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AN ENGINEERING STUDY OF THE HUMAN PELVIS USING MODELS AND DATA FROM THE LITERATURE

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ABSTRACT

The paper presents a human pelvis study, building on data and methods sourced from the literature. The study provided a better understanding of the main pelvic parameters, including Sagittal Pelvic Thickness (SPT), that can be applied in designing industrial trunk support exoskeletons and their test benches. In addition, the study improved on the methods presented in the literature by developing models capable of calculating various human pelvic dimensions from different data. Electronic spreadsheets were also developed to calculate SPT from a variety of available information. Trigonometric methods proposed in the literature were used to calculate SPT, and the results were compared with those obtained from literature data. This study will make it possible to optimize the pelvis simulator in the Politecnico di Torino Department of Mechanical and Aerospace Engineering (DIMEAS) industrial exoskeleton test bench prototype. This prototype replicates the human body by means of a trunk simulator and a pelvis simulator which currently has a non-adjustable SPT. As a result of the study, a new pelvis simulator can be designed with provision for anthropometric adjustments to simulate different adult human bodies. This information will also be used to design and construct a human pelvis model featuring all its geometric parameters.

Keywords: human pelvis analysis; human pelvis geometrical characteristics; calculation methods for human pelvis dimensions; human pelvis study for industrial exoskeleton trunk design; engineering methods to study human pelvis.

1 INTRODUCTION

Wearable exoskeleton design entails extensive testing. The prototype must be tested for functionality, performance and wearer safety. It is also necessary to carry out a risk analysis [1-3]. Exoskeleton performance is also studied to prevent joint strain or chafed skin [3]. Performance metrics must be compared with the baseline for human subjects not wearing the exoskeleton. Test benches are often designed to test a single exoskeleton performance characteristic, e.g., flexural strength, actuators, resistance limits of joints or structural elements, etc. In some cases, dummies are used to replicate human features, size and body weight [4].

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A number of rehabilitation and industrial exoskeleton prototypes have been designed and constructed at the Politecnico di Torino Department of Mechanical and Aerospace Engineering (DIMEAS) [5-8].Work on designing a test bench for industrial trunk support exoskeletons started in 2019. While design initially focused on a test bench featuring a trunk simulator, it became apparent that an appropriate pelvis simulator was also needed, with provision for anthropometric adjustments to simulate different adult exoskeleton wearers. Accurate measurement of pelvic parameters is essential in many clinical and research fields and is particularly important in this case in the optimization of a prototype test bench for industrial exoskeletons [9-15]. Among these parameters, the line connecting the axis of the femoral head and the midpoint of the sacral plate, on the sagittal plane (defined as sagittal pelvic thickness or SPT), plays a crucial role in understanding the anatomical variations of the pelvis and in practical application in the industrial context. This study aims to calculate the value of the SPT through two distinct methods: the use of values from the literature and the calculation based on a geometric transposition of the pelvis, integrating additional pelvic parameters and using trigonometric methods from the literature [9-21]. The data analysis was conducted on a representative sample, presenting the results in the form of mean, standard deviation and maximum and minimum values for three confidence intervals. Before proceeding with the analysis, several case studies and scientific articles were examined, from which the pelvic parameters necessary for the calculation were extracted. This research not only aims to provide a precise definition of the SPT but also to contribute to the existing literature with empirical data that can be used for future scientific investigations. The combination of tabular and geometric methods [9-21] offers a potentially more accurate perspective for the measurement of this parameter, ensuring a comparison between different assessments and increasing the probability that the defined range reflects real values. The examination of the SPT involved a lot of parameters and methods, both experimental and numerical [11, 12, 14-16]. The parameters were often analysed using standing radiographic imaging then compared with normal subjects. All the main study carried out on the human pelvis demonstrate that SPT and S1 (sacral tilt) can be considered reflecting the action lever arm of the spinopelvic muscles and capable of expressing the ability of the subject to compensate a possible sagittal unbalance. The study presented here is useful both as an engineering study of the human pelvis and in improving the DIMEAS exoskeleton test bench. In fact through these considerations and literature data and methods elaboration, authors succeeded to know the proper SPT range variation that allows to realize in the DIMEAS test bench a pelvis simulator with important anthropometric regulations. In the future, it will be possible to interact with doctors involved in these studies, but always with engineering-based research purposes in mind. The human pelvis represents a crucial link between the upper and lower body, and it plays a key role in trunk motion and in the static and dynamic balance of the entire body. Therefore, future interactions with doctors will be important both to improve knowledge of this part for balance and rehabilitation, including cerebral rehabilitation, and to better design exoskeletons to assist the trunk. To date, the study of the pelvis has focused mainly on data and literature research in order to allow the authors to improve their knowledge and engineering modeling for subsequent interdisciplinary studies.

2 AIM OF THE STUDY

The study analyzes the range of variation in the Sagittal Pelvic Thickness (SPT) of adult subjects in order to determine pelvis simulator dimensions. The DIMEAS test bench prototype is pneumatically controlled (Figures 1). Hip joint (H) and the lumbo-sacral joint (L) axis are separate, as in the physiological human pelvis.

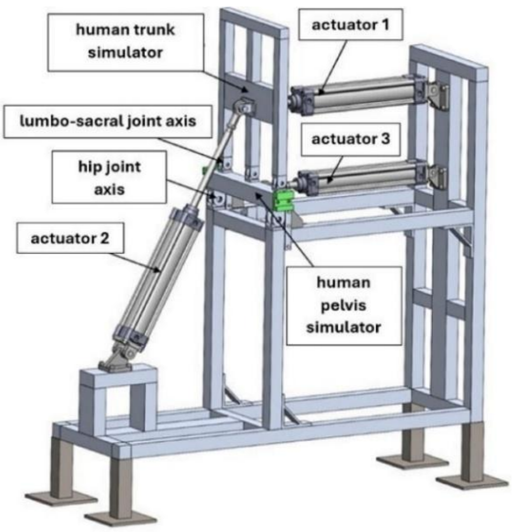


Figure 1a A scheme of the DIMEAS exoskeleton test bench prototype.

Figure 1b Some details of the current pelvis simulator.

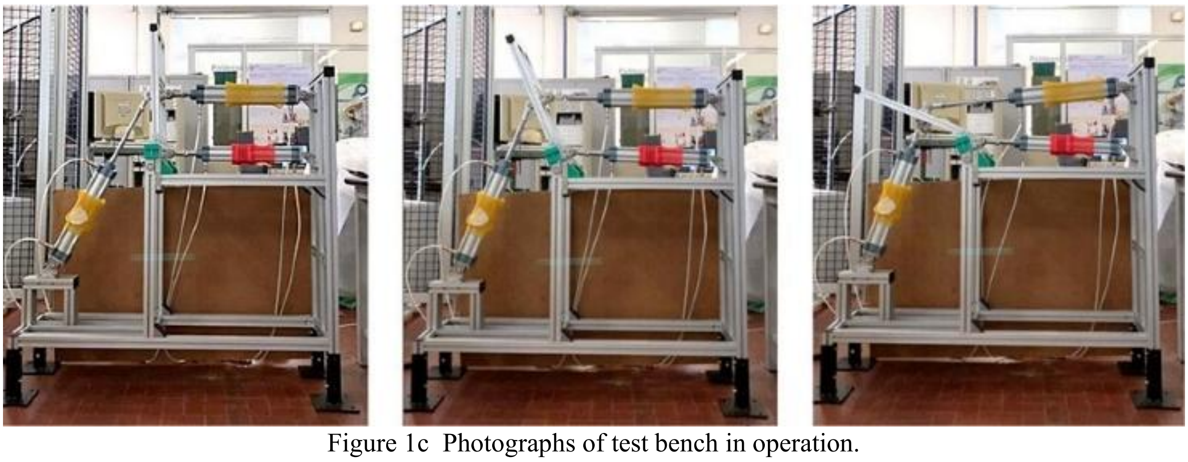


Figure 1c Photographs of test bench in operation.

Pneumatic actuator 3 moves the pelvis simulator during trunk flexion and extension, while cylinders 1 and 2 respectively simulate the trunk weight effect and muscle action during trunk movement. The pelvis simulator features two flat hinges, simulating joints H and L. The current SPT value is 102 mm and it is a fixed dimension.

3 MAIN GEOMETRIC PARAMETERS

The main pelvis nomenclature for the human pelvis study is shown in Table I. These parameters are illustrated in Figure 2. Specifically, parameters include: length of S1 (line joining the anterior and posterior sacral plate points); offset of S1 (the distance between the femoral head axis and the midpoint of the sacral base S1 projection on the horizontal); pelvic angle (between the pelvic radius and the vertical through the femoral head axis; pelvic radius (line joining the center of the femoral head to the posterior point of the sacral plate); angle α_1 (the complementary angle to pelvic incidence) [9,10]. Several values are directly linked to SPT. They include: PI (the angle between the perpendicular to the sacral plate at its midpoint and line connecting this point to the femoral head axis); SS (sacral angle [10] between the sacral plane and the horizontal); PT (angle between SPT and the vertical through the femoral head axis; PR-S1 (Jackson's angle [11] or pelvic lordosis), angle between the sacral plate plane and line joining the sacral plate posterior point and the femoral head axis.

Table I – Main pelvis nomenclature

Name	Abbreviation
Sagittal pelvic thickness	SPT, PTH
Pelvic incidence	PI
Pelvic tilt	PT
Pelvic angle	PA
Sacral angle	SS
Jackson's angle	PR-S1, α_2
Half of the length of vertebra S1	d
Pelvic radius	PR
Overhang or offset of vertebra S1	OVS1, PO
Femoral head diameter	D
Femoral axis	HA
SPT projection on the vertical	A, DYp
SPT projection on the horizontal	B, DZp
Length b + length d	c
Complement of PI	α_1
Lumbar lordosis angle	LLA, LL
Sacropelvic angle	PSA
Lumbosacral angle	LSA
Sacral tilt	S1

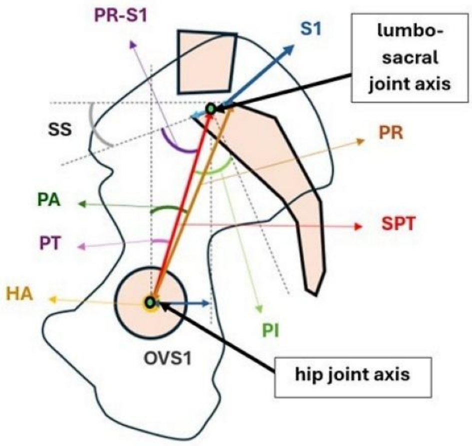


Figure 2 Main nomenclature.

3.1 FACTORS INFLUENCING SPT

As a number of studies [9,12-22] have shown, SPT is influenced by pathologies, age, gender and ethnicity. Analysis of many lateral radiographs of the pelvis has shown how pathologies such as lumbago and spondylosis can influence pelvic incidence, Jackson's angle and the length of vertebra S1. Significant changes in pelvic incidence and Jackson's angle (α_2) also lead to a significant changes in SPT. Pelvic thickness is around 130 mm for healthy subjects and those with relatively minor pathologies, with a pelvic incidence of around 50° and Jackson's angle from 32° to 38° and PI between 60° and 70° (PR-S1 between 17° and 25°), corresponding to an SPT between 108 and 116 mm for subjects affected by more serious pathologies [16]. Several studies have addressed changes in pelvic parameters as a function of the subjects' age, using computed tomography to determine pelvic incidence, pelvic thickness and vertebra S1 width. With advancing age, pelvic incidence increases, while sagittal pelvic thickness decreases. Japanese researchers have also analyzed the increase in pelvic incidence with age using linear regression equations to evaluate subjects' parameters [10,13,14]. Studies have investigated differences between men and women with respect to fundamental pelvic parameters [9-11]. One such study evaluated a group of subjects [11] consisting of 55 men and 53 women. For the men, average age was 49.3 ± 30.1, height 166.0 ± 11.4 cm, and body weight 63.3 ± 16.6 kg, while for the women, average age was 49.1 ± 29.6, height 151.9 ± 12.1 cm, body weight 52.4 ± 14.6 kg. The study found no substantial difference between males and females for all examined parameters, though on average SPT was relatively higher in women considering the difference in body height in particular [11]. In another study [13], radiographic measurements were taken with subjects aged between 18 and 80 years belonging to different ethnic groups across five countries (France, Japan, United States, Singapore and Tunisia). It was found that pelvic parameters vary considerably among ethnicities. SPT was higher among the Asian population than among Arabo-Bèrbère subjects, while Caucasians had a higher pelvic incidence than Asians [9-16].

4 STATE-OF-THE-ART: PELVIS ANALYSIS METHODS IN THE LITERATURE

Some pelvis analysis methods from the literature are presented. In one method, radiographic angles were measured for pelvic incidence [17,20], vertebra S1 offset, and pelvic tilt, which can provide a tool for calculating SPT and sagittal balance. Trigonometric models have also been used to determine pelvic radius and Jackson's angle [12], where sometimes the pelvic thickness is the hypotenuse of a triangle formed by a and b (Figure 3). Geometric relations for calculating SPT as a function of the other parameters developed using Figure 3 will be illustrated in the following sections. Standing lateral radiographs can also be used to calculate SPT from the pelvic radius and PR-S1 defined by Jackson in his studies of 1998,18 200019 and 2003,20 analyzing pelvic morphology (pelvisacral angle, pelvic incidence, and pelvic lordosis) and calculating the combined angles. In a 2005 study [14] two different methods were used to determine the relationship between sagittal pelvic thickness and pelvic incidence in 12 subjects, and the results of each method were compared. The first method consisted of direct anatomical measurement of incidence and thickness by means of an electromagnetic system. The second method used measurements from radiographs in the sagittal plane.

In a study from 2006 [21] pelvic parameters were measured on standing lateral radiographs of 145 adults without vertebral problems and 35 adults with spondylosis in order to assess sagittal spinal balance. Specifically, pelvic thickness was determined by calculating pelvic incidence (PI) and Jackson's angle (PR-S1), defining angles α_1 and α_2. Sagittal spinal balance has also been assessed using the pelvic radius technique [17]. In this case, pelvic radius and Jackson's angle were analyzed in 75 healthy subjects, 75 subjects with spondylolisthesis, 194 subjects with spinal deformity, and 60 subjects with scoliosis, for a total study population of 40

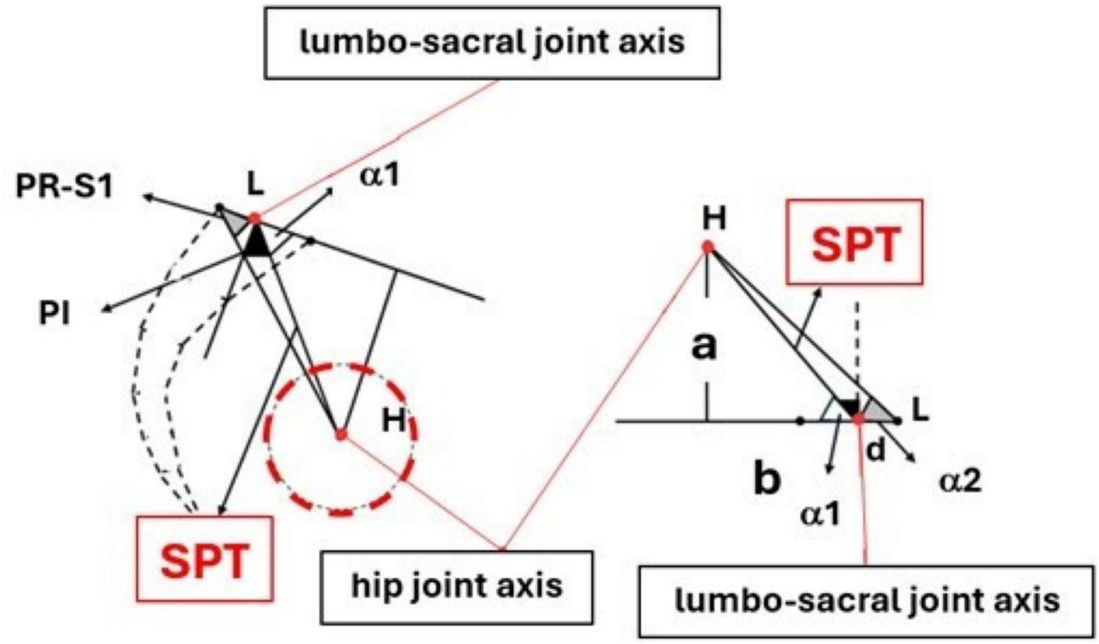


Figure 3 Details of the trigonometric method [12].

The study cites a number of published measures: Jackson et al. (1998) with N = 50, age 39.4 ± 9.5, PR (mm) 135 ± 8.6, PRS1 (°) 31.2 ± 7.9; Jackson et al. (2000) with N = 20, age 46, PRS1 (°) 31± 8.7; Jackson et al. (2003) with N = 75, age 39, PR (mm) 136,8 ± 8.9, PRS1 (°) 30.9 ± 9.8; Legaye (2007) with N = 145, age 40.7 ± 18.7, PRS1 (°) 35.2 ± 9.6.

Studies carried out by Japanese researchers [13] use linear regression equations to determine correlations among radiographic parameters in order to support the hypothesis that pelvic incidence increases with age. The study cohort consisted of 126 healthy adult volunteers (without spinal pathologies), 30 males and 96 females, aged between 20 and 69 years, for an average age of 39.4 years. These equations will also be used by the present authors. S1 offset and the pelvic tilt angle were also indicated. A 2022 study [22] compared pelvic parameter measurements from 43 subjects affected by spondylosis before and after they received spondylodesis. The following parameters were measured to evaluate sagittal lumbar alignment: segmental lordosis (SL); ventral (vDH) and dorsal (dDH) disc height as distances of the ventral and dorsal edge of the treated vertebral disk; lumbar lordosis (LL); pelvic incidence (PI); pelvic tilt (PT); and sacral slope (SS). A study published in 1998 [16] measured anatomical parameters on orthogonal plane

radiographs of individuals in a standing position. The data were then processed by means of a software package used to reconstruct the spinal column and pelvis in three dimensions and perform statistical analysis. Subjects were divided into two categories: normotypes (49 in total, 28 men and 21 women) and those affected by scoliosis (66 individuals).
Some physical characteristics are also indicated: the population consisting of healthy individuals has an average age of 24 years (19-50), height of 173 cm and body weight of 65.8 kg; the subjects with scoliosis have an average age of 33 years, height of 161 cm and body weight of 55 kg [20-27].

5 AUTHORS' STUDIES

On the basis of the studies outlined above, the authors used trigonometric models [12-16] and direct numerical values from the literature [9-29] to calculate SPT from a range of initial information. Data from the literature [9-29] were also used to validate the trigonometric models' results.

5.1 SPT FROM TRIGONOMETRIC MODELS

Using the two main trigonometric methods [12] illustrated in Figures 4 and 5, the authors calculate the SPT length for different subjects. The trigonometric models were as follows:

- method 1: authors used the trigonometric model shown in Figure 3 [12] and calculated SPT via pelvic incidence and via pelvic radius;
- method 2: authors used a simpler model deriving SPT from pelvic tilt and S1 offset using a trigonometric formula (Figure 4 [12]).
- Average SPTs from the literature were then analyzed for healthy subjects and subjects affected by pathologies. These aspects will be described below.

5.1.1 SPT from Trigonometric Models: Method 1

In this analysis, SPT was calculated starting from the trigonometric model shown in Figure 3 [12] and then using pelvic incidence and pelvic radius, using the expressions proposed in the literature [12] and sometimes also reformulated them:

$$\alpha_1 = 90 - PI \tag{1}$$

$$\tan\alpha_1 = a/b; \quad \tan\alpha_2 = a/c \tag{2}$$

where c = b+d (Figure 3)

$$SPT = a/\sin(\alpha_1); \; SPT = b/\cos(\alpha_1) \tag{3}$$

It should be borne in mind that d=S1/2.
From the measurement of the pelvic radius, we obtain (Figure 4):

$$a = PR \cdot \sin\alpha_2 \tag{4}$$

SPT was calculated using dimensions a and b (Figure 3).

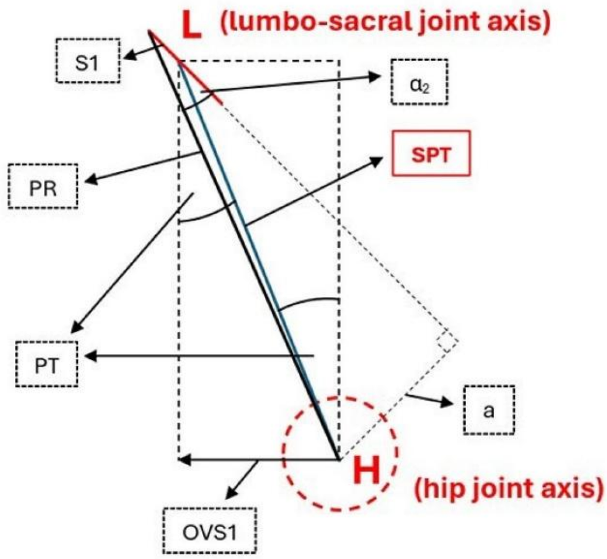


Figure 4 Relationship between SPT, pelvic tilt (PT) and S1 (OVS1) offset in the sagittal plane [12].

5.1.2 SPT from Trigonometric Models: Method 2

With method 2, the authors determined SPT from pelvic tilt and S1 offset using a trigonometric formula, starting from the diagram shown here in Figure 4 [12]:

$$SPT = OVS1/\sin(PT) \tag{5}$$

Further details of these calculation results will be illustrated below.

5.2 SPT CALCULATED FROM LITERATURE DATA

To verify the SPT values obtained using methods 1 and 2 described above, the authors analyzed a number of articles [9-15,18-20] obtaining a sizable quantity of SPT values for different subjects which were then compared with the authors' calculations.

5.2.1 Healthy Subjects

One of authors' first calculations from literature data [12] was the general determination of SPT using pelvic incidence and pelvic thickness measurements. Table II shows the results obtained from analyzing subjects presented in the literature [9-15,18-20] while Table III illustrates the results for PI and α_1. The goal was to derive a defined interval from all measurements, regardless of the subjects' demographic characteristics. In all of the tables, the numbers in bold at the bottom are the overall average measurements for each column. Referring to Table II e III, the total values (in bold) are the average of the values of all the measures based on the number of samples in the study (N = 1657 for SPT, N = 1600 for PI) designated with N. The maximum and minimum are either extreme values of the analyzed population or statistical limits given by doubling the measure of the calculated standard deviation, representing a 95% confidence interval for the total population.

Table II - SPT values analyzed from literature [9-15,18-20]

Average (mm)	Min (mm)	Max (mm)
132.0	103.9	160.1
95.2	7.6	113.8
85.3	64.2	106.4
104.9	87.7	122.1
107.0	87.1	126.9
108.4	91.4	125.4
109.0	95.0	123.0
109.0	89.0	130.0
102.1	100.5	103.7
107.3	106.3	108.3
105.6	104.4	106.8
116.9	98.1	135.7
116.9	99.0	147.0
120.0	105.0	135.0
155.5	136.2	174.8
133.1	117.8	148.4
113.3	**97.9**	**129.1**

Table III - PI and α1 values from literature [9-15,18-20]

PI			α_1		
Average (°)	Min (°)	Max (°)	Average (°)	Min (°)	Max (°)
48.3	28.1	68.5	41.7	21.5	61.9
58.6	37.2	80.1	31.4	9.93	52.8
59.7	39.8	79.6	30.3	10.4 3	50.
47.6	27.2	68.0	42.4	22	62.8
46.2	27.0	65.4	43.8	24.6	63.0
47.0	30.7	63.3	43.0	26.7	59.3
52.3	30.1	74.5	37.7	15.5	59.9
52.3	26.9	82.1	37.7	7.9	63.1
52.0	49.6	54.3	38.0	35.7	40.4
51.0	49.4	52.5	39.0	37.5	40.6
52.5	51.0	54.1	37.5	35.9	39.0
48.5	30.5	66.5	41.5	23.5	59.5
48.5	33.0	69.0	41.5	21.0	57.0
49.8	**34.5**	**65.6**	**40.2**	**24.4**	**55.5**

5.2.2 For Different Conditions

The authors then analyzed SPT in various types of subjects and situations presented in the literature [9-11, 23, 24]. For example, Table IV illustrates the analysis conducted for different genders (M = male, F = female). As can be seen, there is in general a slight difference (in the order of 1°) in pelvic incidence between the female (F) and male (M) population. The gender difference is even smaller for STP, as the average, minimum and maximum figures are practically identical in a population of 238 subjects. Table V and VI show results for non-elderly subjects. As can be seen from the analysis of variations in pelvic incidence angle, the mean values do not vary significantly; here again, the range of values increases on both sides. By contrast, the trend for angle α_1 is the inverse of that for PI (being its complement) and the angle is thus directly proportional to SPT.

Table IV - Selected SPT values by gender [10-12,15]

SPT					
M			F		
Average (mm)	Min (mm)	Max (mm)	Average (mm)	Min (mm)	Max (mm)
104.5	87.3	121.7	105.4	87.6	123.2
108.9	89.8	128.0	110.2	90.4	127.0
119.0	99.5	138.5	114.1	97.5	130.6
107.2	**89.3**	**125.1**	**107.3**	**89.1**	**124.7**

Table V - Average, minimum and maximum SPT excluding distributions with individuals aged over 65 years [9-13]

SPT		
Average (mm)	Min (mm)	Max (mm)
132.0	103.9	160.1
104.9	87.7	122.1
108.9	89.8	128.0
110.2	92.4	128.0
109.0	95.0	123.0
109.0	89.0	130.0
116.9	98.1	135.7
116.9	99.0	147.0
120.0	105.0	135.0
155.5	136.2	174.8
133.1	117.8	148.4
117.1	**96.4**	**138.3**

Table VI - Average, minimum and maximum PI and α_1 excluding distributions with individuals aged over 65 years [9-13]

PI			α_1		
Average (°)	Min (°)	Max (°)	Average (°)	Min (°)	Max (°)
48.3	28.1	68.5	41.7	21.5	61.9
47.6	27.2	68.0	42.4	22.0	62.8
46.1	25.5	66.7	43.9	23.3	64.5
45.8	29.1	62.5	44.2	27.5	60.9
52.3	30.1	74.5	37.7	15.5	59.9
52.3	26.9	82.1	37.7	7.9	63.1
48.5	30.5	66.5	41.5	23.5	59.5
48.5	33.0	69.0	41.5	21.0	57.0
48.9	**28.2**	**70.4**	**41.1**	**19.6**	**61.8**

6 SOME PROCEDURES FOR DETERMINING SPT

As described below, electronic spreadsheets were developed that can be used to determine the SPT range for the DIMEAS pelvis simulator. An example will also be presented of calculating trends for pelvic incidence and pelvic thickness as a function of subjects' age using two linear regression equations. The example involves a total of 6 subjects (3 male and 3 female) divided into 3 ethnic categories.

The SPT values considered in determining the adjustment range of the pelvis simulator section of the DIMEAS exoskeleton test bench are discussed below.

6.1 AUTHORS' ELECTRONIC SPREADSHEETS

The following procedure was used to calculate the pelvic thickness values shown in Table VII from pelvic parameter measurements and geometric/trigonometric models, developing the electronic spreadsheets such as that shown in Table VII as a tool for examining literature data and calculating results, obtaining the corresponding SPT. In Table VII, when a and b are indicated, SPT values are derived from method 1, while when a and b are not indicated, SPT derives from method 2. All values in Table VII were determined with method 1 or 2. Length d (Figure 3) is assumed to be a constant 18 mm, given the limited literature on the subject and given that its between-subjects variation is negligible compared to that of the other parameters [12,24,25]. From the perspective of statistical analysis, it should be borne in mind that the SPT measurements are given by the averages of the different distributions presented, since values of the pelvic parameters associated with an individual are not readily available in the literature.

6.1.1 SPT Filtered by Age and Pathologies

Further spreadsheets whereby SPT can be obtained under different conditions were developed by filtering for values associated with elderly subjects and those with more serious spinal pathologies. The resulting data will be used statistically to define the range of values. To that end, the mean of the distribution will be calculated as a weighted mean based on the number of subjects, the variance (again based on N) and the associated standard deviation. The maximum and minimum are defined by the deviation of twice the standard deviation from the mean of the values, as here defined: average value 115.20 mm; minimum value 93.92 mm; maximum value 136.47 mm; variance 113.17 mm^2 ; standard deviation 10.64 mm.

6.1.2 PI and SPT Trends Using Linear Regression Equations

Some of the articles cited in this study [9,10,13] are useful in investigating how pelvis parameters vary as a function of age, and provide linear regression equations that can also be used to visualize pelvic parameter variation. Specifically, the two equations to define pelvic incidence and SPT based on age and the subjects' gender and ethnicity [9,10,13] are as follow:

$$PI = 44.3 + 0.2 * age \tag{6}$$

$$SPT = (115.2 - 0.05 * age + 1.07 * gender - 1.68 * a + 0.63 * b - PI)/0.55 \tag{7}$$

In the SPT equation, gender can be male (zero) or female (one), the letter a designates Arab ethnicity, b designates Asian ethnicity, while if both are set to zero the ethnicity is Caucasian. Further electronic spreadsheets (not shown for space reasons) were constructed whereby the influence of subjects' ages and ethnicities on PI and SPT can be examined. Average SPT for each year of age was then generated and graphed together with PI as shown in Figure 5.

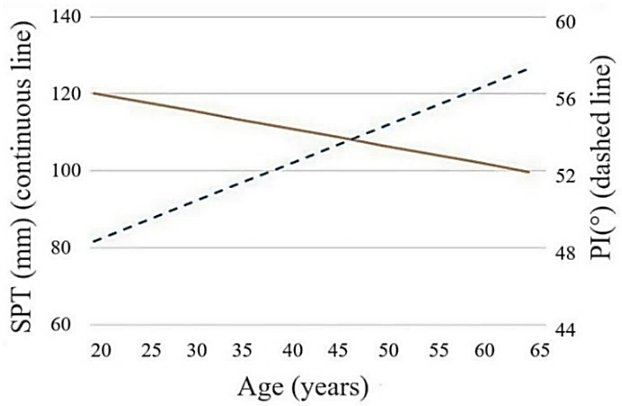


Figure 5 PI and SPT as a function of age.

Estimated variation in pelvic thickness is about 20 mm, while that of pelvic incidence is about 10°. The variation in the two measures is inversely proportional: pelvic thickness tends to decrease with age, while pelvic incidence increases. The electronic spreadsheets shown in Figure 7 allows to obtain the SPT values starting from different information from the literature data or calculated from the models proposed. SPT values are important both for the proper design of automatic devices applied to the human trunk (active or passive) and for a general study and knowledge of the human pelvis. The key for reading Table VII is: referring to the trigonometric models illustrated above and the two methods proposed by the authors. In fact the SPT can be calculated in various ways, depending on the known parameters (PI, PRS1, PR, PT, etc.). Therefore, where there are blank spaces in the columns of the respective parameters (Table VII), it means that the parameter is unknown, but the SPT can still be calculated using the other available parameters.

7 COMPARISON AND ANALYSIS OF RESULTS

Calculated and literature data for STP and other pelvic parameters, including pelvic incidence and Jackson's angle in particular, were compared to improve this study. It should also be borne in mind that the issue of measurement uncertainty cannot be addressed here, as the study draws on data and literature analysis. However, it is an important study, as it is difficult to find information on SPT and construct, as the authors did, useful tools for its calculation.

7.1 CALCULATED AND LITERATURE DATA FOR SPT

In comparing the means and standard deviations of the SPT values from the literature data and resulting from calculation, it was found that the two distributions have a very similar means: 117.01 mm for the literature data, and 115.20 mm for the calculated values, resulting in a delta of 1.8 mm. The delta for the standard deviation, on the other hand, tends to zero, as the two values are practically identical (around 10.6 mm).

Table VII - SPT values calculated from pelvic parameters from literature data or using trigonometric models [16-29]

PI (°)	PRS1 (°)	PR (mm)	PT (°)	OVS1 (mm)	α_1 (°)	α_2 (°)	a (mm)	b (mm)	SPT (mm)
50.2	35.2		11.5		39.8	35.2	82.8	69.0	107.8
49.6	35.8		10.6		40.4	35.8	85.1	72.4	111.7
62.0	24.3		14.7		28.0	24.3	53.9	28.7	61.1
58.0	32.0	137.0			32.0	32.0	72.6	98.2	122.1
76.0	14.0	137.0			14.0	14.0	33.1	114.9	119.6
66.0	24.0	135.0			24.0	24.0	54.9	105.3	118.8
60.0	30.0	138.0			30.0	30.0	69.0	101.5	122.7
			11.9	22.6					109.6
			10.3	19.2					107.4
			12.3	22.4					105.2
			16.0	25.0					90.7
			12.6	20.8					95.4
			14.0	24.6					101.7
54.3	31.2	135.0			35.7	31.2	69.9		119.8
54.7	30.9	136.8			35.3	30.9	70.3		121.6
60.8	34.3				29.2	34.3	55.7	99.6	114.1
39.6	45.5				50.4	45.5	115.8	95.8	150.3
52.6	33.2				37.4	33.2	81.7	106.9	134.6
48.3	36.9				41.7	36.9	85.9	96.4	129.2
52.8	32.5				37.2	32.5	71.4	94.0	118.0
47.3	38.1				42.7	38.1	93.9	101.8	138.5
60.5	25.9				29.5	25.9	61.7	109.0	125.2
70.6	17.2				19.4	17.2	46.1	130.8	138.7
			10.3	18.8					105.1
			10.0	18.3					105.4
			11.5	21.7					108.6
			12.3	21.3					99.9
			11.9	22.4					108.5
			12.9	24.1					107.8
46.3	38.9				43.7	38.9	94.2	98.6	136.3
51.6	34.4				38.4	34.4	89.5	112.8	144.0
			9.3	18.2					112.7
48.5	37.1	128.9			41.5	37.0	85.4	84.9	120.4

This indicates that the distributions have practically identical behavior, with widths that are approximately equal and means with a very small deviation. The value that differentiates the two measures is the number of subjects in the sample population, 1138 for the literature data and 2156 for the calculated data, almost double. Individual SPT values can also be compared graphically, analyzing their dispersion (Figure 6). The curves for the two series of data differ (given that different subjects are analyzed), but the extremes coincide and the curves meet at a point close to the average values.

It can thus be concluded that the literature values for SPT are comparable to the calculated values, and the calculation model is consistent.

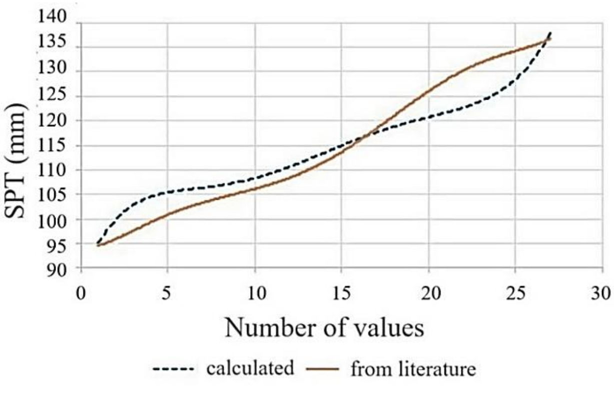


Figure 6 SPT versus number of results for the two distributions.

7.2 FINAL SPT RANGE

A preliminary possible proposal for studying these data is presented here. Table VIII was compiled to define the range of pelvic thickness variation. It illustrates the mean and the standard deviation calculated for the parameter. Values were divided into three confidence intervals (a confidence interval provides a range of values within which a population parameter, such as a mean or proportion, is believed to lie with a certain probability or "confidence," typically expressed as a percentage (e.g., 95% or 99%)) based on standard deviation. Standard deviation (the standard deviation (or root mean square) is a statistical measure of dispersion that indicates how much the values in a set of data deviate from their arithmetic mean) is here indicated as SD. The ranges of 1, 2 or 3 standard deviations represent the confidence intervals (in the order 68.6, 95.4 and 99.7). These intervals represent the percentage probability (it is the most common way to express the probability of an event, converting the fraction (favorable cases / possible cases) into a percentage. To do this, divide the numerator by the denominator to obtain a decimal, and then multiply this decimal by 100, adding the "%" symbol) of finding a subject within the range represented by the SD: for example, the interval obtained from 2*SD represents a 95.4% probability that a subject will fall within that interval.

Table VIII - SPT values for three confidence intervals.

SPT					
Confidence interval	Average value (mm)	Min value(mm)	Max value (mm)	SD (mm)	Probability (%)
SD	115.2	105	126	10.64	68.6
2*SD	115.2	94	136	10.64	95.4
3*SD	115.2	83	147	10.64	99.7

By calculating the minimum and maximum values and deviation from the mean, the probability that a subject has a pelvic thickness that falls within that range is approximately 68%. This increases to 99% by deviating by three standard deviations (SD). It is also interesting to introduce the distribution of pelvic thickness (Figure 7).

This normal distribution indicates the probability considered on N=33 subjects in the sample population here from SPT values calculated and not from the literature data. On the other hand the whole number of subjects examined by the authors was N = 115. It follows that an average useful range of SPT variations for the DIMEAS pelvis simulator is from 80 mm to 190 mm.

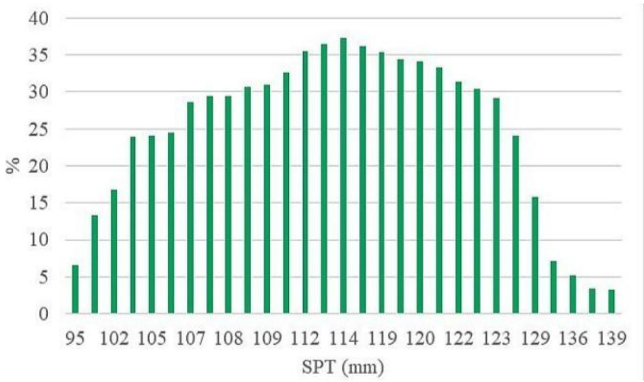
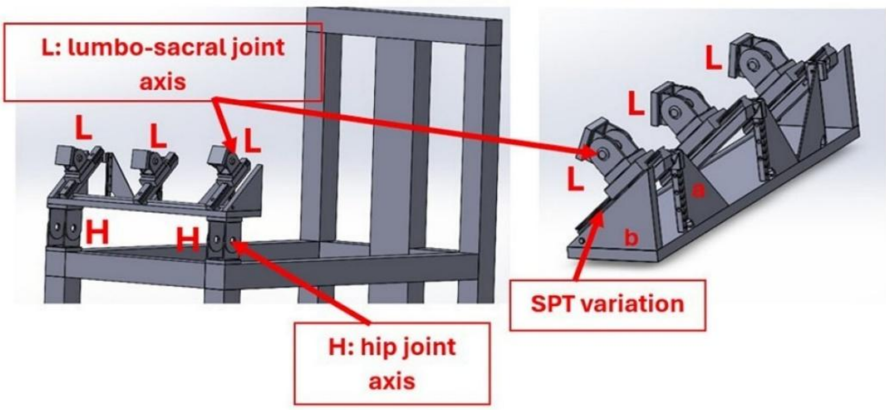


Figure 7 Normal distribution of SPT.

In the future, all these analyses may be refined through studies conducted in collaboration with physicians in the field. The study presented here is useful for improving engineering knowledge of the human pelvis and thus future interactions with clinicians [30-32].

8 DIMEAS PELVIS SIMULATOR MODIFICATION

The study presented here was the basis for developing a new configuration of the DIMEAS exoskeleton test bench pelvis simulator. SPT can be adjusted by varying the dimension either along the hypotenuse of the right triangle shown in Figure 3 or along the sides. Figure 8 shows a possible preliminary design solution. The SPT regulation is in this case obtained using commercial recirculating ball guides for all movements. Each regulation is currently foreseen in manual mode. Future work will focus on optimizing this configuration to arrive at the final test bench layout featuring an SPT adjustment range of 80 mm to 190 mm.



a) b)

Figure 8 A possible configuration of the new pelvis simulator in the DIMEAS test bench: a) overall view; b) details.

9 CONCLUSIONS

The study presents an original analysis of data from the literature that can help in gaining a better understanding of human pelvis dimensions and geometry.

Starting from a literature review, the authors developed a method for calculating several main human pelvis parameters, including sagittal pelvic thickness.

The analysis also resulted in a human pelvis engineering study that can be fruitfully applied in designing industrial trunk support exoskeletons and their test benches.

The study and construction of a 3D-printed scale model of the human pelvis (95% ile of which is Italian male) is currently underway. This will allow both to improve understanding of this part of the human body and to present and explain it to students in the field.

A physical model of the human pelvis will also be constructed, perhaps with movable parts, in order to analyze pelvic function and characteristics.

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Authors underline that Figures 3 and 4 were partially modified by the authors from the original ones for exigence of the study here presented and are from the paper [12]

Legaye J. The sagittal pelvic thickness: A determining parameter for the regulation of the sagittal spinopelvic balance. ISRN Anatomy 2013; 4: 1–9, were in the beginning is this note: *“Copyright © 2013 Legaye Jean. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited”.*

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