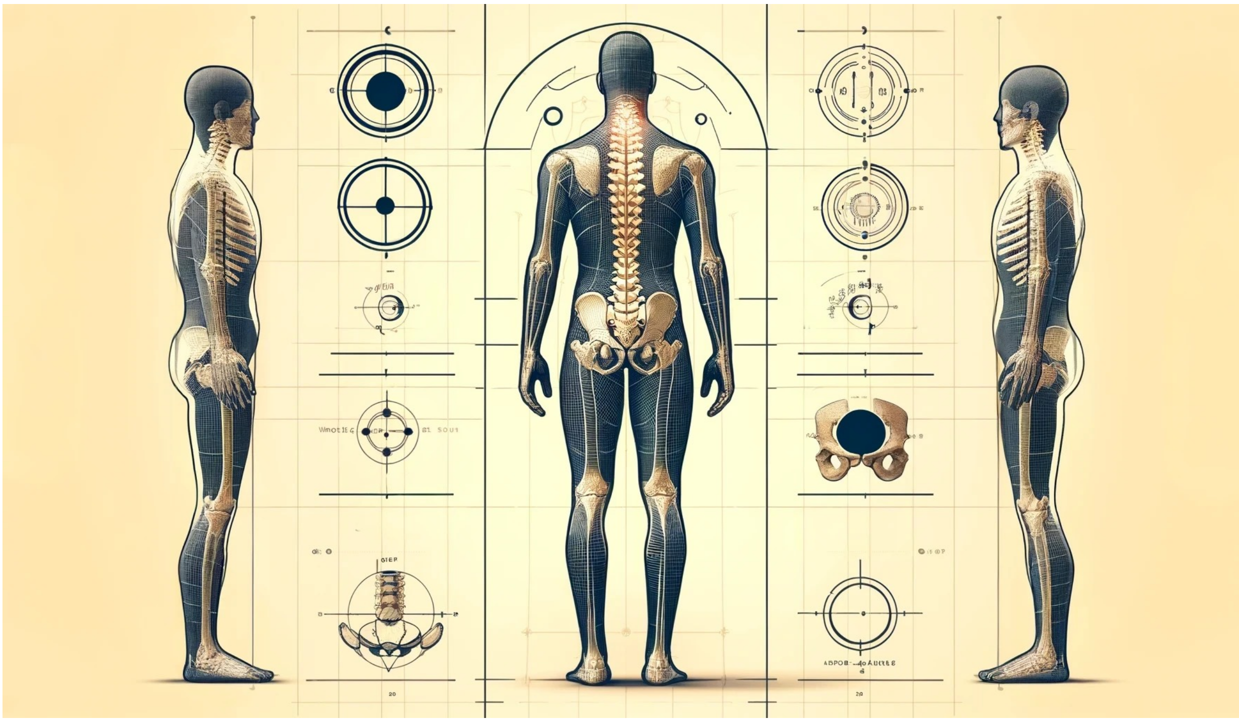
Postural Analysis using 3D Body Scans - Shapescale



1. Introduction

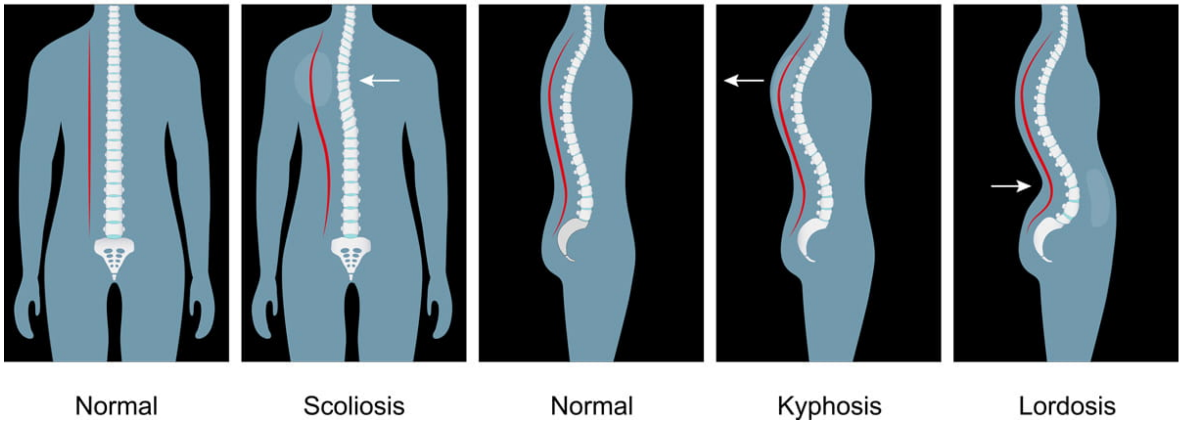
The assessment of human posture is very helpful for diagnosing and managing various musculoskeletal disorders. Accurate and reliable postural analysis offers valuable insights into the health of the spine and other body parts, enabling the early detection of conditions such as scoliosis, kyphosis, and lordosis. This report aims to provide a comprehensive overview of a postural analysis pipeline that utilizes whole-body 3D scans to deliver detailed metrics of overall posture. Additionally, it offers the scientific and academic context necessary to draw informed conclusions from these measurements, whilst also highlighting the limitations of the pipeline.

The main goal of this project is to create a postural analysis framework utilizing musculoskeletal metrics typically used in medical and research contexts. This framework aims to offer users dependable data and insights into potential posture issues, however it doesn't intend to guide actual clinical decisions. One primary concern is repeatability of measurements derived from standing scans. Factors such as slight variations in body position, scan quality or clothing can influence the results. Additionally, creating a standardized framework for evaluating posture, given the complexity of human anatomy, is extremely challenging. Bearing this in mind, a key aspect of this project was to combine each measurement with a confidence score, to provide the user with information regarding the reliability of the results.

The structure of this report is as follows: Each measurement is described in detail, including the underlying algorithm and metrics used, followed by a discussion of average values and thresholds beyond which users should be alerted to potential health concerns, based on scientific literature and empirical data. Finally, the report analyzes the repeatability and reliability of each metric, along with an explanation of the confidence score.

2. Pipeline Description

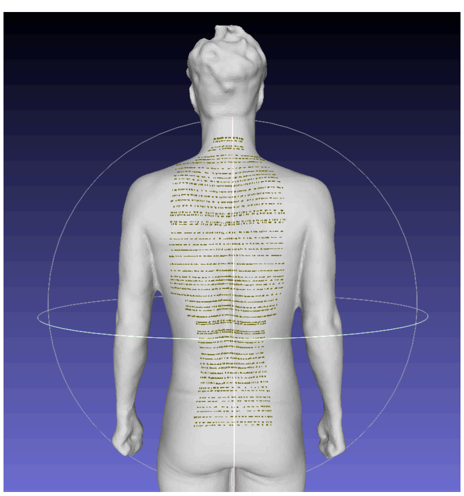
a. Spine Posture



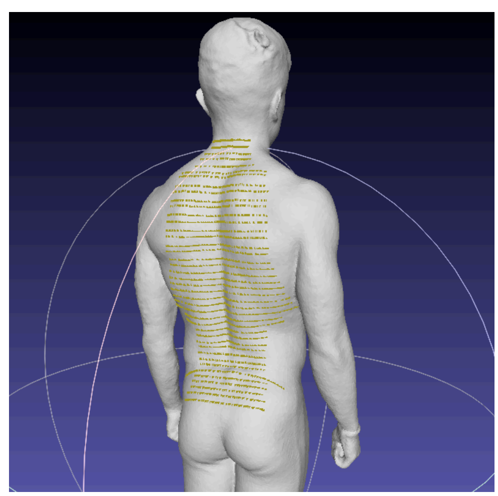
The spine is the central pillar of the human body, playing a crucial role in supporting weight, enabling flexible movement, and protecting the spinal cord. Postural analysis of the spine is the most important aspect of overall posture assessment because misalignments or deformities can lead to significant health issues, such as chronic pain, reduced mobility, and impaired function of vital organs. Accurate evaluation of the spine's alignment and curvature is essential for identifying early signs of conditions like scoliosis, kyphosis, and lordosis, which can be managed more effectively with early intervention[1].

Before discussing the four key metrics of spinal analysis, it is important to understand the process of spine mapping algorithm. This involves several steps:

1. *Horizontal Lines Drawing:* The first step in spine mapping involves drawing horizontal lines along the back of the subject. The number of lines is defined by a predetermined parameter. Each line serves as a reference for locating the spine at different vertical levels.



Back-view of Horizontal Slices n°1



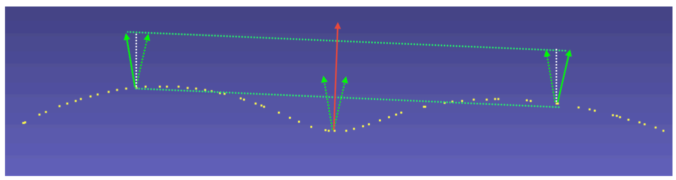
Back-view of Horizontal Slices n°2

[1] "A fresh look at spinal alignment and deformities: Automated analysis of a large database of 9832 biplanar radiographs," Frontiers in Medicine. This study highlights the importance of spinal alignment and the impact of deformities on overall health (frontiersin).

2. *Spine Location Methods:* For each horizontal line, the spine's location is determined using a series of three methods in succession:

   - **Maximum Curvature Detection:** This is the preferred method, especially effective for individuals with well-defined musculature. It involves analyzing the 3D mesh to find the point of maximum curvature, which often corresponds to the spine due to the muscle definition around it creating a distinct channel.

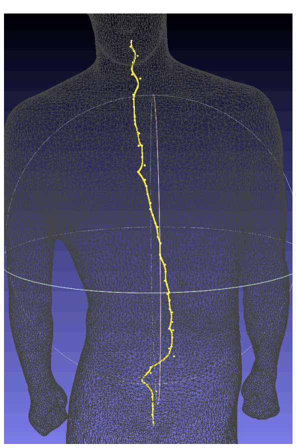
   - **Symmetry Analysis:** When the curvature is not well defined, which can occur if the person is overweight or wearing a top, the second method utilizes the body's symmetry. A normal vector is computed at each point along the horizontal line. The figure bellow should illustrates the idea.



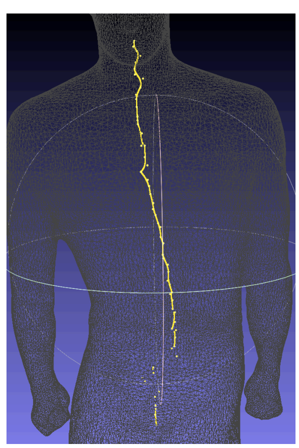
Symmetry Analysis schematic

   - **Vertical Line Intersection:** The third method is a backup, used when the previous two methods fail to yield accurate results. It involves drawing a line between the known lowest and highest points of the spine. The intersection of this new line with each horizontal line defines the key point.

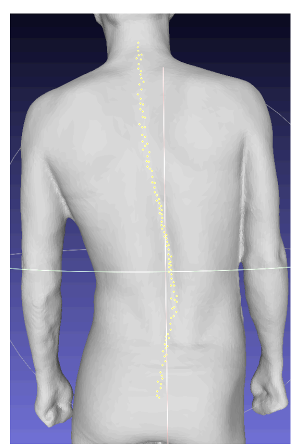
3. *Bezier Line Smoothing:* Once the key points are identified, a third-degree Bezier curve is used to interpolate a smooth curve that passes through these points. However, the data can contain noise. To address this, we filter out points along the curve that have a curvature higher than a given threshold. From the remaining points, we sample a new set of key points. The sampling is weighted based on the reliability of the initial point location method: points found using the maximum curvature detection method have the highest weight, those from the symmetry analysis have medium weight, and those from the vertical line intersection have the lowest weight. This weighting favors the more reliable points. From the new set of key points, a new Bezier curve is computed, resulting in a far smoother line.



First Bezier Curve



Filtered Bezier Curve

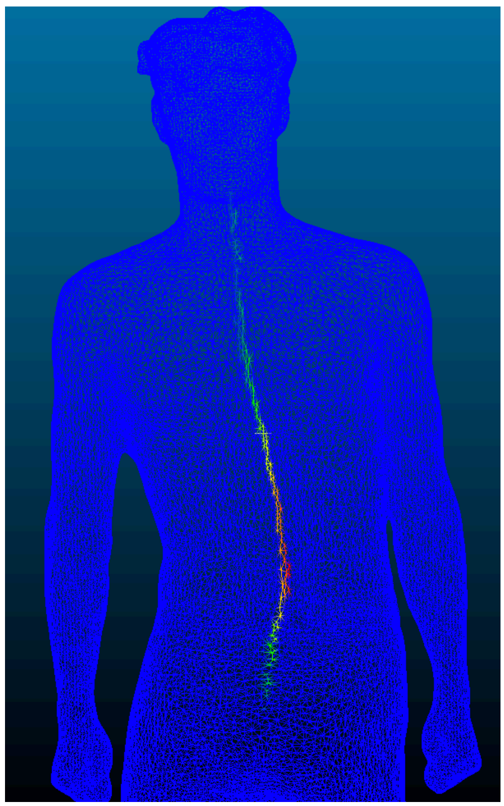


Second Weighted Bezier Curve

With the spine mapping established, the subsequent sections will delve into specific spine metrics crucial for postural analysis:

I. Scoliosis:

This section focuses on the lateral deviation of the spine that characterizes scoliosis. While Cobb's Angle is the typical measure for this deformity, it requires a precise X-ray view of the vertebrae. Therefore, a simpler metric was chosen that calculates the average lateral distance between each spine point and the straight line drawn from the lowest to the highest point of the spine. Although this metric makes intuitive sense, it lacks scientific validation, and any conclusion drawn from these measurements is based on empirical evidence. For the sake of clarity, this metric will be referred to as "Scoliosis distance".



Heat-map View of "Scoliosis Distance"

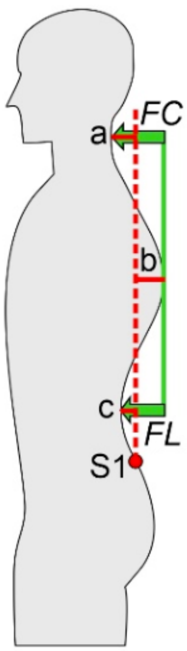
Threshold Values: Lower than 5mm (Good), lower than 10mm (Medium), higher than 10mm (Poor)

II. Kyphosis & Lordosis:

Kyphosis refers to an excessive outward curvature of the spine, causing a rounding of the upper back. This condition is commonly known as "hunchback" or "roundback." While a certain degree of kyphosis is normal, excessive curvature can lead to postural issues, back pain, and in severe cases, difficulty breathing.

Lordosis, on the other hand, is an excessive inward curvature of the spine, primarily in the lower back region. It is often referred to as "swayback." Like kyphosis, some degree of lordosis is normal, but too much curvature can lead to lower back pain and discomfort.
Following the methodology described by *Ludwig et al*[2], the kyphosis and lordosis are quantified by locating 4 key markers: The apices of cervical, thoracic and lumbar spine curves and the spinous process of the first sacral vertebra. Following the schematic bellow, the following three vectors are then calculated:

- *Flèche cervicale:* $FC = a + b$
- *Flèche lombaire:* $FL = b + c$
- *Kyphosis index:* $KI = (FC + FL)/2$



Red lines: horizontal distances of the 3 vertices to the perpendicular (dotted red line) through the first sacral vertebra (S1). Green arrows: flèche cervicale (FC) and flèche lombaire (FL).

As well explained in this same study: "*Flèche cervicale* and *flèche lombaire,* as well as the kyphosis index calculated from it, represent easy-to-measure parameters with which posture can be quickly assessed. FL values appear to remain stable from adulthood onward, whereas FC, FC%, KI, and KI%[3] increase with age in males, and sex differences become more pronounced with age. Taking into account age and sex differences, the posture can thus be assessed using the reference values presented in this study in order to initiate preventive or therapeutic measures if necessary".

[2] Ludwig, O.; Dindorf, C.; Kelm, J.; Simon, S.; Nimmrichter, F.; Fröhlich, M. Reference Values for Sagittal Clinical Posture Assessment in People Aged 10 to 69 Years. *Int. J. Environ. Res. Public Health* **2023**, *20*, 4131. https://doi.org/10.3390/ ijerph20054131

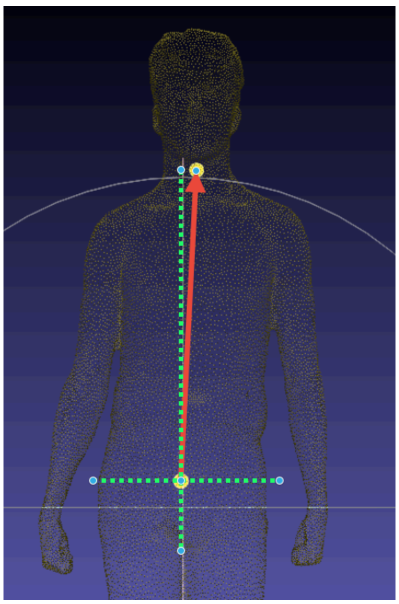
[3] FC%, FL% and KI% are normalized with trunk height

Therefore, using the data provided in the study, we can make reasonable assumptions about the kyphosis and lordosis of the spine. Furthermore, given that FC, FC%, KI and KI% increase with age, an estimate of the spine age can be made, which condenses the information in an elegant way.

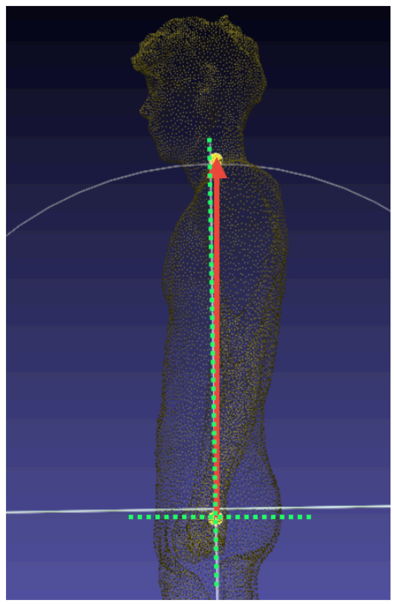
Threshold values are found in the paper and in the code.

III. Axis-Angles:

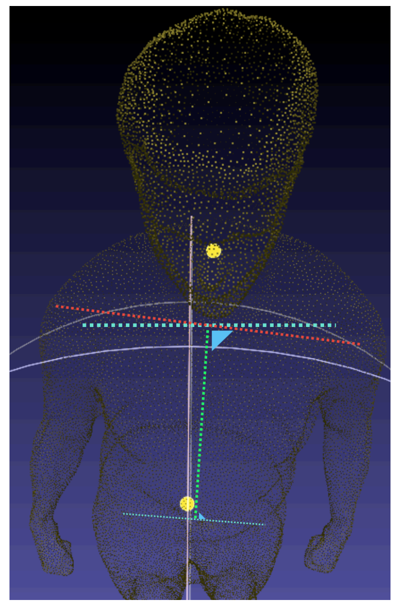
The final metrics used in the spine posture analysis are the axis-angles between a straight line passing through the lowest and highest points of the spine and the global frame (except for Y-Axis angle, which is the angle between hips and shoulders). Once again, there is no clear scientific validation to this measurement, however, it is often used by our competitors for it's intuitive nature and clarity.



Z-Axis Angle



X-Axis Angle



Y-Axis Angle

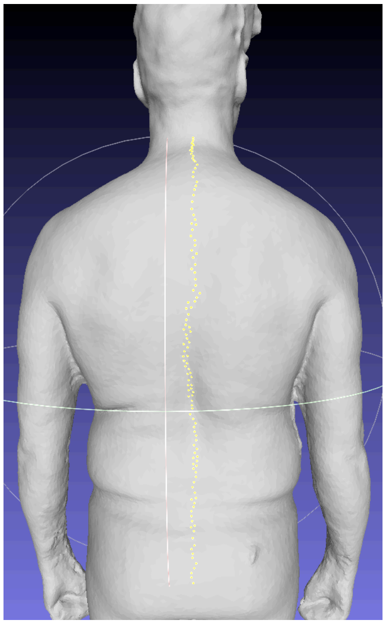
****Threshold value*** is irrelevant.

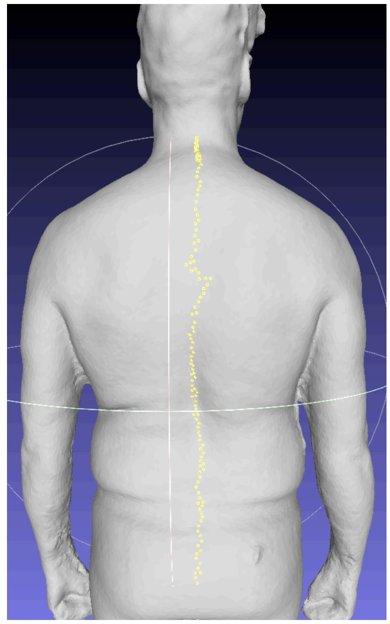
Reliability and Repeatability Assessment:

Based on the data collected thus far, the measurements of spinal posture appear to demonstrate strong repeatability, showing only slight variations from one scan to another, which is consistent with the presence of random sampling. However, the reliability of the spine measurements depends highly on the precision of the mapping process. As previously mentioned, the accuracy of this mapping process will vary among individuals. Here are three potential failure scenarios:

- *Lack of Muscle Definition*:

The mapping process primarily relies on detecting the channel formed by a well-defined muscle structure in the back. If an individual lacks muscle definition, the spine mapping must depend solely on body symmetry, often leading to noisy results. While this doesn't cause program crashes, it can result in the algorithm sometimes overlooking the presence of scoliosis, while at other times detecting scoliosis that isn't actually there. Other measurements remain unaffected.

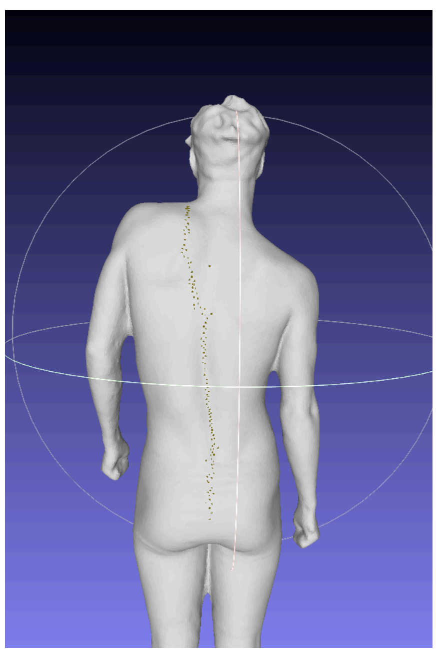




Here we have a man with poor muscle definition in the thoracic spine section, resulting in a higher likelihood of producing minor errors as observed on the right image.

- *Failed Neck Measurements:*

Although rare, severe shoulder asymmetry may lead to a failure in neck measurements. As the top of the spine's location depends on this measurement, a failure in neck measurement renders the spine mapping unreliable.



Severe shoulder imbalance causing the neck girth line to be be too low.

- *Clothing*:

If the individual wears clothing, the secondary spine mapping method is likely to fail, rendering measurements of scoliosis, kyphosis, and lordosis unreliable.
In some instances, a thick or tight sports bra worn by female users may also introduce erroneous results, as depicted in the right image below.

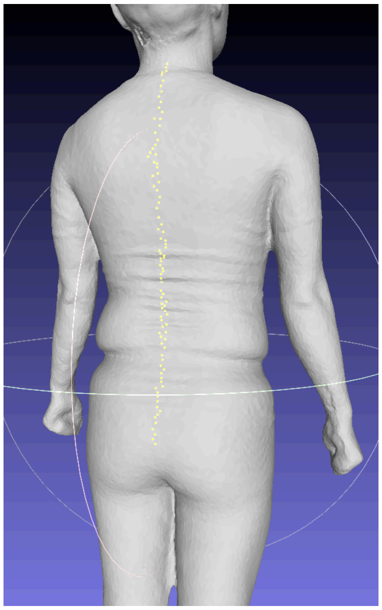
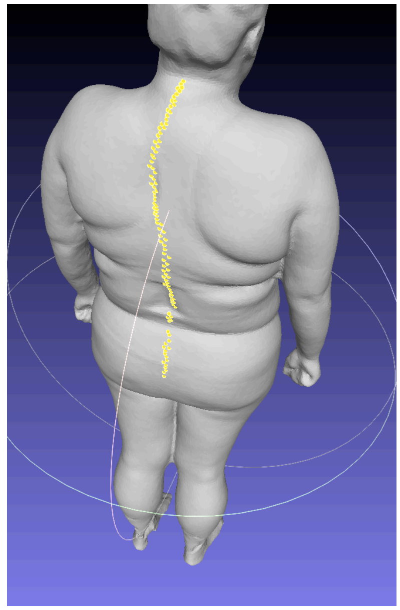


Figure showing a man wearing a t-shirt.



The spine mapping algorithm mistakes the skin fold created by the sports bra as the spine channel, resulting in an erroneous mapping.

Confidence score: The aim of the confidence score is to help identify these failure scenarios. Each key point in the spine line has a designated weight assigned to it, that depends on which spine location method is used. When employing the maximum curvature method, the assigned weight falls between 75% and 100%, contingent upon the depth of the spine channel. Points identified through symmetry analysis method carry weights ranging from 0% to 75%. Meanwhile, points detected through the third method do not contribute to the score.The confidence score is the average weight of all points.

While the confidence score excels in detecting both the absence of muscle definition and the presence of clothing, it struggles to reliably distinguishing between the two. Furthermore, it falls short in identifying erroneous mappings occasionally generated by sports bras. In such cases, the algorithm mistakenly identifies a spine channel, leading to an inflated confidence score.

b. Hips

I. Anterior Pelvic Tilt (APT)

Anterior pelvic tilt is a postural imbalance characterized by the forward rotation of the pelvis, causing the front of the pelvis to tilt downward and the lower back to arch excessively. This tilt results in an increased curvature of the lumbar spine, often termed as "hyperlordosis" or "swayback." Anterior pelvic tilt can be caused by a variety of factors including muscle imbalances, prolonged sitting, poor posture, and certain structural abnormalities.

For estimation the APT, an optimization based approach (Gradient Descent) is used. The process is almost identical to the neck measurement, however the cost function is different. Additionally, in an attempt to avoid local minima, the optimization algorithm is initialized at multiple heights before computing a weighted average of all output APTs.

Cost function: For a given input tilt angle, a ring of points is computed around the hips, and the points along the side flanks are filtered out. The function then calculates the normal vector for each remaining point and compares it to its corresponding point on the opposite side. Ideally, the angle between these corresponding normal vectors would be 180 degrees. We refer to this angle as the normal correspondence angle (NCA). To simplify, we normalize the NCA by subtracting 180, centering it around 0. Thus, the higher the average NCA for a given input tilt angle, the higher the cost. Hopefully, the following illustrations will help understanding.

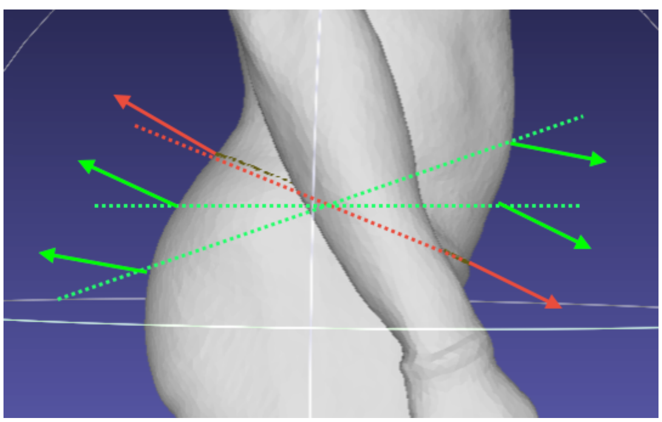
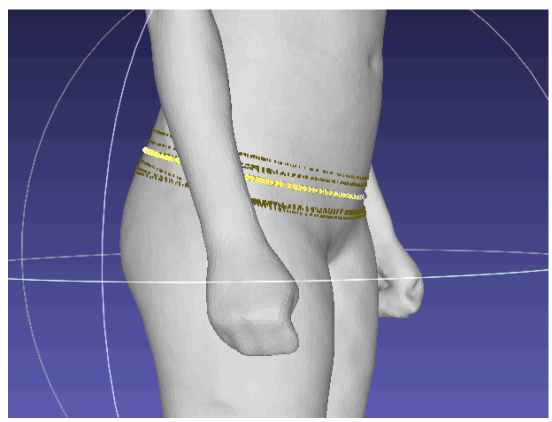


Illustration of the Gradient Descent with three iterations



Visualization of APT measurement in a female subject (APT =14.4°)

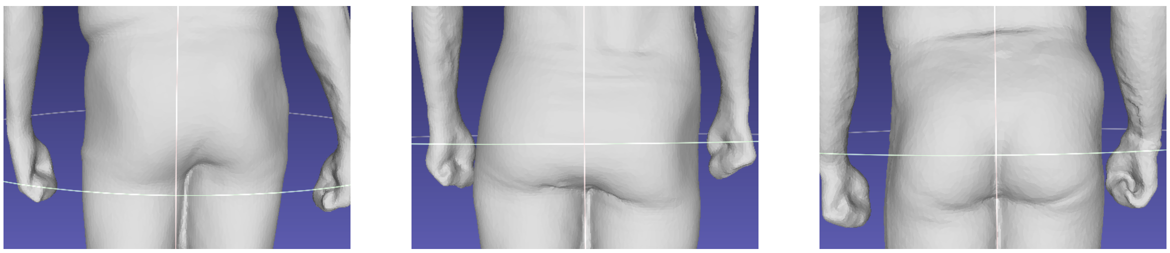
II. Lateral Pelvic Tilt (LPT)

Lateral pelvic shift refers to a postural deviation where the pelvis is shifted to one side when viewed from the front or back. This shift can occur due to various factors such as muscle imbalances, leg length discrepancies, scoliosis, or compensatory mechanisms to alleviate pain or discomfort in the lower back or hips.

It often results in asymmetrical weight distribution on the lower limbs and can lead to issues such as uneven wear on joints, hip or lower back pain, and altered gait mechanics.

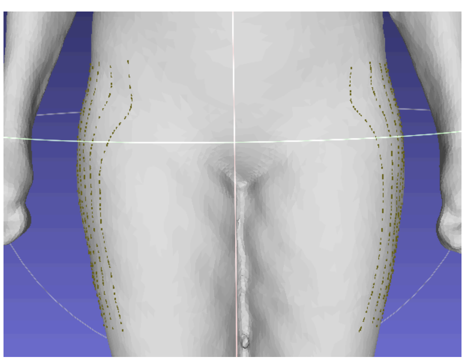
Measuring the LPT without any physical markers is extremely challenging. The approach proposed here showed interesting results, that are consistent with visual inspection of the scan. However, this method is novel at best, with no medical or scientific validation of any kind.

The idea is simple. A lateral pelvic shift will create asymmetry between the left and right flanks of the hips that can be exploited. The images bellow help visualize this effect.

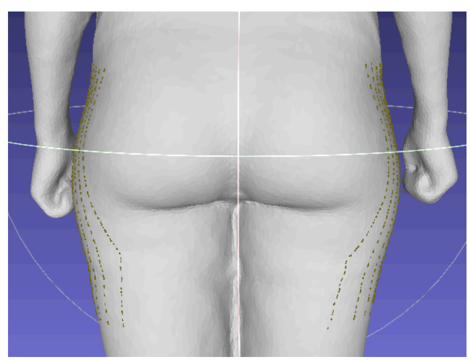


Typical asymmetry of the hips due to Lateral Pelvic Tilt

By drawing vertical lines along both flanks at fixed levels along the Z-Axis, the normal vector of each point along the line of one flank and projected onto the XY-plane is compared to it's correspondence on the opposite flank. This process is similar to the APT cost function.



Front view of the LPT lines

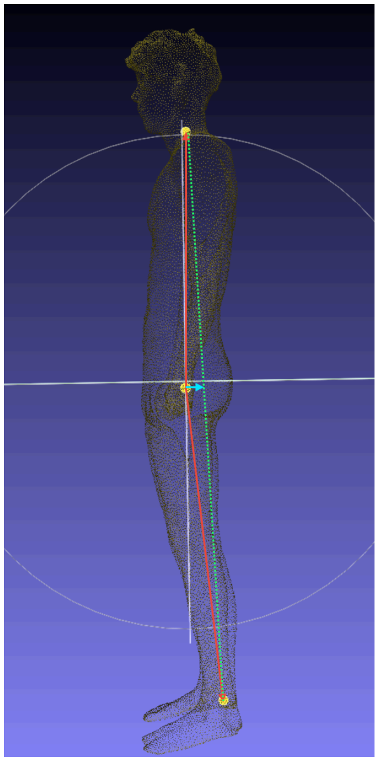


Back view of the LPT lines

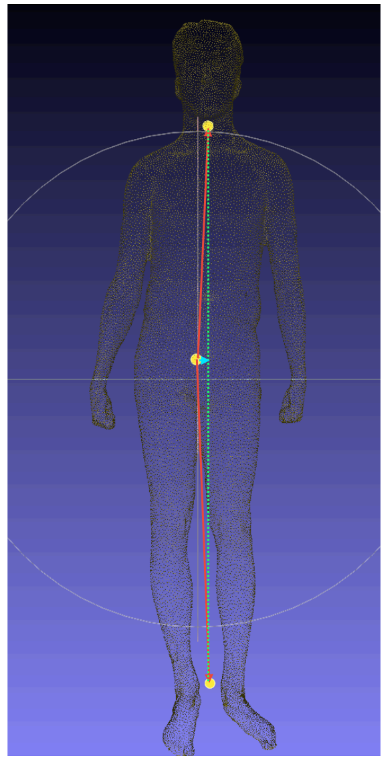
By computing the average of all NCA's at all levels, we get an estimation of the LPT.

III. Pelvic Shifts

Metric commonly found among competitors for it's simplicity and intuitive nature. Although it lacks scientific validation, it's clearly correlated to both APT and LPT.



Pelvic Shift along the Z-axis



Pelvic Shift along the X-axis

Threshold Values:

- APT: Male -> Mean = 8.5°, SD = 4° ; Female -> Mean = 12°, SD = 5°. [4]
- LPT: Mean = 0°, SD = 2° (Empirical)
- Pelvic Shifts: Lower than 20mm (Empirical)

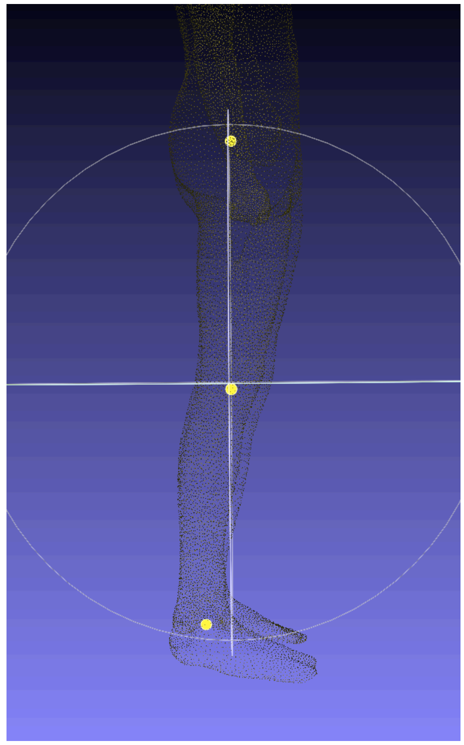
c. Legs

For the leg measurements, 3 distinct structural conditions are investigated:

I. Hyperflexion vs Hypoflexion:

- Hyperflexion: This occurs when the knee joint is flexed or bent beyond its normal range of motion. It can result from activities like deep squats or certain yoga poses, potentially leading to injuries such as strains, sprains, or tears. Chronic hyperflexion may also contribute to overuse injuries or joint degeneration over time.
- Hypoflexion: Contrarily, hypoflexion refers to limited flexibility of the knee joint, characterized by reduced ability to fully bend or flex. This restriction can stem from muscle tightness, joint stiffness, injuries, arthritis, or structural abnormalities, causing difficulties in activities requiring knee bending and potentially altering gait patterns.

[4] Nguyen, A.-D., & Shultz, S. J. (2007). Sex Differences in Clinical Measures of Lower Extremity Alignment. *Journal of Orthopaedic & Sports Physical Therapy*, 37(7), 389-398.



Sideview showing the 3 points used for measuring knee flexion angle (KFA)

Threshold values:

- Up to 10° hyperflexion is considered normal[5], deformity is considered mild if bellow 15°.
- Up to 15° hypoflexion is considered mild.[6]

II. Bow Legs (Genu Varum):

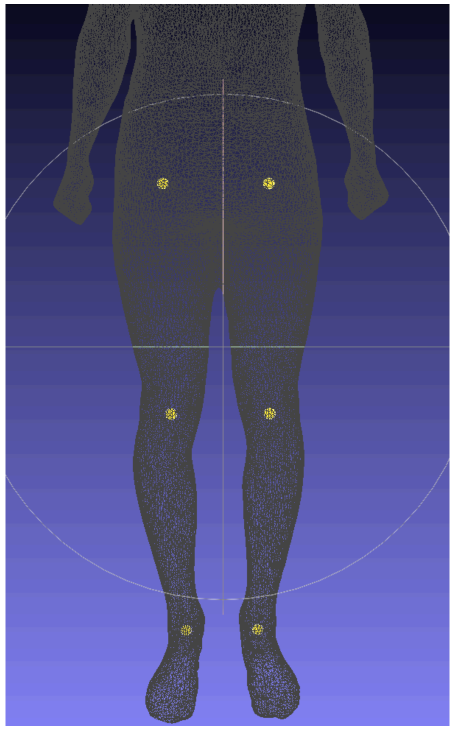
- Bow legs describe a condition where the knees are spread apart while the ankles are together, creating a noticeable gap between the lower legs and knees. While common in infants and toddlers during development, persistent bow legs may indicate underlying issues such as bone deformities or medical conditions.

III. Knock Knees (Genu Valgum):

- The opposite of bow legs, knock knees occur when the knees angle inward and touch each other while the ankles remain apart. Although often observed in early childhood, persistent knock knees beyond adolescence may suggest bone disorders, ligamentous laxity, or other medical conditions.

[5] https://www.knee-pain-explained.com/knee-range-of-motion.html

[6] https://www.physio-pedia.com/Flexion_Deformity_of_the_Knee#cite_note-14



Front view showing all the key
points used for leg measurements

Threshold values: An angle lower than 3° (Varum or Valgus) is considered standard.[7] Higher than 5° is abnormal.

Reliability and Repeatability Assessment: Leg measurements have shown to produce consistent and reliable results, even when the hip, knee and ankle points are not very accurate.

d. Ankles

- **Pronation**: Pronation is the natural inward rolling motion of the foot during the gait cycle. It helps distribute shock and stabilize the foot on impact, but excessive pronation, often seen in individuals with flat feet, can lead to overuse injuries such as plantar fasciitis and knee pain.

- **Supination**: Supination is the outward rolling motion of the foot, especially during the propulsion phase of the gait cycle. It provides leverage for forward movement and stability, but too much supination, common in people with high arches, can increase the risk of ankle sprains and stress fractures.

The Standing Rearfoot Angle (SRA) is a biomechanical measure used to assess the alignment of the heel in relation to the leg while standing. It involves drawing and measuring the angle between the vertical axis of the lower leg and the midline of the calcaneus. A neutral SRA indicates a properly aligned foot, while a positive SRA suggests overpronation (inward tilt) and a negative SRA indicates oversupination (outward tilt).

[7] Kenneth A. Krackow, M.
Clinical Director, Department of Orthopaedic Surgery Kaleida Health System Buffalo General

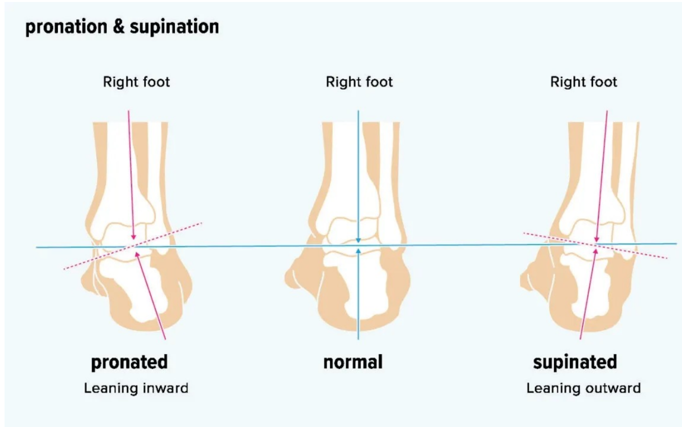


Figure illustrating pronation & supination

The ankle measurement algorithm is similar to the spine mapping, however some nuances call for more detailed explanations:

1. *Horizontal lines:* In a similar fashion to the spine mapping, the program starts by drawing horizontal lines along the rear section of the foot and each line serves as a reference for locating the achilles tendon at different vertical levels.

2. *Maximum Curvature Detection:* The point of maximum curvature is found using a method inspired from the Rolle Theorem.

3. *Linear Regression:* Two least square lines are drawn using the set of key points. The first starting from the bottom of the heel to the height of the ankle point, and the second from the height of the ankle to 100mm above it. The angle between the two lines projected on the XY plane provide the SRA.

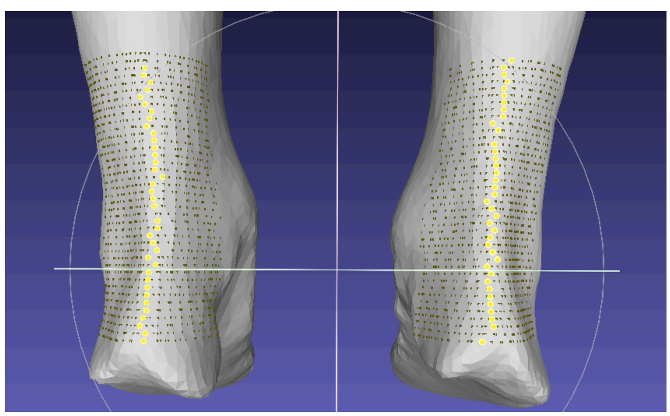


Figure showing the horizontal slices and the corresponding key points.

Threshold values: Lower than 5° (Empirical, when working).

Reliability and Repeatability Assessment:

Both reliability and repeatability are severely hindered by the low quality of the foot scanning. Even with intense numerical conditioning to remove outliers, the algorithm cannot handle situations where portions of the rear foot are missing.

e. Other

1. Shoulder Height Difference

Simple metric linked to lateral pelvic shift and scoliosis, it is commonly found in competitors. This metric has no medical validity, however it remains visually interesting.

2. Neck Angle

Simple metric linked to kyphosis. Computed by running a tangent along the upper spine and selecting the max angle with the vertical. Whilst visually interesting, a study from *Tomlinson et al.*[8] demonstrated that head and neck postures had poor repeatability in 3D scan based posture assessments. Subjects have a tendency to stand taller during the scanning process resulting in inconsistent measurements.

3. Posture Report Example

```
/======================================/
*SPINE METRICS*
    Confidence Score: 0.803839 GOOD
    Length: 728.306 mm
    Scoliosis: 7.14424 mm MEDIUM
    Trunk Angles (deg): X-Axis = 4.67423° Y-Axis = 3.21605° Z-Axis = 0.398838
    Neck Angle (deg): 26.7142°
----------------------------------------
*KYPHOSIS*
    FC: 63.4985    FC%: 0.0881325, Compared to average: 0.933939
    FL: 40.4189    FL%: 0.0560992, Compared to average: 1.0067
    KI: 51.9587    KI%: 0.0721159, Compared to average: 0.960953
# Estimated Spine Age Range # 17-19
/======================================/
*HIP METRICS*
    Lateral Pelvic Tilt (deg): 1.18916°
    Anterior Pelvic Tilt (deg): 8.85558°
    Lateral X Pelvic Shift: -7.38601 mm
    Lateral Z Pelvic Shift: 48.2221 mm
/======================================/
*LEFT LEG METRICS*
    Tibio-Femoral Angle: -3.19506° Varus (Pushing Out)
    Genu Recurvatum Angle: 2.90831° No Hyperflexion Visible
    Standing Rearfoot Angle: 9.54208° Pronated
     -> R-square: 0.996681 GOOD
/======================================/
*RIGHT LEG METRICS*
    Tibio-Femoral Angle: -1.51653° Varus (Pushing Out)
    Genu Recurvatum Angle: 6.20973° No Hyperflexion Visible
    Standing Rearfoot Angle: -1.40524° Supinated
     -> R-square: 0.988883 GOOD
/======================================/
*OTHER METRICS*
    Shoulder Height Difference: -> Left Shoulder is Heigher by 4.13988 mm
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