation aims to: (1) comprehensively evaluate spinal and lower extremity static flexibility using standardized digital protocols, (2) identify common flexibility deficit patterns in healthy population, (3) compare measured values against established normative references, (4) determine statistical significance of observed restrictions, and (5) provide evidence-based clinical recommendations for flexibility optimization.

2. MATERIALS AND METHODS

2.1 Study design and participants

This preliminary cross-sectional study included three healthy adults (n=3) meeting inclusion criteria: age 18-35 years, no current musculoskeletal pathology, no spinal or lower extremity surgical history, ability to perform full range of motion without pain. The protocol received Institutional Ethics Committee approval; all participants provided written informed consent.

2.2 Assessment protocol

Standardized laboratory conditions (temperature 22±2°C, humidity 50±10%, testing 09:00-12:00), no warm-up, barefoot assessment. For each movement: (1) standardized positioning, (2) Mobee Med gyroscope placement on anatomical landmark, (3) neutral-zero calibration, (4) active movement to end range, (5) digital data recording, (6) bilateral comparison.

2.3 Evaluated regions and movements

- **Cervical spine:** flexion/extension (sagittal), lateral bending left/right (frontal), rotation left/right (transverse);
- **Thoracolumbar spine:** flexion/extension (sagittal), lateral bending left/right (frontal), rotation left/right (transverse);
- **Coxofemoral joint:** flexion/extension, abduction/adduction, external/internal rotation;
- **Knee:** flexion/extension;
- **Ankle:** dorsiflexion/plantarflexion, eversion/inversion.

2.4 Statistical Analysis

IBM SPSS Statistics 26.0; significance α=0.05. Descriptive statistics (mean±SD, range, median/IQR) and one-sample *t*-tests comparing measured values against Mobee Med reference standards. Effect sizes (Cohen's *d*) and 95% confidence intervals calculated.

3. RESULTS

3.1 Cervical spine assessment

Table 1. *Cervical spine flexibility measurements*

Movement	Mean±SD (°)	Reference (°)	Deficit (%)	*t*-value	*p*-value
Flexion	70.67±3.06	80	13.21	-5.292	0.034*
Extension	43.67±3.51	50	14.51	-3.124	0.089
Lateral Bending Left	53.00±9.17	70	32.08	-3.213	0.085

Movement	Mean±SD (°)	Reference (°)	Deficit (%)	*t*-value	*p*-value
Lateral Bending Right	59.00±5.57	70	18.64	-3.132	0.089
Rotation Left	77.67±3.51	85	9.44	-6.102	0.026*
Rotation Right	75.33±6.51	85	12.83	-2.460	0.133

Note. *Significant at $p<0.05$

Individual subject data:

Subject	Flexion	Extension	Lateral L	Lateral R	Rotation L	Rotation R
A.R	74	44	43	62	80	83
V.A	70	40	55	63	76	70
H.T	68	47	61	52	77	73

Key findings: Statistically significant restrictions in cervical flexion (p=0.034) and left rotation (p=0.026) indicate reduced mobility in anterior musculature (sternocleidomastoid, anterior scalenes) and rotational musculature (obliquus capitis inferior, multifidi). The 32.08% left lateral bending deficit, while non-significant (p=0.085), suggests trapezius and levator scapulae tightness characteristic of unilateral occupational postures.

3.2 Thoracolumbar spine assessment

Table 2. *Thoracolumbar spine flexibility measurements*

Movement	Mean±SD (°)	Reference (°)	Deficit (%)	*t*-value	*p*-value
Flexion	98.33±8.08	110	11.87	-2.500	0.130
Extension	15.00±3.61	25	66.67	-4.804	0.041*
Lateral Bending Left	61.67±4.04	70	13.51	-3.467	0.074
Lateral Bending Right	62.67±5.86	70	11.70	-1.790	0.215
Rotation Left	80.33±3.06	85	5.81	-2.646	0.118
Rotation Right	76.33±7.02	85	11.35	-1.765	0.220

Note. *Significant at $p<0.05$

Individual subject data:

Subject	Flexion	Extension	Lateral L	Lateral R	Rotation L	Rotation R
A.R	107	19	65	69	83	86

Subject	Flexion	Extension	Lateral L	Lateral R	Rotation L	Rotation R
V.A	97	12	57	64	77	70
H.T	91	14	63	55	81	73

Critical finding: The 66.67% extension deficit (p=0.041) represents the most substantial thoracolumbar restriction identified. This finding reflects chronic flexion positioning from prolonged sitting, creating adaptive shortening of anterior abdominal musculature (rectus abdominis, external obliques) and lengthening of posterior spinal extensors (erector spinae, multifidus). The restriction predisposes to low back pain through altered spinal loading patterns (McGill, 2015).

3.3 Coxofemoral joint assessment

Table 3. *Coxofemoral joint flexibility measurements*

Movement	Left (°)	Right (°)	Reference (°)	*t*-value	*p*-value
Flexion	118.33±2.52	122.00±5.20	125	-4.588/-2.291	0.004*/0.149
Extension	21.00±4.58	21.00±5.20	30	-3.402/-2.946	0.077/0.098
Abduction	56.00±9.17	55.33±3.51	70	-2.514/-10.094	0.128/0.010*
Adduction	23.67±5.51	24.33±4.16	30	-1.872/-2.429	0.202/0.136
External Rotation	36.00±4.58	36.67±3.79	45	-3.402/-4.110	0.077/0.054
Internal Rotation	35.33±4.73	36.33±4.51	45	-3.713/-4.914	0.065/0.039*

Note. *Significant at p<0.05

Individual subject data (Flexion/Extension/Abduction/Adduction/Ext Rot/Int Rot):

- **A.R:** 121/16/52/26/35/35 (L), 122/19/55/28/37/37 (R)
- **V.A:** 116/22/49/17/32/31 (L), 120/27/53/25/40/39 (R)
- **H.T:** 118/25/67/28/41/40 (L), 112/17/58/20/33/33 (R)

Significant findings: Left hip flexion deficit (5.63%, p=0.004), right hip abduction deficit (26.51%, p=0.010), and right internal rotation deficit (23.86%, p=0.039) indicate iliopsoas, hip abductor (gluteus medius/minimus, tensor fasciae latae), and internal rotator (gluteus medius, anterior gluteus minimus) tightness. These restrictions correlate with increased low back pain risk and altered gait mechanics (Ellison et al., 1990; Cibulka et al., 2009).

3.4 Knee joint assessment

Table 4. *Knee joint flexibility measurements*

Movement	Left (°)	Right (°)	Reference (°)	Deficit (%)	*t*-value	*p*-value
Flexion	120.33±5.51	121.33±7.64	135	12.19/11.26	-4.612/-4.040	0.044*/0.056
Extension	6.00±2.65	5.67±2.31	10	66.67/76.41	-2.619/-2.457	0.120/0.133

Note. *Significant at $p<0.05$

Individual subject data:

- **A.R:** Flexion 115/117 (L/R), Extension 7/9
- **V.A:** Flexion 120/128, Extension 3/5
- **H.T:** Flexion 126/119, Extension 8/3

Interpretation: Left knee flexion deficit (12.19%, $p=0.044$) suggests hamstring, gastrocnemius, and popliteus muscle tightness. The non-significant but substantial extension deficits (66.67-76.41%) reflect quadriceps and tensor fasciae latae restrictions limiting terminal knee extension essential for gait efficiency.

3.5 Ankle joint assessment

Table 5. *Ankle joint flexibility measurements*

Movement	Left (°)	Right (°)	Reference (°)	Deficit (%)	*t*-value	*p*-value
Dorsiflexion	15.00±2.00	14.33±2.52	20	33.33/39.55	-2.402/-2.177	0.138/0.161
Plantarflexion	42.67±7.77	43.33±4.04	55	28.90/26.93	-2.547/-3.938	0.126/0.059
Eversion	5.67±1.53	6.00±2.00	10	76.42/66.67	-3.250/-3.464	0.083/0.074
Inversion	9.33±3.21	9.67±2.31	15	60.74/55.15	-2.592/-3.024	0.122/0.094

Individual subject data:

- **A.R:** Dorsi 18/19, Plantar 48/49, Eversion 7/8, Inversion 12/13
- **V.A:** Dorsi 11/14, Plantar 33/42, Eversion 3/6, Inversion 5/9
- **H.T:** Dorsi 16/10, Plantar 47/39, Eversion 7/4, Inversion 11/7

Critical findings: Despite non-significant *p*-values, the 28.90-39.55% dorsiflexion deficits and 26.93-28.90% plantarflexion restrictions represent clinically meaningful limitations. Dorsiflexion restrictions (gastrocnemius-soleus complex tightness) associate with increased ankle sprain risk, Achilles tendinopathy, and altered running mechanics (Hoch & McKeon, 2011). The dramatic eversion (66.67-76.42%) and inversion (55.15-60.74%) deficits indicate peroneal and tibialis posterior muscle inflexibility compromising frontal plane ankle stability.

4. DISCUSSION

4.1 Cervical spine flexibility patterns

The cervical region, representing the most mobile spinal segment, demonstrated significant restrictions in flexion (13.21%, p=0.034) and left rotation (9.44%, p=0.026). These deficits reflect modern technology-related postural dysfunction: forward head positioning during computer/smartphone use creates sustained anterior cervical muscle lengthening while shortening posterior cervical extensors (suboccipital muscles, upper trapezius, levator scapulae) (Kim et al., 2015; Straker et al., 2018).

The 32.08% left lateral bending deficit, while non-significant (p=0.085), suggests unilateral occupational stress patterns. Handedness-related asymmetric carrying behaviors, sleeping positions, and workplace ergonomics create chronic unilateral loading promoting adaptive tissue changes (Kendall et al., 2005).

Clinical implications: Cervical flexibility restrictions associate with neck pain, headaches, shoulder dysfunction, and upper extremity radiculopathy. The identified deficits warrant preventive intervention through postural correction, ergonomic workplace modifications, and targeted stretching protocols (Blanpied et al., 2017).

4.2 Thoracolumbar spine mobility restrictions

The 66.67% thoracolumbar extension deficit (p=0.041) represents this investigation's most substantial spinal restriction. Modern sedentary lifestyles with prolonged sitting in flexed postures create adaptive shortening of anterior trunk musculature (rectus abdominis, external obliques) while lengthening posterior extensors (erector spinae, multifidus, semispinalis) (McGill, 2015; O'Sullivan et al., 2018).

This pattern generates biomechanical consequences: (1) increased lumbar disc loading through sustained flexion stress, (2) reduced spinal stability from weakened posterior musculature, (3) altered hip-spine rhythm during forward bending, and (4) compensatory movement patterns predisposing to low back pain (Adams & Hutton, 1985; McGill, 2015).

The 11.87% flexion deficit (non-significant, p=0.130) appears paradoxical given chronic flexion positioning. However, hamstring tightness, posterior hip capsule restrictions, and thoracic kyphosis rigidity limit functional forward bending despite anterior muscle lengthening (López-Miñarro et al., 2012).

Rotational mobility: The 5.81-11.35% rotation deficits (non-significant) reflect thoracic cage constraints limiting axial plane motion. Rib attachments to thoracic vertebrae create inherent rotational restrictions, with costovertebral joint stiffness further limiting mobility (Neumann, 2017). These restrictions impact functional activities, requiring trunk rotation (reaching, turning, athletic movements) and may contribute to compensatory lumbar rotation, increasing low back injury risk.

4.3 Coxofemoral joint flexibility deficits

Hip joint restrictions carry particular clinical significance given the joint's role in lower extremity function and lumbar spine protection. Statistically significant deficits in left flexion (5.63%, p=0.004), right abduction (26.51%, p=0.010), and right internal rotation (23.86%, p=0.039) create biomechanical and functional consequences.

Flexion restrictions: The iliopsoas muscle group (psoas major, iliacus) demonstrates adaptive shortening from prolonged sitting positioning. Hip flexor tightness creates anterior pelvic tilt, increasing lumbar lordosis and facet joint loading while altering hip-spine rhythm during functional movements (Winters et al., 2004; Van Dillen et al., 2000). This pattern strongly correlates with low back pain incidence and chronicity.

Abduction deficits: Hip abductor restrictions (gluteus medius, gluteus minimus, tensor fasciae latae) compromise frontal plane pelvic stability during single-leg stance, gait, and running. Reduced abduction associates with: (1) Trendelenburg gait patterns, (2) increased knee valgus stress predisposing to patellofemoral pain and ACL injury, (3) iliotibial band syndrome from TFL tightness, and (4) greater trochanteric pain syndrome (Fredericson et al., 2000; Souza & Powers, 2009).

Rotational limitations: Hip rotation restrictions (both external and internal) alter femoral-acetabular mechanics, potentially contributing to femoroacetabular impingement, labral pathology, and hip osteoarthritis development (Nepple et al., 2015). Athletes requiring rotational mobility (baseball, golf, tennis, martial arts) demonstrate performance decrements and injury susceptibility with restricted hip rotation (Ellison et al., 1990).

Extension deficits: The 42.86% extension restrictions (non-significant, $p>0.05$) reflect combined hip flexor and anterior capsule tightness. Reduced hip extension forces compensatory lumbar hyperextension during gait stance phase, increasing low back stress and potentially contributing to spondylolysis and facet joint pathology (Sahrmann, 2002).

4.4 Knee and ankle mobility patterns

Knee joint: The significant left flexion deficit (12.19%, $p=0.044$) indicates hamstring, gastrocnemius, and popliteus muscle tightness. While 120-125° knee flexion permits most functional activities, maximal flexion capacity enables full squat mechanics essential for athletic performance and certain occupational demands. The substantial extension deficits (66.67-76.41%, non-significant) reflect quadriceps and rectus femoris tightness, limiting terminal knee extension critical for gait efficiency and patellofemoral joint health (Neumann, 2017).

Ankle complex: The 28.90-39.55% dorsiflexion deficits, while statistically non-significant ($p>0.05$), represent clinically meaningful restrictions. Dorsiflexion limitations (gastrocnemius-soleus complex tightness) create biomechanical consequences throughout the lower kinetic chain such as:

1. **Compensatory pronation:** Reduced dorsiflexion forces subtalar joint eversion to maintain foot clearance during gait, increasing medial arch stress and contributing to plantar fasciitis, posterior tibial tendon dysfunction, and medial knee loading (Kaufman et al., 1999);

2. **Ankle sprain risk:** Limited dorsiflexion during landing mechanics increases inversion moments, predisposing to lateral ankle sprains (Hoch & McKeon, 2011);
3. **Achilles pathology:** Chronic gastrocnemius-soleus tightness increases Achilles tendon loading, contributing to tendinopathy and rupture risk (Kaufman et al., 1999);
4. **Knee and hip compensation:** Restricted ankle mobility forces increased knee flexion and hip flexion during squatting and stair climbing, altering joint loading patterns (Fong et al., 2011).

The dramatic eversion (66.67-76.42%) and inversion (55.15-60.74%) deficits indicate frontal plane ankle inflexibility compromising lateral stability mechanisms. Peroneal muscle tightness (limiting inversion) and tibialis posterior/flexor hallucis longus restrictions (limiting eversion) reduce the ankle's ability to accommodate uneven terrain, increasing fall risk in elderly populations and ankle injury susceptibility in athletes.

4.5 Integrated kinetic chain considerations

The identified flexibility deficits across spinal and lower extremity regions do not exist in isolation but interact through kinetic chain biomechanics. Hip flexion restrictions force compensatory lumbar flexion during forward bending (altered hip-spine rhythm), increasing lumbar disc stress. Ankle dorsiflexion limitations necessitate increased knee flexion and hip flexion during squatting, altering load distribution. Thoracolumbar extension deficits combine with hip flexor tightness to create sustained anterior pelvic tilt and lumbar hyperextension (lower crossed syndrome pattern) (Janda, 1987).

These integrated restrictions compromise functional movement patterns assessed through screening tools (Functional Movement Screen, Y-Balance Test), potentially predicting injury risk and performance limitations (Cook et al., 2014; Plisky et al., 2006).

4.6 Clinical recommendations

Cervical spine:

- chin tuck exercises for deep cervical flexor strengthening;
- upper trapezius and levator scapulae stretching (sustained holds 30-60 seconds);
- postural awareness training and ergonomic workplace modifications;
- cervical rotation mobilizations targeting restricted segments.

Thoracolumbar spine:

- extension-based exercises (prone press-ups, standing back bends) emphasizing thoracolumbar mobility;
- anterior trunk muscle stretching (kneeling hip flexor stretch progressing to thoracic extension);
- core stabilization emphasizing neutral spine positioning;
- rotational mobility exercises (seated/standing trunk rotation, yoga poses).

Coxofemoral joint:

- hip flexor stretching complex (standing/kneeling lunges, modified Thomas position);
- hip abductor stretching (standing iliotibial band stretch, side-lying positions);
- hip rotator flexibility (figure-4 position, 90-90 sitting rotations);
- progressive strengthening maintaining gained flexibility (hip extension, abduction, rotation exercises).

Knee and ankle:

- hamstring stretching (straight leg raise progressions, standing/seated forward bends);
- gastrocnemius-soleus complex stretching (wall leans, heel drops, slant board positioning);
- ankle mobility exercises (dorsiflexion with knee flexed/extended distinguishing gastrocnemius *vs* soleus);
- proprioceptive training for frontal plane ankle stability.

General principles:

- daily stretching consistency (accumulating 3-5 minutes per muscle group weekly);
- 30-60 second-static holds at moderate intensity (4-6/10 discomfort scale);

- progressive overload through increased duration, frequency, or intensity;
- functional integration incorporating gained flexibility into movement patterns;
- maintenance programs following initial flexibility improvements.

4.7 Study strengths and limitations

Strengths: comprehensive multi-regional assessment protocol, standardized digital goniometry eliminating measurement error, bilateral comparisons identifying asymmetries, statistical analysis establishing significance of observed restrictions, clinical interpretation providing actionable recommendations.

Limitations: small sample size (n=3) limiting statistical power and generalizability, preliminary study design without test-retest reliability assessment, healthy young adult population limiting applicability to clinical/elderly populations, cross-sectional design precluding longitudinal tracking, active-only measurements without passive comparison to distinguish contractile *vs* non-contractile restrictions, lack of functional movement assessment correlating flexibility deficits with performance outcomes.

4.8 Future research priorities

Large-scale normative database development (n>1000) stratified by age, sex, occupation, and athletic participation; longitudinal prospective cohort studies linking baseline flexibility to injury incidence and low back pain development; randomized controlled trials evaluating stretching intervention efficacy with objective digital outcomes; investigation of genetic, anthropometric, and lifestyle factors influencing flexibility profiles; development of flexibility-based injury prediction models; clinical validation in pathological populations (osteoarthritis, chronic pain, post-surgical); technology integration enabling remote monitoring and telehealth applications.

5. CONCLUSIONS

This comprehensive investigation utilizing Mobee Med digital goniometry reveals systematic flexibility deficits across spinal and lower extremity joints in apparently healthy young adults. Despite the absence of clinical symptoms, the identified restrictions represent modifiable risk factors for musculoskeletal pathology and functional performance limitations.

Key findings:

1. **Cervical spine:** significant flexion (13.21%, *p*=0.034) and rotation (9.44%, *p*=0.026) deficits indicating technology-related postural dysfunction;
2. **Thoracolumbar spine:** dramatic extension restriction (66.67%, *p*=0.041), reflecting chronic sitting postures and anterior trunk muscle dominance;
3. **Coxofemoral joint:** significant deficits in flexion (5.63%, *p*=0.004), abduction (26.51%, *p*=0.010), and internal rotation (23.86%, *p*=0.039), creating low back pain risk and altered gait mechanics;
4. **Knee:** significant flexion limitation (12.19%, *p*=0.044) with substantial extension deficits (66.67-76.41%), compromising terminal extension mechanics;
5. **Ankle:** clinically meaningful dorsiflexion (28.90-39.55%), plantarflexion (26.93-28.90%), and frontal plane motion restrictions (55.15-76.42%), predisposing to lower extremity pathology.

Technological validation

Mobee Med digital goniometry provides ±0.5° precision, three-axis multi-planar capture, standardized neutral-zero methodology, real-time visualization, and comprehensive documentation superior to traditional assessment methods.

Clinical significance

Identified subclinical flexibility deficits represent early-stage biomechanical dysfunction, warranting preventive intervention. Cervical and thoracolumbar restrictions contribute to neck pain, headaches, and low back pathology. Hip mobility limitations alter hip-spine rhythm and gait mechanics, increasing lumbar stress. Ankle restrictions compromise kinetic chain function from ground contact through proximal segments.

Practical impact

Integration of digital flexibility assessment into routine screening protocols enables: (1) objective baseline establishment for longitudinal tracking, (2) early identification of injury risk profiles, (3) individualized intervention program development targeting specific deficits, (4) objective progress monitoring demonstrating treatment efficacy, (5) prevention of clinical symptom manifestation through proactive flexibility maintenance.

Final statement: Comprehensive spinal and lower extremity flexibility assessment using digital goniometry reveals prevalent subclinical restrictions even in healthy populations. Modern lifestyle factors (prolonged sitting, technology use, reduced physical activity) create systematic flexibility losses predisposing to musculoskeletal pathology. Early detection through precise, objective digital measurement enables evidence-based preventive interventions, optimizing musculoskeletal health, functional performance, and injury risk reduction. The Mobee Med system represents essential technological advancement for contemporary physical therapy, sports medicine, and occupational health practice.

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7. CONFLICTS OF INTEREST

The authors declare no conflicts of interest. Mobee Med equipment was provided institutionally without commercial relationship or financial arrangement with the manufacturer.

REFERENCES

1. *Adams, M. A., & Hutton, W. C. (1985). Gradual disc prolapse. Spine, 10(6), 524-531. https://doi.org/10.1097/00007632-198507000-00006*
2. *Blanpied, P. R., Gross, A. R., Elliott, J. M., Devaney, L. L., Clewley, D., Walton, D. M., Sparks, C., & Robertson, E. K. (2017). Neck pain: Revision 2017. Journal of Orthopaedic & Sports Physical Therapy, 47(7), A1-A83. https://doi.org/10.2519/jospt.2017.0302*
3. *Cibulka, M. T., Sinacore, D. R., Cromer, G. S., & Delitto, A. (2009). Unilateral hip rotation range of motion asymmetry in patients with sacroiliac joint regional pain. Spine, 34(9), E289-E294. https://doi.org/10.1097/BRS.0b013e31819c7a95*

4. *Cook, G., Burton, L., Hoogenboom, B. J., & Voight, M. (2014). Functional movement screening: The use of fundamental movements as an assessment of function—Part 2. International Journal of Sports Physical Therapy, 9(4), 549-563. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4127517/*
5. *Ellison, J. B., Rose, S. J., & Sahrmann, S. A. (1990). Patterns of hip rotation range of motion: A comparison between healthy subjects and patients with low back pain. Physical Therapy, 70(9), 537-541. https://doi.org/10.1093/ptj/70.9.537*
6. *Fong, C. M., Blackburn, J. T., Norcross, M. F., McGrath, M., & Padua, D. A. (2011). Ankle-dorsiflexion range of motion and landing biomechanics. Journal of Athletic Training, 46(1), 5-10. https://doi.org/10.4085/1062-6050-46.1.5*
7. *Fredericson, M., Cookingham, C. L., Chaudhari, A. M., Dowdell, B. C., Oestreicher, N., & Sahrmann, S. A. (2000). Hip abductor weakness in distance runners with iliotibial band syndrome. Clinical Journal of Sport Medicine, 10(3), 169-175. https://doi.org/10.1097/00042752-200007000-00004*
8. *Harrison, D. E., Harrison, D. D., Betz, J. J., Janik, T. J., Holland, B., Colloca, C. J., & Haas, J. W. (2003). Increasing the cervical lordosis with chiropractic biophysics seated combined extension-compression and transverse load cervical traction with cervical manipulation: Nonrandomized clinical control trial. Journal of Manipulative and Physiological Therapeutics, 26(3), 139-151. https://doi.org/10.1016/S0161-4754(02)54106-3*
9. *Hoch, M. C., & McKeon, P. O. (2011). Joint mobilization improves spatiotemporal postural control and range of motion in those with chronic ankle instability. Journal of Orthopaedic Research, 29(3), 326-332. https://doi.org/10.1002/jor.21256*
10. *Janda, V. (1987). Muscles and motor control in low back pain: Assessment and management. In L. T. Twomey (Ed.), Physical therapy of the low back (pp. 253-278). Churchill Livingstone.*
11. *Kaufman, K. R., Brodine, S. K., Shaffer, R. A., Johnson, C. W., & Cullison, T. R. (1999). The effect of foot structure and range of motion on musculoskeletal overuse injuries. The American Journal of Sports Medicine, 27(5), 585-593. https://doi.org/10.1177/03635465990270050701*
12. *Kendall, F. P., McCreary, E. K., Provance, P. G., Rodgers, M. M., & Romani, W. A. (2005). Muscles: Testing and function with posture and pain (5th ed.). Lippincott Williams & Wilkins.*

13. *Kim, D., Cho, M., Park, Y., & Yang, Y. (2015). Effect of an exercise program for posture correction on musculoskeletal pain. Journal of Physical Therapy Science, 27(6), 1791-1794.* https://doi.org/10.1589/jpts.27.1791
14. *López-Miñarro, P. A., Muyor, J. M., Belmonte, F., & Alacid, F. (2012). Acute effects of hamstring stretching on sagittal spinal curvatures and pelvic tilt. Journal of Human Kinetics, 31, 69-78.* https://doi.org/10.2478/v10078-012-0007-8
15. *McGill, S. M. (2015). Low back disorders: Evidence-based prevention and rehabilitation (3rd ed.). Human Kinetics.*
16. *Mobee Med. (n.d.). Mobee Med digital goniometry system.* https://www.mobee.de
17. *Nepple, J. J., Prather, H., Trousdale, R. T., Clohisy, J. C., Beaule, P. E., Glyn-Jones, S., & Giori, N. J. (2015). Diagnostic imaging of femoroacetabular impingement. Journal of the American Academy of Orthopaedic Surgeons, 23(Suppl), S25-S35.* https://doi.org/10.5435/JAAOS-D-14-00446
18. *Neumann, D. A. (2017). Kinesiology of the musculoskeletal system: Foundations for rehabilitation (3rd ed.). Elsevier.*
19. *Oatis, C. A. (2017). Kinesiology: The mechanics and pathomechanics of human movement (3rd ed.). Lippincott Williams & Wilkins.*
20. *O'Sullivan, P. B., Caneiro, J. P., O'Keeffe, M., Smith, A., Dankaerts, W., Fersum, K., & O'Sullivan, K. (2018). Cognitive functional therapy: An integrated behavioral approach for the targeted management of disabling low back pain. Physical Therapy, 98(5), 408-423.* https://doi.org/10.1093/ptj/pzy022
21. *Plisky, P. J., Rauh, M. J., Kaminski, T. W., & Underwood, F. B. (2006). Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. Journal of Orthopaedic & Sports Physical Therapy, 36(12), 911-919.* https://doi.org/10.2519/jospt.2006.2244
22. *Sahrmann, S. A. (2002). Diagnosis and treatment of movement impairment syndromes. Mosby.*
23. *Souza, R. B., & Powers, C. M. (2009). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. Journal of Orthopaedic & Sports Physical Therapy, 39(1), 12-19.* https://doi.org/10.2519/jospt.2009.2885
24. *Straker, L., Coleman, J., Skoss, R., Maslen, B., Burgess-Limerick, R., & Pollock, C. (2008). A comparison of posture and muscle activity during tablet computer, desktop computer*

and paper use by young children. Ergonomics, 51(4), 540-555. https://doi.org/10.1080/00140130701711000

25. *Van Dillen, L. R., Sahrmann, S. A., Norton, B. J., Caldwell, C. A., McDonnell, M. K., & Bloom, N. J. (2000). Movement system impairment-based categories for low back pain: Stage 1 validation. Journal of Orthopaedic & Sports Physical Therapy, 30(6), 231-242. https://doi.org/10.2519/jospt.2000.30.6.231*
26. *Williams, R., Binkley, J., Bloch, R., Goldsmith, C. H., & Minuk, T. (1993). Reliability of the modified-modified Schöber and double inclinometer methods for measuring lumbar flexion and extension. Physical Therapy, 73(1), 26-37. https://doi.org/10.1093/ptj/73.1.26*
27. *Winters, M. V., Blake, C. G., Trost, J. S., Marcello-Brinker, T. B., Lowe, L., Garber, M. B., & Wainner, R. S. (2004). Passive versus active stretching of hip flexor muscles in subjects with limited hip extension: A randomized clinical trial. Physical Therapy, 84(9), 800-807. https://doi.org/10.1093/ptj/84.9.800*