Case Report

Pilot Study: Full-Body Postural Morphological Assessment Using a Non-Invasive Dual-Camera Structured Light System

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Pilot Study: Full-Body Postural Morphological Assessment Using a Non-Invasive Dual-Camera Structured Light System

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Abstract

Background: Postural assessment is fundamental for the diagnosis and monitoring of musculoskeletal disorders. Radiographic techniques, while being the gold standard, expose patients to ionizing radiation, limiting their use in repeated screenings. Structured light systems offer a non-invasive, safe, and repeatable alternative. This pilot study introduces a new-generation Spine3D system, with a dual-camera architecture, for a full-body morphological assessment. **Methods:** An observational-descriptive study was conducted on 44 healthy male subjects (age 25–65 years). Posture was assessed using the Spine3D system, which utilizes two Time-of-Flight (ToF) cameras for instantaneous, radiation-free acquisition. Descriptive statistics and a Pearson correlation analysis (with FDR correction) were calculated for 38 postural parameters. **Results:** The analysis identified 148 statistically significant correlations ($p_{FDR} < 0.05$). Among the most relevant were a strong positive correlation between cervical and lumbar lordosis ($r = +0.666$) and a moderate negative correlation between cervical lordosis depth and craniovertebral angle ($r = -0.465$), indicating that a more pronounced cervical curve is associated with a more protruded head posture. **Conclusions:** The updated Spine3D system proved to be an effective tool for a global, rapid, and safe postural assessment. Its non-invasive nature and high repeatability make it ideal for longitudinal monitoring, screening, and evaluating therapeutic interventions. The data confirm the close interdependence between the various body segments, emphasizing the importance of a holistic approach.

Keywords: posture; rasterstereography; structured light; sagittal balance; spine; non-invasive; Spine3D

1. Introduction

The assessment of posture and spinal morphology is a cornerstone in the diagnosis and monitoring of numerous musculoskeletal disorders, whose impact on quality of life is widely documented [1,2]. Physiological aging induces progressive changes in the spine, including reduced bone mass and degenerative changes in discs, facet joints, and ligaments [3,4]. These alterations can compromise spinal biomechanics, affecting posture and load-bearing capacity [5].

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Traditionally, the analysis of spinal curves has relied on radiographic imaging (X-ray), which, despite being the gold standard for measuring bone angles [6], exposes the patient to ionizing radiation. This exposure, a known and documented risk [7,8], severely limits the **repeatability** of assessments, making radiographs an unsuitable tool for longitudinal screenings, frequent monitoring of deformity progression, or analysis in sensitive populations [9].

In recent years, the importance of sagittal balance has been widely recognized as a critical factor for spinal health and quality of life [10,11]. Consequently, the need for alternative diagnostic tools has grown. **Non-invasive** structured light technologies, such as rasterstereography, have emerged as a safe, reliable, and validated solution [12,13]. These systems allow for a 3D reconstruction of the trunk surface, from which clinical parameters related to the underlying spinal morphology can be derived with high precision and **repeatability**, as demonstrated by numerous intra- and inter-operator reliability studies [14–16]. The integration of postural assessment with the analysis of plantar pressure distribution is also gaining interest, as the foot is a key element in the postural chain [26].

This **pilot study** fits into this context with a dual objective:

1. To **present the technological evolution** of a Spine3D system, which moves from a single mobile camera architecture to a fixed **dual-camera Time-of-Flight (ToF)** configuration, capable of performing an instantaneous and complete full-body scan.
2. To **highlight the clinical potential** of this integrated approach, which, thanks to the extended analysis to the **cervical spine** and **lower limbs**, is proposed as a tool for a global (*in toto*), **non-invasive**, rapid, and, above all, highly **repeatable** morphological assessment of the subject.

2. Materials and Methods

2.1. Study Design and Sample

An observational-descriptive pilot study was conducted to characterize postural parameters in a convenience sample, using the updated Spine3D system. **44 male subjects** were recruited, with an age range of 25 to 65 years (mean age: 45 years).

The selection of an exclusively male sample at this stage was dictated by the need to optimize data acquisition, which requires the removal of the bra for a correct visualization of the dorsal anatomical landmarks, in line with standard protocols for back surface analysis [17].

2.2. Inclusion and Exclusion Criteria

Inclusion criteria were being male and having a chronological age within the 25–65 year range. The following **exclusion criteria** were applied:

1. Positive history of traumatic events affecting the musculoskeletal system in the last 6 months.
2. Current use of orthodontic appliances, bites, or other intra-oral devices.
3. Use of hearing aids.

2.3. Instrumentation: Spine3D Dual-Camera System

Postural assessments were performed using the updated version of the **Spine3D** structured light system (Sensor Medica, Guidonia Montecelio, Rome, Italy), a **non-invasive** device already used in previous studies for postural analysis in sports [18]. The technological upgrade replaced the previous single mobile camera configuration (Microsoft Kinect v2) with a fixed architecture of **two VZense DS86 cameras**.

The new hardware configuration includes:

- **Upper Camera**: Positioned at 1365 mm from the ground, dedicated to acquiring the upper trunk and head.
- **Lower Camera**: Positioned at 600 mm from the ground, dedicated to acquiring the pelvis and lower limbs.

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This arrangement ensures an instantaneous full-body acquisition (from head to heels) with a single shot, eliminating waiting times and possible patient motion artifacts. To overcome engineering challenges, specific solutions were implemented for managing interference between the ToF sensors (temporal desynchronization) and for aligning the two point clouds into a single 3D mesh (Iterative Closest Point, ICP, algorithm).

Table 1. Technical specifications of the VZense DS86 cameras used in the updated Spine3D system.

Technical Feature	New System (VZense DS86)
RGB Camera Resolution	1600x1200 pixels @ 30 fps
ToF Camera Resolution	640x480 pixels @ 15 fps
Operating Range	0.15 – 5 meters
Accuracy Error	< 1% at 1 meter distance
Data Connection	Gigabit Ethernet

2.4. Landmark Identification and Biomechanical Parameters

The accuracy of the system is based on the identification of specific anatomical landmarks. The updated software integrates an **automatic recognition system based on Artificial Intelligence**, which uses a deep neural network trained on a dataset of over 3000 images validated by expert operators. This approach minimizes human error and maximizes the **repeatability** of the measurements.

The full-body acquisition allowed for the implementation of new clinical parameters:

- **Advanced Cervical Spine Analysis**: Calculation of the **Cranio-Vertebral Angle** (estimation of head protrusion), **Lateral Head Tilt**, and **Head Rotation** on the transverse plane.
- **Lower Limb Analysis**: Measurement of pelvic discrepancy and tilt, **knee valgus/varus and flexion/extension angles** (coronal and sagittal planes), and morphometric length of femur and tibia.

2.5. Acquisition Protocol

All measurements were performed in an environment with standardized lighting conditions. Participants were asked to assume a natural, relaxed orthostatic position, barefoot and wearing only underwear (briefs). Subjects wearing prescription glasses were asked to keep them on. The acquisition was initiated by an expert operator with a single command.

2.6. Statistical Analysis

Data analysis was performed using the Python programming language and the Matplotlib and SciPy scientific libraries. Descriptive statistics (mean and standard deviation) were calculated for the main postural parameters. The normality of the data distribution was verified using the Shapiro-Wilk test.

To investigate the relationships between variables, a correlation analysis was conducted. The Pearson correlation coefficient (r) was calculated for all pairs of parameters. To manage the problem of multiple comparisons, the False Discovery Rate (FDR) correction according to the Benjamini-Hochberg method was applied. A correlation was considered statistically significant if the corrected p-value (p_FDR) was less than 0.05.

3. Results

3.1. Descriptive Statistics

The descriptive analysis of the main postural parameters of the cervical spine and the coronal plane is summarized in the following table. All parameters were calculated on a sample of N=44 subjects.

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Table 2. Descriptive statistics of the main cervical and coronal parameters.

Parameter	Unit	Mean	Std. Dev.	Min	Max
CervicalLordosisDepth_SAG	mm	56.36	13.25	33.0	88.0
CervicalArrow_SAG	mm	77.75	20.36	39.0	116.0
CraniovertebralAngle_SAG	°	62.54	8.35	45.8	81.6
LateralHeadTilt_COR	°	-0.89	2.12	-5.8	3.2
Head Rotation	°	0.62	2.47	-5.0	4.7

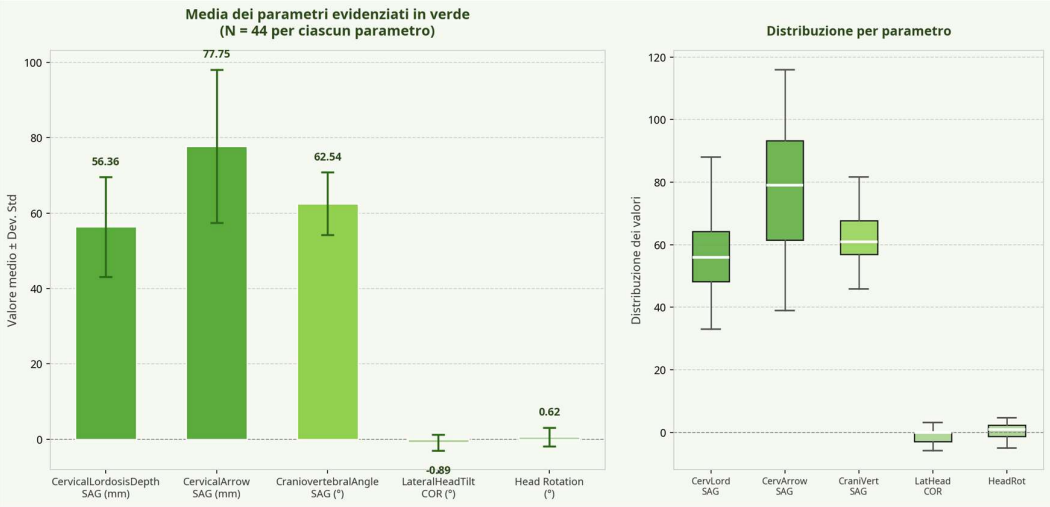

Figure 1. Descriptive statistics of the main cervical parameters. The left panel shows the mean and standard deviation for each parameter. The right panel shows the boxplot distribution for each parameter.

3.2. Correlation Analysis

3.2.1. Correlation between Cervical Lordosis and Craniovertebral Angle

The specific analysis between the depth of the cervical lordosis (*CervicalLordosisDepth_SAG*) and the craniovertebral angle (*CraniovertebralAngle_SAG*) revealed a **negative, statistically significant, and moderate correlation** (r = -0.465; p = 0.0015). This result indicates that as the depth of the cervical lordosis increases, the craniovertebral angle tends to decrease, suggesting an association between a more pronounced cervical curve and a more protruded head posture (Figure 2).

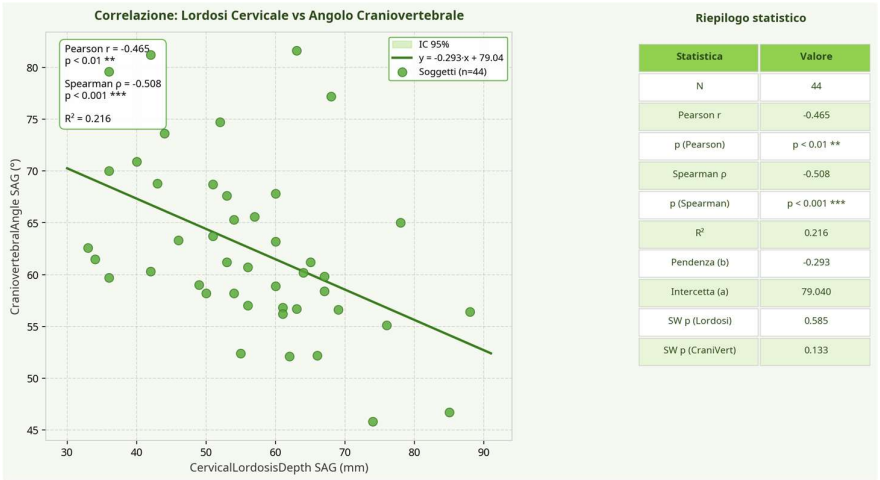

Figure 2. Scatter plot showing the negative correlation between cervical lordosis depth (mm) and craniovertebral angle (°). The line represents the linear regression line, with the 95% confidence interval shown in light green.

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3.2.2. Global Correlation Matrix and Clinically Relevant Relationships

The correlation analysis extended to 38 postural parameters identified **148 pairs with a statistically significant correlation** (p_FDR < 0.05 and |r| ≥ 0.3) after correction for multiple comparisons. Figure 3 shows the heatmap of the complete correlation matrix, while Figure 4 graphically summarizes the most clinically relevant correlations, grouped by anatomical domain.

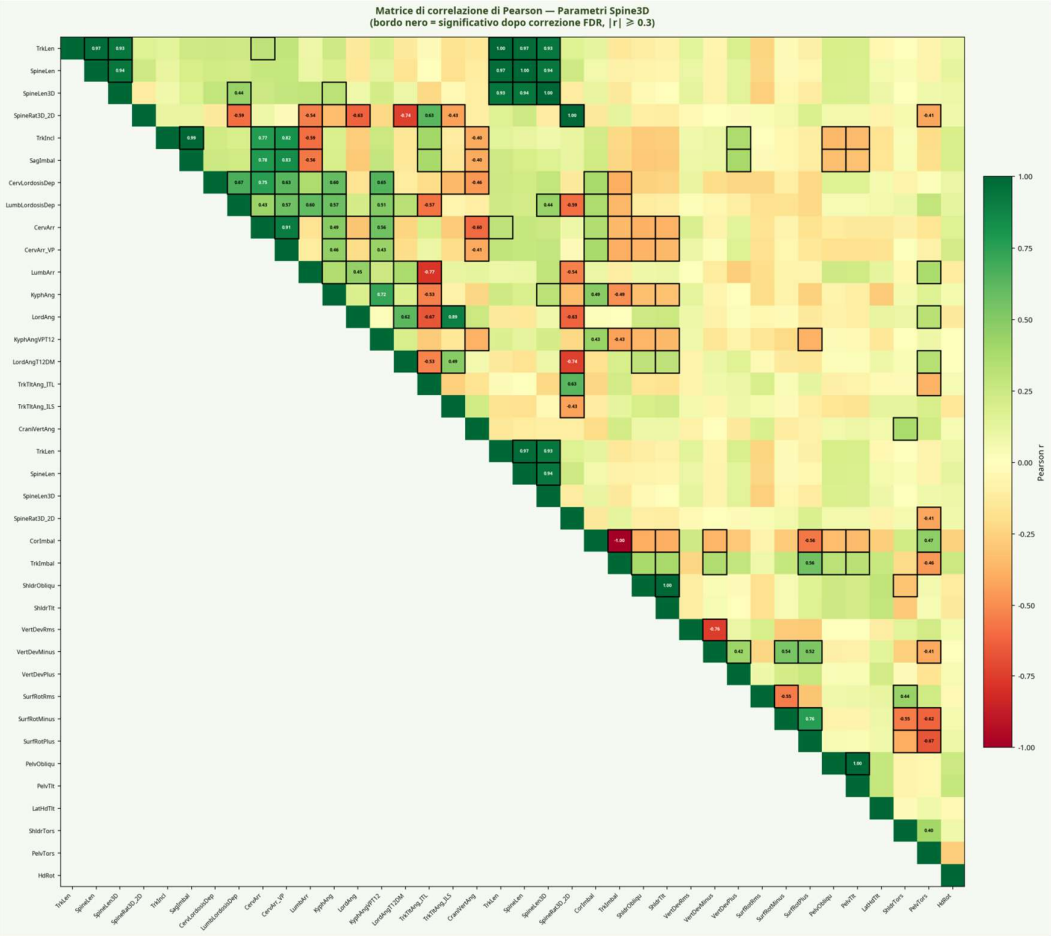

Figure 3. Heatmap of the Pearson correlation matrix between all 38 postural parameters. The color scale indicates the value of the correlation coefficient (r). Black borders highlight statistically significant correlations after FDR correction.

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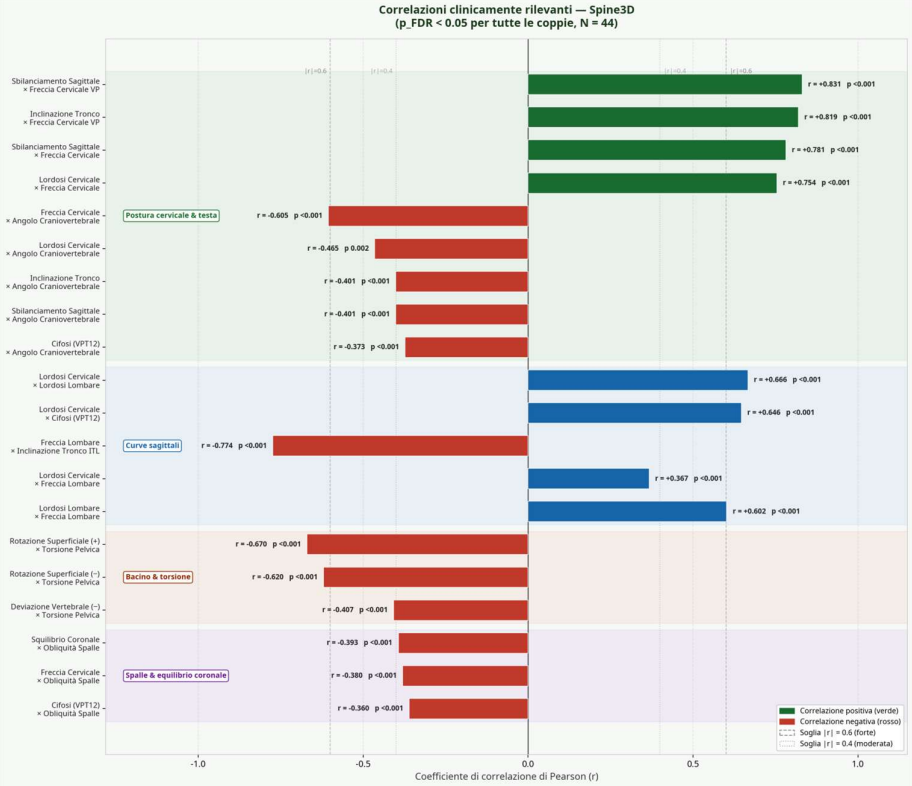

Figure 4. Bar chart of the main clinically relevant correlations, grouped by anatomical area. Green bars indicate a positive correlation, red bars a negative correlation. All pairs shown are statistically significant (p_FDR < 0.05).

The main results can be summarized as follows:

- **Cervical Posture & Head Domain**: A strong positive correlation is observed between the sagittal imbalance of the trunk and head protrusion (measured as *CervicalArrow_VP*, r = +0.831). The craniovertebral angle, as already seen, is negatively correlated not only with cervical lordosis (r = -0.465) but also with the cervical arrow (r = -0.605), confirming that head posture is closely linked to the morphology of the entire cervical and thoracic spine.
- **Sagittal Curves Domain**: A strong positive co-variation emerges between cervical and lumbar lordosis (r = +0.666), supporting the hypothesis of a functional coupling between the two curves. A positive correlation is also noted between cervical lordosis and the angle of thoracic kyphosis (r = +0.646).
- **Pelvis & Torsion Domain**: The surface rotation of the trunk was found to be negatively correlated with pelvic torsion (r up to -0.670), suggesting a possible compensatory mechanism between the two body districts on the transverse plane.

4. Discussion

This pilot study demonstrated the capabilities of the updated Spine3D system as a tool for a global, **non-invasive**, and rapid postural assessment. The dual-camera architecture and AI-based analysis algorithms allowed for the acquisition of a rich and complex dataset, from which numerous clinically relevant correlations emerged, in line with the literature investigating postural interdependencies [19,20].

The data confirm the close interconnection between the various body districts. The strong positive correlation between cervical and lumbar lordosis (r = +0.666) supports the concept of functional coupling between the spinal curves, a concept discussed in the literature [21,22]. Head posture, in particular, is not an isolated phenomenon but appears to be the result of a complex

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postural chain, being significantly correlated with the morphology of the sagittal curves of the trunk and the overall balance of the patient [11,23].

The main strength of this study lies in the use of a state-of-the-art technology that overcomes the limitations of traditional methods. The completely **non-invasive** and radiation-free nature of Spine3D makes it an ideal tool for clinical and research applications where **repeatability** is crucial. It is possible, for example, to perform serial assessments to monitor the progression of a deformity, evaluate the effectiveness of a rehabilitation intervention (such as postural gymnastics or physiotherapy) [24,25], or conduct screenings on large populations without any health risk to the participants [9]. Furthermore, the instantaneous acquisition minimizes motion artifacts and improves patient comfort.

5. Conclusions

In conclusion, this pilot study validated the use of the updated Spine3D system as a powerful tool for global postural assessment. The results not only provide preliminary normative data for an adult male population but, more importantly, highlight the complex interrelationships between the different body segments, reinforcing the need for a holistic approach in clinical practice.

The high **repeatability** and total **non-invasiveness** of the system make it a candidate to become a routine tool in clinical practice for the early diagnosis, monitoring, and management of postural disorders. Further studies on larger and more diverse populations, including female subjects and different age groups, are necessary to define complete normative values and to further explore the clinical applications of these advanced parameters in specific pathological contexts.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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