10

Analysis of the Dynamic Sagittal Balance of the Lumbo-Pelvi-Femoral Complex

Legaye Jean
University of Louvain, Mont-Godinne
Belgium

1. Introduction

The acquisition of bipedalism has enabled the human species an intellectual, technological and social development. However, the transition to the standing position was possible only through morphological adaptations, particularly in the lower limbs, the pelvis and the spine. The pelvis has changed from an elongated shape (called "in tension", typical of quadrupeds), to a more squat morphology (called "in pressure", characteristic of bipedalism). The pelvis was indeed a key holder of these transformations as a pivot basis submitted to the loads of gravity from the trunk and to the reaction forces from the ground, transmitted by the femoral heads. Parallel to the adaptation of the pelvis, the appearance of the spinal curvatures has allowed establishing a balance defined as stable and economic in terms of stress on the musculo-ligamentous structures and of muscle contractions necessary for its maintenance. However, maintaining this balance when standing was precarious: all the stresses of gravity were to be maintained within this entire vertical body and inside a narrow sustentation polygon. (Figure 1).

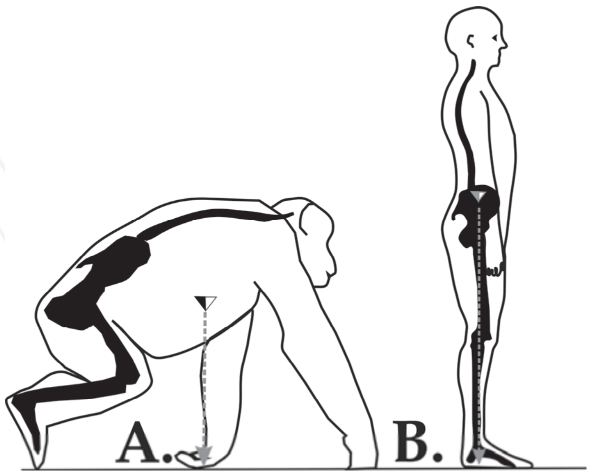

Fig. 1. Differences in lombo-pelvi-femoral morphology, gravity line and sagittal balance between a quadruped chimpanzee (A.) and a standing human (B.).

Dynamic management of the position of gravity was therefore essential. For the standing human, any unbalancing disruption has negative effects inducing pain and anatomical deterioration. An effective analysis of the sagittal balance in standing position was so primordial for biomechanical and medical purposes. This procedure was reported here. It involves both a morphological evaluation of the lumbo-pelvi-femoral complex by the analysis of the relations between pelvic anatomy and spinal curvatures, and a mechanical assessment of the strengths of gravity on each of the vertebral and pelvic anatomical structures. The integration of such data allowed a personalized analytical and functional assessment of the sagittal balance in vivo for a standing individual.

2. Morphological analysis of the lumbo-pelvi-femoral complex

2.1 Prior descriptions

Many sagittal morphotypes have been described by anthropologists. Stagnara has proposed a classification based on the intensity and the topography of the spinal curvatures. So, he defined the morphotypes as "normal", "kyphosis", "lordosis", "kypho-lordosis", in "total lordosis or kyphosis", "inverted back", "flat back" according to the angular and millimetric values of the respective curves. Subsequently, authors have reported the influence of the lordosis on the sagittal rotation of the pelvis, expressed by the tilt of the sacral plate. Several spinal parameters were proposed. The "lumbar lordosis" was defined as the angle between the upper plate of the first sacral vertebra S1 (or the sacral plate) and the upper plate of L1, "lordosis" was differently described according to the authors: the bottom limit was either the sacral plate or the lower plate of L5, the top limit either the most backward tilted plate or other specified vertebrae. The normality was assessed by comparing the observed value to a range of normal mean values. Using the mean values of these parameters, however, remained inadequate for an individual assessment of spinal curvatures because of the great range of variations for physiological values (Table 1 for lordosis and kyphosis), greater than simply due to differences in the measurement techniques.

	"Lordosis" (°)			"Kyphosis" (°)		
	Min.	**Max.**	**range**	**Min.**	**Max.**	**range**
Duval-Beaupère (1998)	46	87	41	33	71	38
Guigui (2003)	37	89	52	7	65	58
Vaz (2002)	26	76	50	25	72	47
Gelb (1995)	38	84	46	9	66	57
Jackson (2000)	35	90	55	22	75	52

Table 1. Ranges of variation of normal values of "Lordosis" and "Kyphosis" reported by several authors.

2.2 Descriptive morphological parameters

2.2.1 The "Pelvic radius" and the "Lumbo-pelvic lordosis"

Jackson emphasized sagittal descriptive parameters of the pelvis and spine. (Jackson, 2000) (Figure 2) They aimed to compare an individual with ranges of values proposed as the normality.

2.2.1.1 The anatomical parameter

The "Pelvic Lordosis" or "Pelvic Radius" (PR-S1): the angle between the upper plate of S1 and the line connecting the posterior point of the sacral plate to the bi-coxo-femoral axis.

2.2.1.2 The positional parameters

The "Sacral Inclination" (SI): the angle between the vertical and the posterior edge of S1
The "Pelvic Angle" (PA): the angle between the vertical and the line connecting the posterior point of the sacral plate to the bi-coxo-femoral axis.
The "Lumbo-Pelvic Lordosis": the angle between the upward extension of the line defining PR-S1 and the upper plate of T12.

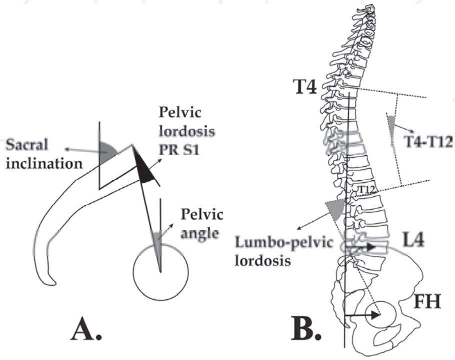

Fig. 2. The angular anatomical and positional parameters described by Jackson (2000).

2.2.1.3 Method of evaluation

3 criteria were defined as the normality:

- The center of the femoral heads and the center of the body of L4 are positioned in front of the vertical downwards of the center of the body of T4 (Figure 2 B)
- "Pelvic Angle" between 0 and 35 °
- "Lumbo-Pelvic Lordosis" between 60 and 120

Moreover, the quotient of the angles "Thoracic Kyphosis" (T4-T12) / "Lumbo-Pelvic Lordosis" had to be between 0.15 and 0.75 (Figure 2 B)

2.2.2 The sagittal "Overhangs"

2.2.2.1 The Overhang of C7

Many authors considered the plumb-line from C7 on the underlying structures as an evidence of the overall sagittal balance of the lumbo-pelvi-femoral complex. Jackson assessed that C7 has to be projected at the upper posterior angle of S1, with a margin of 60 mm in front and behind. (Jackson, 2000) The more important was the global lordosis or the segmental lordosis L4L5 and L5S1, the greater was C7 projected behind. C7 was also observed to project optimally 35 mm behind the femoral heads (25 mm forwards to 85 mm backwards) in normal subjects. The overhang of C7 on the sacral plate was observed significantly correlated with the lumbar lordosis (r=0.36), but not the overhang of C7 on the femoral heads. It was considered specific to characterize the sagittal balance of the individual.

The overhangs of C7 on the body of T12 were analyzed by Vedantam: the more C7 was behind the sacrum, the more the apex of the thoracic curve was located upwards and the more T12 and the lumbar apex were forwards. (Vedantam, 1998) Unfortunately, the radiological definition of the body of C7 was often imprecise and makes this reference unusable. The two plates of C7 were reported visible only in 50 to 63% of the cases, due to the superposition of the shadow of the shoulders. On 150 radiographs of adolescents, Vedantam reported that 41% of the cases were rejected because of this lack of precision. The definition of T1 was even worse. (Vedantam, 1998) These two markers were so difficult to use in clinical practice. Moreover, nor the pelvis sagittal morphology or the femoral heads were taken into account by these techniques. They were unable to detect a pelvic well or mal rotation. They appraised only the global balance, but not an eventual reciprocal pelvic or spinal adaptation to a local disturbance.

2.2.2.2 The Overhang of the ear canals

Gangnet reported a normal projection of the ear's canals 28 mm posterior to the femoral heads. (Gangnet, 2003) Nevertheless, this overhang was greatly affected by the position of the heads or an eventual disturbance of the cervical lordosis.

2.2.2.3 The Overhang of T4

For normal subjects, the vertical down from the center of T4 was observed behind the center of L4 and the femoral heads. (Jackson, 2000) (Figure 2B)

2.3 The analytical parameters of the sagittal balance

Using the parameters described above and comparing the observed values to normal standards provided purely descriptive analysis of sagittal balance. Dubousset proposed in 1984 to consider the pelvis as the foundation of the spine: a mobile base interposed between the spine and the lower limbs. (Dubousset, 1984) In 1998, Duval-Beaupère defined an essential anatomical sagittal pelvic parameter, the "Pelvic Incidence", and pelvic and spinal positional parameters (i.e. varying with the position of the subject). The evaluation of the harmony of their values allowed an analytical study of the individual sagittal balance of the lumbo-pelvi-femoral complex. (Duval-Beaupère, 1998)

The position of the arms was reported greatly influential on the sagittal shape of the spine. (Vedantan, 2000) The arms lying on a support were considered as reproducible and minimally influencing the position of the spine.

The angular parameters were expressed in degrees, the dimensional parameters in millimeters. A positive value was posterior, a negative anterior.

2.3.1 Positional pelvic parameters (Figure 3A)

- "Sacral Slope" (SS): angle between the upper plate of S1 (or sacral plate) and a horizontal line. A vertical sacrum was described by a low value of SS, a horizontal sacrum by a high value. The reported values (expressing a forward tilt of the sacral plate) were negative (-40.6 ° ± 8.5 from 25 to 59);
- "Pelvic Tilting" (PT): angle between the vertical and the line joining the middle of the sacral plate to the bi-coxo-femoral axis (11.4 ° ± 5.9 from -0.1 to 29.2);
- "Overhang of S1" (OVH S1): distance between the bi-coxo-femoral axis and the vertical projection of the middle of the sacral plate (21mm ± 10.8 from 43.5 to -1.5);

- "Pelvic Thickness" (PT): distance between the middle of the sacral plate and the bi-coxo-femoral axis (95mm ± 9 from 83 to 112).

2.3.2 Spinal positional parameters (Figure 3B)

- "Lordosis" (L): angle between the sacral plate and the more backward tilted plate of another lumbar or thoracic vertebra (63.5 ° ± 10.9 from 45 to 87);
- "Kyphosis" (K): angle between the more backward tilted plate used for "LA" measurement and the more forward tilted upper vertebral plate (49.3 ° ± 9.2 from 33 to 71).

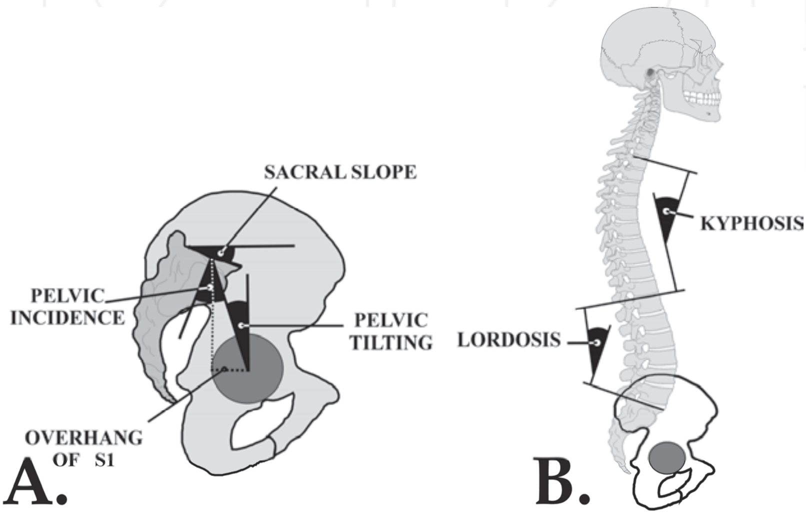

Fig. 3. The sagittal pelvic and spinal parameters

2.3.3 The anatomical parameter "pelvic incidence" (Figure 3A)

"Pelvic Incidence" (PI): angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the bi-coxo-femoral axis. This angle was anatomical (i.e. independent of the position of the pelvis) and specific for each individual. It reflected the mutual relations between the ilium and the sacrum through the sacroiliac joints, whose mobility was considered negligible, but in which were concentrated the forces of the weight of the trunk and these provided by the femoral heads from the ground. The mean value of PI was 53 ° ± 9 (min 33.7, max 77.5) for Duval-Beaupère, corroborated by numerous publications. (Boulay, 2006; Duval-Beaupère, 1998; Guigui, 2003; Marty, 2002; Vaz, 2002; Vialle, 2005a) A geometric relationship demonstrated that the anatomical parameter "Pelvic Incidence" was equal to the sum of the positional parameters "Sacral Slope" and "Pelvic Tilting" (PI = SS + PT).

2.3.4 Correlations between pelvic and spinal parameters (Figure 4)

A sequence of significant correlations between parameters was reported by Duval-Beaupère, confirmed by other authors (Boulay, 2006; Duval-Beaupère, 1998; Marty, 2002; Guigui, 2003; Vaz, 2002).

The first fundamental correlation linked the anatomical parameter "Pelvic Incidence" and the positional parameter "Sacral Slope" (r = 0.86). The second highly significant correlation was between the "Sacral Slope" and the "Lordosis" (r = 0.84). The relation between "Lordosis" and "Kyphosis" was poorly significant (r=0.36).

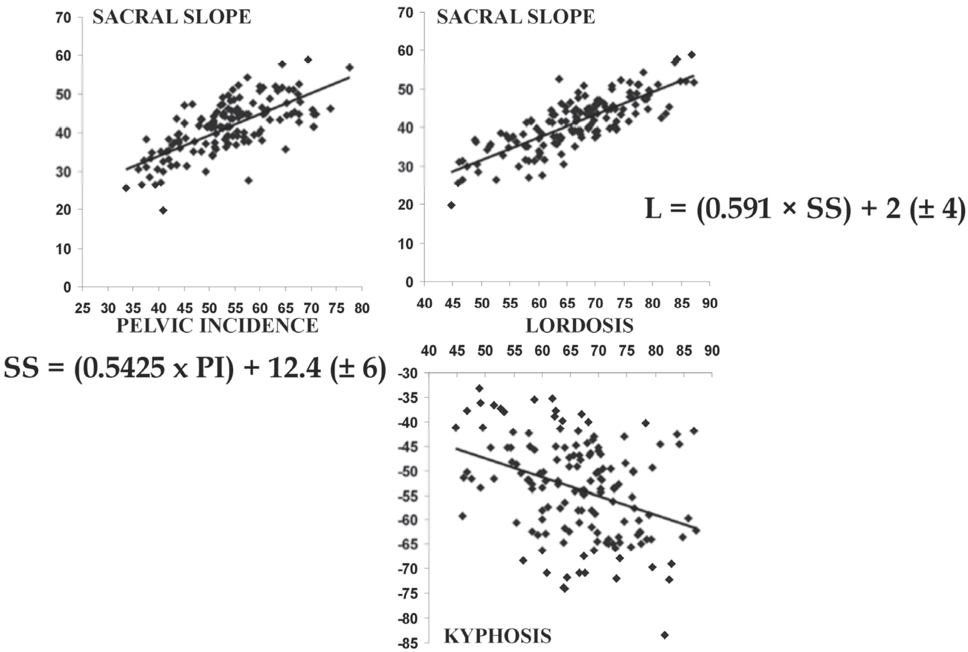

Fig. 4. Significant correlations between parameters and their predictive equations

These correlations allowed establishing the essential role of the pelvic morphology in the regulation of the sagittal spinal curves: high value of “Pelvic Incidence” was associated to high “Sacral Slope” value and an important “Lordosis” (Figure 5 A), low “Pelvic Incidence” value was associated with low “Sacral Slope” value and a more flat “Lordosis”. (Figure 5 B)

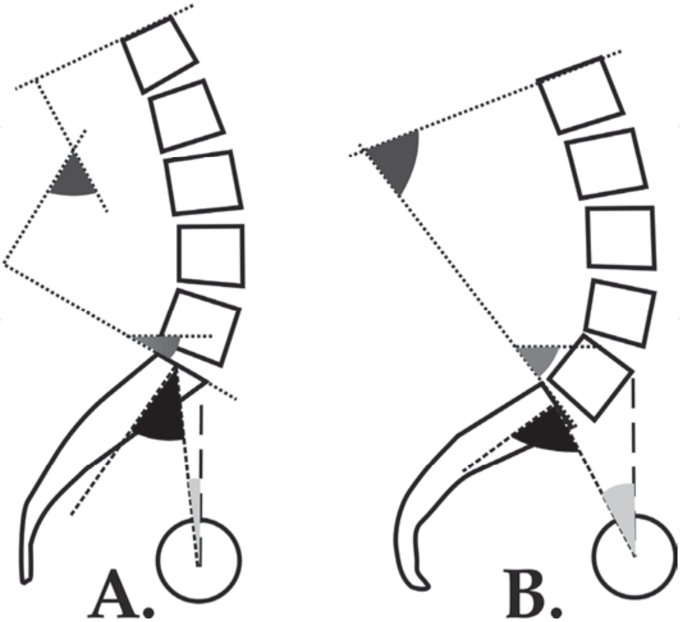

Fig. 5. Low (A.) and great (B.) value of “Pelvic Incidence” and sagittal lumbar shape.

The normality of a sagittal shape was attested by the harmony of these relationships, and not by comparing observed and average values. Using these equations, it became possible to assess the “Sacral Slope” adapted to the individual value of “Pelvic Incidence”. The difference between the observed and this optimal value was named “ΔPS”. Similarly, the value of “Lordosis” adapted to the observed “Sacral Slope” was determinable (the difference between observed and calculated value was named “Δlord”) and even the optimal value of “Lordosis” according to the “Sacral Slope” adapted by the “Pelvic Incidence” (the difference with the observed value was named “Δlord optimal”). This analytic evaluation allowed detecting a global or a local disturbance (pelvic, lumbar, kyphotic …). A pelvic tilt was considered significant if “ΔPS” exceeded 12 °, lordosis was unsuited to the observed sacral slope if “Δlord” was more than 8 ° or unsuited to the pelvic incidence if “Δlord optimal” was more than 8 °.

2.3.5 Individual pelvic sagittal shapes

Individual anatomical variations of the pelvis were related to the value of “Pelvic Incidence”. Greater was the value of the “Pelvic Incidence” more was the sacral plate forwards tilted and the sacrum curved, greater were the values of “Pelvic Tilting” and “Overhang of S1” relatively to the femoral heads and lower the value of “Pelvic Thickness”. (Figure 6)

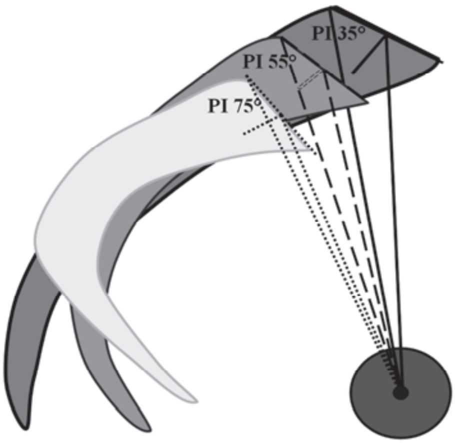

Fig. 6. Individual shapes of the sacrum and of the pelvis according the value of "Pelvic Incidence".

It was interesting to differentiate the application of this concept to an individual and to the population. At the population scale (normality of the harmony between the parameters), the value of "Pelvic Tilting" increases with the value of the "Sacral Slope", but inversely at the individual scale, the value of "Pelvic Tilting" decreases with the value of the "Sacral Slope" by pelvic retroversion (in case of disturbance). This apparent paradox highlighted the necessity of an individualized analysis of the harmony between parameters rather than a comparison with standard values.

2.3.6 Reported values, correlations and gender differences

After the first description of these sagittal parameters (Duval-Beaupère, 1998), several studies reported similar observations, both for the values and for the significant chain of correlations. This confirms the validity and reproducibility of these parameters and the usefulness of the method. (Tables 2 and 3)

	Duval-Beaupère (1998)		**Guigui (2003)**		**Vaz (2002)**	
Parameters	**Mean**	**sd**	**Mean**	**sd**	**Mean**	**sd**
Pelvic Incidence (°)	52	*11*	55	*11*	52	*12*
Sacral Slope (°)	41	*9*	42	*9*	39	*9*
Pelvic Tilting (°)	11	*6*	13	*6*	12	*6*
Lordosis (°)	64	*11*	61	*13*	47	*11*
Kyphosis (°)	49	*9*	41	*9*	47	*9*
Coefficients "r"						
"PI"/"SS"	0.84		0.81		0.86	
"SS"/"L"	0.86		0.86		0.75	
"L"/"K"	0.34		0.31		0.36	

Table 2. Reported angular values expressed of the parameters and Spearman's coefficients "r" for the significant relation between parameters.

	Duval-Beaupère (1998)			Guigui (2003)		
	Women	**Men**	Sign.	**Women**	**Men**	Sign.
Pelvic Incidence (°)	49	58	**	57	54	*
Sacral Slope (°)	39	45	**	44	41	**
Lordosis (°)	57	65	**	63	59	***
Kyphosis (°)	45	46	ns	39	42	ns

Table 3. Values of the parameters: differences according to gender (* $p<0.05$ ** $p<0.01$ *** $p<0.001$)

2.3.7 Relationships between the descriptive and analytic methods

The most important factor missing on the descriptive method (Jackson, 2000) was the low correlation between the anatomical parameter (PR-S1) and the positional parameters, whereas these correlations were strong for the analytic parameters of Duval-Beaupère (1998). (Table 4) The parameter "PR-S1", although significantly correlated with the "Pelvic Incidence" ($r = 0.998$, $p<0.001$), was less related with lordosis ($r = 0.66$, $p<0.01$). This was because, unlike the "Pelvic Incidence", it involved in its measure the slightly trapezoidal shape of S1 (Marty, 2002). In addition, the "Lumbo-Pelvic Lordosis" incorporates both anatomical and positional components. The descriptive method, however, was complex because it required a lot of measures. It was also imprecise as a consequence of the numerous physiological values and the large areas of overlap with the pathological situations.

	Gelb (1995)	**Vedantam (1998)**	**Jackson (2000)**		**Duval (1998)**	**Guigui (2003)**	**Vaz (2002)**
SI/ lordosis	0.47	0.68	0.56	**SS / lordosis**	0.86	0.85	0.75
PRS1 / lumbo-pelvic lordosis			ns	**PI / lordosis**	0.60		

Table 4. Reported Spearman's coefficients (r) between parameters

2.3.8 Analytic evaluation of a clinical imbalance

Three types of disturbances may arise, leading to a displacement of the trunk forwards and inducing an sagittal unbalance with excessive stresses of the anatomical structures and necessitating muscle contractions, possibly painful:

- Type A: lack of "Lordosis" with a "Sacral Slope" value too low for the value of PI; (Figure 6A) It was the most frequently observed disturbance in clinical practice for low back pain. The loss of "Lordosis" was the consequence of lumbar disorders, mostly at the lower levels (disc diseases with local inter vertebral reduction of the lordosis, fractures …), the result of fusion in inadequate lordosis or the result of muscular atrophy (often with obesity, sometimes by muscular or neurological disorders s as Parkinson's disease). The pelvic reaction to this loss of lordosis was a backward rotation (retroversion) achievable by extension of the hips, and then by flexion of the knees (and flexion of he ankles).

- Type B: excessive “Sacral Slope” value reflecting a forward pelvic rotation (anteversion), by stiff flexion of the hips, sufficiently or not compensated by an accentuation of the “Lordosis”. (Figure 6 B) This situation occurred mostly in cases of hip (and knee) osteoarthritis. Only the treatment of the origin was useful (as by hip arthroplasty).
- Type C: “Lordosis” insufficient to compensate an excessive kyphosis, with backwards pelvic rotation (low value of SS), and finally flexion of the hips and the knees. (Figure 6 C) This situation occurred mostly with aging, by disc thoracic narrowing or osteoporotic factures, after traumatic fractures or in majors Scheuerman’s diseases cases.

Each of these 3 situations tends to induce an anterior translation of the gravity loads, unfavorable for the evolution of the subject.

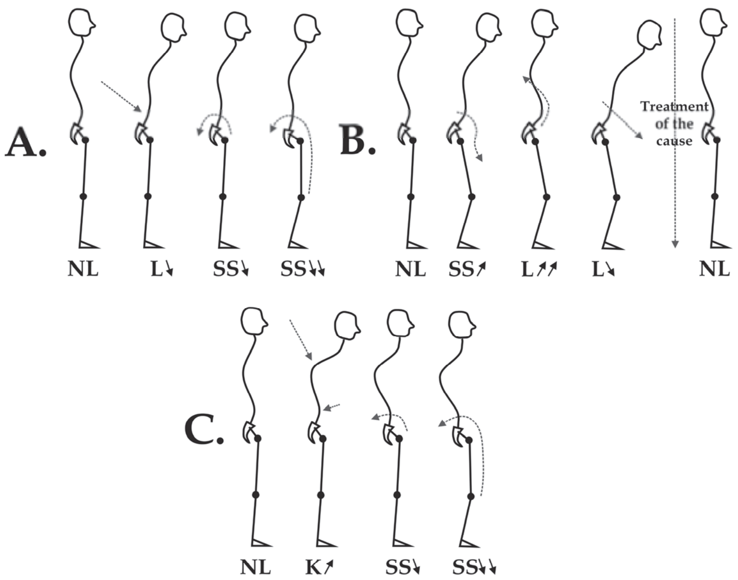

Fig. 6. Types of sagittal disturbances and their evolution

The value of “Pelvic Incidence” determines the stability of a balanced attitude, the ability of a subject to react to a disturbance and also the individual risks of a loss of “Lordosis”. A subject with a low “Pelvic Incidence” value has a lower capacity to adapt to a disturbance because of low potential of “Lordosis”, contrary to those with a great value of “Pelvic Incidence” with a great reserve of compensation. Conversely, the risk of insufficient “Lordosis” will be greater for the subjects with high “Pelvic Incidence” value, necessitating a high “Lordosis” value to be adapted. In case of lumbar fusion, the risk of insufficient “Lordosis” will be greater than in subjects with small “Pelvic Incidence” value, necessitating less “Lordosis” to compensate. Similarly, interventions not allowing an increase of lordosis (as inter-somatic cages, disc prosthesis, inter spinous blocks) should be avoided for cases with high “Pelvic Incidence” value, easily resulting in a disturbed sagittal balance by loss of “Lordosis” (and a late compensation on the overlying levels, difficult to treat).

The analytic evaluation is so individual. It must be integrated into the evolution of the subject. In further paragraph 4, this analytic method will also be functional because it allows integrating the biomechanical loads of gravity on the spine and pelvis.

3. The sagittal balance in spinal diseases

3.1 The spondylolisthesis

3.1.1 Isthmic spondylolisthesis

Significantly higher values of “Pelvic Incidence” and “Sacral Slope” were reported by several authors. (Hanson, 2002; Huang, 2003; Labelle, 2004, 2005; Vialle, 2005b, 2007a, 2007b) The sacral plate was described more tilted, inducing a marked lordosis and a slip of L5 on S1. This generated a forward shift of the center of gravity of the trunk. The correction was attempted by flattening of the kyphosis (the decrease in the sagittal slope of T9 expressed the anterior displacement of the trunk). (Figure 7) Additionally, the increased lordosis L4L5 L5S1 was considered damaging the isthmus. The importance of the value of pelvic incidence may be considered a prognostic factor for the progression of the listhesis. (Hanson, 2002; Huang, 2003; Labelle, 2004; Vialle, 2005b, 2007a, 2007b)
The adult form of the sacrum was also described more curved in kyphosis, particularly between S1 and S2, and nearly similar to the sacrum of children before the acquisition of standing position with a lower angle between the frontal edge of S1 and the sacral plate. (Marty, 2002)

3.1.2 Degenerative spondylolisthesis

In degenerative spondylolisthesis, the sagittal balance was described differently: the angle of kyphosis was not influenced, but the lordosis was significantly flattened with pelvic retroversion (lower value of the “Sacral Slope”). (Morel, 2005) In this way, the slope of T9 was in the range of normal values. (Figure 7) The “Pelvic Incidence” was reported greater than for younger subjects. An accentuation of this age-related value can be attributed to torsion stresses on the sacroiliac joints during life.

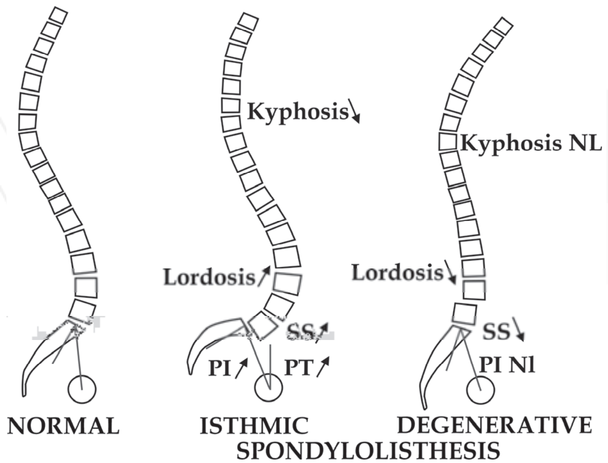

Fig. 7. Sagittal shape in normal case and in isthmic and degenerative spondylolisthesis

3.2 Lombo-arthritis – Low back pain

The pelvic incidence values were identical to the normal adult population. In most cases, the essential of the disturbance was a loss of lumbar lordosis (by disc degeneration, by pelvic retroversion reacting to obesity ...) sometimes associated with stiffness in flexion of the hip. It induced an anterior displacement of the trunk often progressive because of the muscular weaknesses frequently occurring in aging individuals. This more anterior application of gravity on the pelvis tends to tilt the sacrum forwards, but the ground reaction forces transmitted through the femoral heads tend to tilt the iliac bones backwards. (Figure 8) This induced a twisting phenomenon into the sacroiliac joints, which was source of back and leg pain (the "Pyriform Syndrome"), and eventually of an increasing of the value of "Pelvic Incidence". The loss of lordosis (occurring mainly in the lower levels) was then compensated by a pelvic retroversion and a hyperextension in the higher lumbar levels.

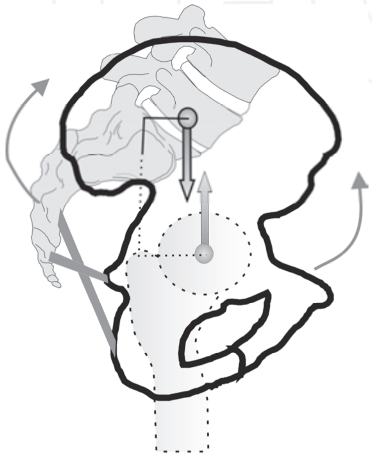

Fig. 8. Torsion stresses on the sacro-iliac joint induced by the inverse move of the ilium and sacrum in case of forwards displacement of the loads of the trunk

3.3 Herniated discs

A lower pelvic incidence (47.3°) was observed only in patients under 40 year old with a herniated lumbar disc. (Guigui, 2003) A pelvic retroversion was frequently observed, independently of the age.

3.4 Implications on the result of surgical lumbar fusion

Respect of the harmony of the parameters was crucial in such surgical procedures. A significant pelvic retroversion was reported in patients remaining painful after lumbar fusion comparing to painless cases. (Gottfried, 2009; Kawakmi, 2002; Lazennec, 2000) Similarly, Kumar reported degenerative changes in the adjacent levels 5 years after surgery only in 8% of the well balanced cases but in 50% of the unbalanced cases. (Kumar, 2000) The twisting phenomenon into the sacroiliac joints occurred when lumbar lordosis was inadequate, especially if L5-S1 was included in the fusion. In addition, the critical effect of the upper lordosis with compensation by retro- (or ante-) listhesis of the overlying disc in a hypo-lordotic fusion was to fear. (Figure 9)

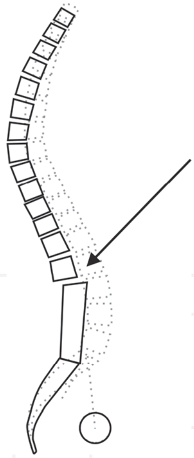

Fig. 9. Retro listhesis of the upper lordosis in compensation of a fusion insufficiently curved

Any imbalance, no matter the indication (degenerative disease or deformity such as scoliosis) was detrimental to clinical outcome in the short and long term. The origin was vertebro-discal stresses, painful muscle cramps and twisting in the sacroiliac joints.

3.5 Deformations on osteoporosis

The negative factor was the progressive thoracic kyphosis by disc narrowing for which lumbar and pelvic compensation became progressively inadequate. (Figure 10) The same principle applied in the event of osteoporotic spinal fractures, in kyphosis or badly reduced. The forward displacement of the trunk, especially if lumbar compensation was reduced, had to be avoided. The hyper kyphosis produced by osteoporotic fractures induced a forward tilting of the trunk that compensated as much as possible an accentuation of the lumbar lordosis, in the limits of possible as far as age and lumbar discs go. A pelvic retroversion occurred to help compensate this evolutionary hyper-kyphosis in intensity and topographic extension, and finally a flexion of the hips and of the knees.

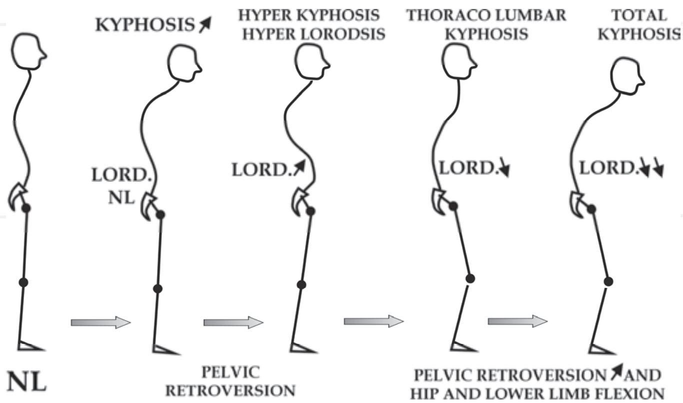

Fig. 10. Sagittal evolution with aging for kyphotic osteoporosis

3.6 The aging

Aging was observed to be accompanied with an accentuation of the thoracic kyphosis: 30 ° for 30-39 y.o., 40 ° for 50-59 y.o., 50 ° increasing from 60 to 80 y.o.. (Korovessis, 1998) In parallel, the lumbar lordosis disappeared gradually: 68 ° for 40 - 49 y.o., 62 ° for 50 - 69 y.o., less than 60 ° after 70 y.o. . (Gelb, 1995) This induced a progressive displacement forwards of the trunk, resulting in the projection of C7 more anterior to the sacral promontory: 4.3 cm behind for 40 - 49 y.o., 3.7 for 50 - 59 y.o., 2.4 for 60 - 69 y.o., only 1.9 cm after 70 y.o. . (Gelb, 1995; Jackson, 1994) A significant correlation between PI and age (r = 0.14) was reported (Guigui, 2003). These alterations of the curves imposed an evaluative and functional analysis considering the impact on the stresses of gravity.

3.7 Hyper-kyphosis related to age

The loss of lordosis by aging induced in the early evolution a decrease of kyphosis with a pelvic retroversion. The displacement forwards of gravity of the trunk relatively to the thoracic and especially the lumbar vertebrae accentuates the curving stresses on the thoracic spine that will finally decompensate, resulting in accentuation of the kyphosis which is related to age (loss of disc height, osteoporotic fractures). T9, and the loads of gravity on the thoracic and lumbar structures, were too much forward, requesting the disco-ligamentar structures and inducing more rebalance muscle contractures, themselves becoming painful.

3.8 Sheuerman's disease

This disease was local to the thoraco-lumbar vertebrae. The “Pelvic Incidence” was so similar to the normal population, as well as “Pelvic Tilting” and “Sacral Slope” although “Lordosis” was increased in compensation.

3.9 Influence of the sport activities

The pelvic incidence was observed significantly higher ($p < 0.0001$) among soccer players (55.7 °) than in non-athletic subjects (50.3 °). (Wodecki, 2002)

4. Functional analysis by assessment of the gravity loads on the lumbo-pelvi-femoral complex: The mechanical model

The analytic concept of the harmony of the pelvi-spinal balance expressed a balance "economical" in terms of loads on the disco-ligamentar structures and muscular efforts required for its maintenance. This concept was developed by Duval (1987) in conjunction with an innovative individual determination of the gravity loads on the spine in station and in vivo: the “barycentremetry”. In this way, the sagittal analysis has become “functional”.

4.1 Measurement of the gravity loads

4.1.1 The mathematical models

Mathematical models were performed to evaluate the mechanical stress applied to the spine. The first were based on analysis of the axial compression of the spine in a standing position from the lever arms of action of muscles and other structures. The initial assessment was from the body cross sections, (Shultz, 1981) then the finite element models reproducing these forces were developed. Used for research or hardware design, they were totally useless in clinical practice.

4.1.2 The platform of force

Therefore many authors have used the platforms of force in conjunction with radiographs to assess the gravity loads on the spine and pelvis. The position of gravity was assimilated to be vertical from the application point of the whole body weight on the ground. (Gangnet, 2003; During, 1985) However, these techniques remained imprecise because they failed to access to the position in height of gravity and especially were inaccurate because they integrated the whole body (including the legs underlying to the pelvis) in establishing the position of the gravity loads applied to the segmental spinal and pelvic structures. If it was a good approximation in normal standing position, it was inaccurate in case of spinal or pelvic disturbance because the gravity of the whole body was no more assimilative to segmental gravity (of the trunk, of bodily segments supported by each vertebra…). (Figure 11)

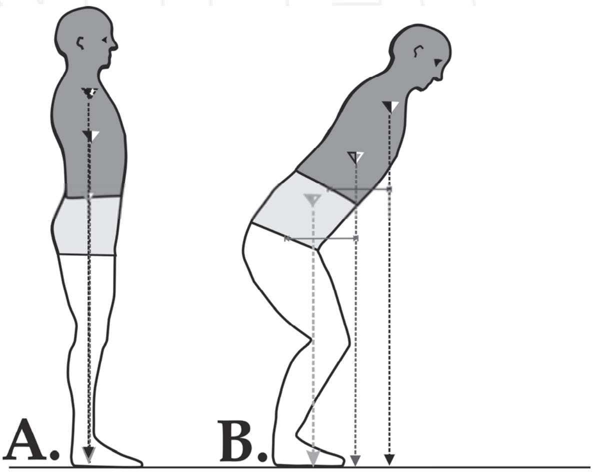

Fig. 11. Segmental lever arms and centers of gravity in normal (A) and unbalanced (B) standing position

4.1.2.1 Barycentremetry

A prototype gamma-ray scanner (whose absorption was proportional to the crossed mass) has provided access in patients in vivo to the position of gravity of 1 centimeter thick body slices. (Duval, 1987) This scanner was coupled to a system of three-dimensional reconstruction of the spine and pelvis from bi-planar X-rays. After matching the two reference systems, a process of integration provided the lever arms and the loads of gravity on all discs and vertebral levels as well as on the pelvis and on the femoral heads in a standing position: “the barycentremetry”. (Figure 12)

In this way, it was found that the application points of gravity were projected within a cylinder of 1 centimeter diameter, located forwards at the thoracic levels, backwards at the lumbar levels (26 mm behind the middle the upper plate of L3) and crossed the upper plate of the sacrum behind its middle, and backwards to the femoral heads (36 mm). The centre of gravity of the body segment supported by the femoral heads was more often in front of T9 (0 to 14 mm when the thoracic kyphosis was less than 35 °, 20 to 32 mm if it was higher). (Duval 1992 & 2008)

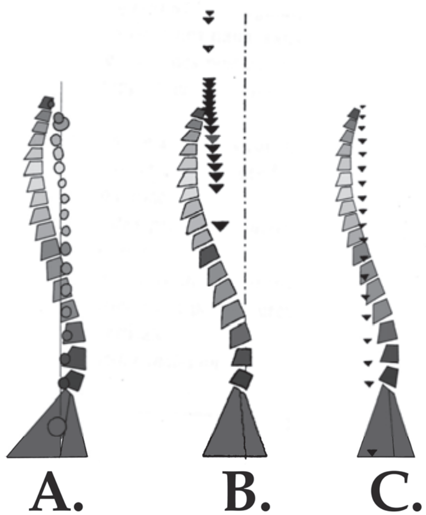

Fig. 12. Barycentremetry by gamma ray scanner providing the elementary center of gravity of body slices centered on vertebrae and pelvis (A), the location in upright position of the centers of gravity supported by each vertebrae and pelvis (B), the projected lever arm of gravity applied on each level of the spinal and pelvic structures (C).

	Mean (in mm)	sd	min	max
L3	25	25	-18	96
S1	18	27	-31	111
Femoral heads	36	21	9	52

Table 5. Values of the lever arms of the gravity on L3, S1 and the femoral heads axis.

4.1.2.2 Barycentremetry confronted to the force platforms

Using force platforms for standing normal subject, the position of the center of gravity of the whole body (including the legs) was observed projected 28 mm (SD 14) behind the femoral heads by Gangnet (2003), 12 mm (SD 12) behind the sacral promontory by During (1985). These data were similar to the barycetremetric observations, testifying the liability of both techniques in such normally balanced position. Nevertheless, only the barycentremetry allowed to determine real segmental centers of gravity for each pelvic and vertebral levels, and to take into account the individual variation of each segments relatively to the others in case of misbalanced position. (Duval, 1992 & 2008)

4.1.2.3 Biomechanical implications of the position of gravity

The loads of gravity backwards to the lumbar levels were balanced by the abdominal muscle chains, saving the back muscles at rest. At the thoracic levels, the forward position was compensated by the posterior spinal muscles and the stiffness of the rib cage. This optimal balance was defined as economical, in accordance to the analytic definition of the harmonious relations of spinal and pelvic parameters. (Figure 13)

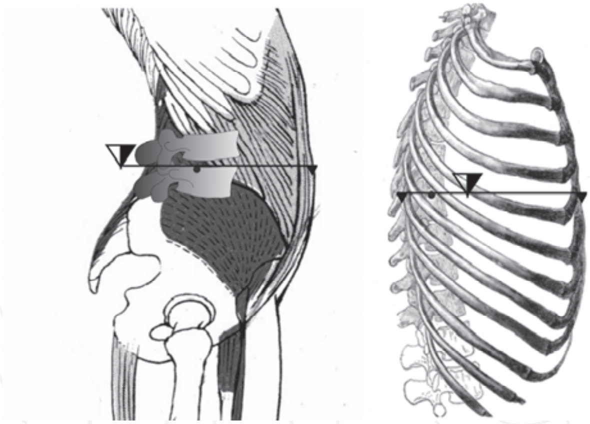

Fig. 13. Optimal balance between gravity and the abdominal muscles at lumbar levels, the rib cage and spinal muscles at the thoracic levels.

It has been found by simultaneous muscle activity detection through direct electromyography recordings and by the gamma ray scanner, that only the respect for the harmonious personal relationships between the parameters allowed a "muscle silent" balance: it is both economical and stable. In cases of pelvic retroversion or anteversion, or inadequate lumbar curve, the lever arm of gravity became relatively forwards to lumbar or femoral structures, thereby inducing excessive mechanical stresses and muscle counterbalancing contractures accentuating the excessive loads on the anatomical structures: the balance was no more economical and instable. (Figure 14)

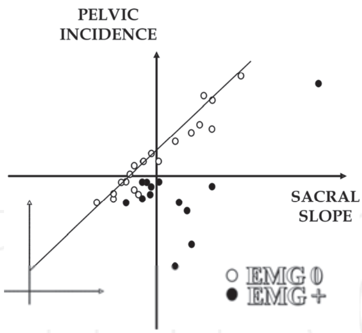

Fig. 14. Correlation between muscular contractions of the posterior muscles of the lumbar spine and the respect of the harmonious relations between the analytic parameters

4.1.2.4 Validation of the mechanical model

The data obtained by barycentremetry were similar to the data obtained by force platform for a normal standing balance. To complete the validation of the method, the values obtained by using the lever arms of the forces defined by barycentremetry were compared with data reported from the biomechanical model of Shultz-Andersson and with experimental data of the loads on the disc L3-L4 measured directly in vivo by Nachemson. (Nachemson, 1981; Shultz-Andersson, 1982)

	Standing	Sitting
Nachemson (1981)	330 N	420 N
Schultz (1982)	440 N	380 N
Duval (27 y.o., 69 kg)	362 N	396 N

Table 6. Comparison of the values of loading forces on the disc L3-L4 determined by barycentremetry and the data published by Schultz and Nachemson.

4.1.2.5 The "barycentremetry" as mechanical model of the sagittal balance

The sagittal balance of the spine was economical in terms of levers arms of the loads of gravity at each levels of the lumbo-pelvi-femoral unit, well-balanced by minimal muscular activity exerting a low flexing force in a long lever arm (the abdominal muscles, the posterior spinal muscles being inactive) or strengths in the bone or ligament structures (the rib cage). It was possible if:

- For each lumbar level, the supported center of mass was projected behind the center of rotation (which was at the posterior third within the disc)
- The center of gravity of the body segment supported by the femoral heads was projected behind the femoral heads. It was assimilated to a point located forwards of T9.

An application of gravity too far anterior will induce compressive forces and shear stresses on the vertebral structures, the discs and the ligaments, and induce rebalancing muscle contractions, which can become painful and further accentuate the excess loads on inter-vertebral structures. A twisting effect was also induced in the sacroiliac joints, the source of postural back and lower limb pain.

In reaction to a position of gravity much too anterior, the pelvic retroversion with flattening of the lordosis will bring back gravity behind the femoral heads, but the loads will be more anterior at the lumbar level because of backwards movement of the lumbar vertebrae relatively to the gravity line. Thereafter, the flexion of the hips and lower limbs will accentuate this situation less and less economical. The stresses of the posterior spinal muscles will become more important and deleterious and a source of pain throughout the spine and pelvis. (Figure 15)

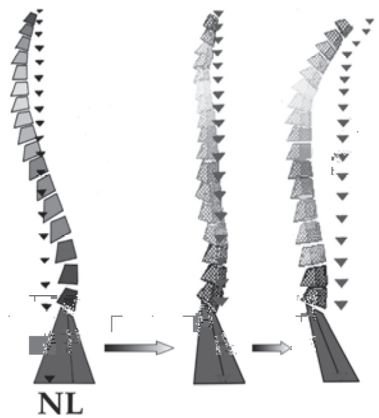

Fig. 15. Lever arms of gravity in normal and progressive anterior sagittal disturbance

4.2 Approximation of the mechanical model using the data of the barycentremetry

The barycentremetry was a laboratory technique substantiating the observations of harmonious relations between the parameters for a sagittal balance economically stable in terms of mechanical stresses. Nevertheless, such a functional evaluation of the sagittal balance appeared of first interest. Therefore, a method usable in daily medical clinical practice was elaborated, easily applicable for an individual sagittal analysis.

4.2.1 The simili-barycentremetry

For a series of 42 asymptomatic subjects and 39 scoliotic cases, the data of gravity obtained by barycentremetry and radiographic were available in concordance. From these radiographic data, several additional parameters have been defined. Since it was possible to produce an equation providing the lever arm of gravity supported at the levels L3, S1 and the femoral heads: the "simili-barycentremetry".

The evaluation was based on the fact that the center of gravity of the trunk supported by the femoral head was at the level of T9 in height. The used data were the relative overhangs of the vertebrae, the number of vertebrae included in the curvatures, anthropometric data, slopes of L3, T9, T1. (Figure 16)

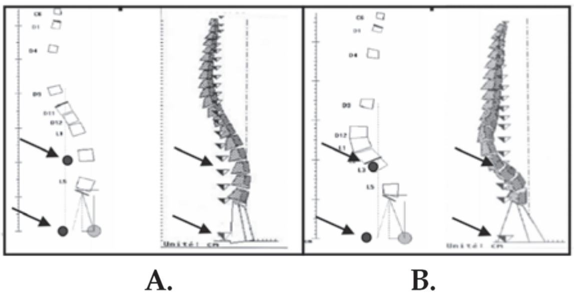

Fig. 16. Simili-barycentremetry compared to Barycentremetry for 2 cases visualizing the similarity of the location of the gravity loads at L3 and the femoral heads levels.

In order to validate the method, the results of this equation were compared with the data of the barycentremetry for the same patients on the same radiographs. (Figure 17)

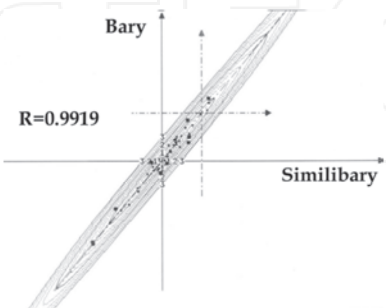

Fig. 17. Correlation of the data of the gravity loads at the level L3 by barycentremetry and using the predictive equation of simili-barycentremetry for 42 normal subjects.

Various media for three-dimensional reconstruction of the spine have integrated this simili-barycentremetry in an automated manner. Biomod 3S® (AXS Ingenery, Bordeaux-Mérignac, France) used semi-automated method for 3D reconstruction of the spine and integrated automatically the measurement of the parameters and the data of simili-barycentremetry numerically and visually. (Figure 18)

Fig. 18. Barycentremetry and simili-barycentremetry by Biomod 3S®

4.2.2 The parameters

The automated simili-barycentremetry might not be available for everyone. However, the use of individual parameters allowed an approximated functional analysis of sagittal balance finer than the analytical analysis initially described (2.3.8.) (Figure 19)

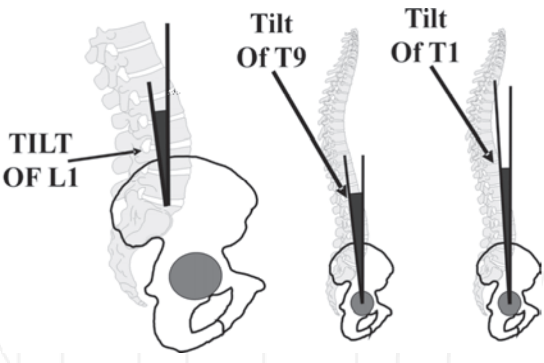

Fig. 19. The tilt parameters used for the simili-barycentremetry

4.2.2.1 The tilt of T9

The position of the center of gravity of the trunk supported by the femoral head was observed in height at T9 level (rarely T8 or T10), in front of the vertebral body from 0 to 14 mm if the kyphosis angle was less than 35 °, 20 to 32 mm if the kyphosis exceeded 35 °. Its projection was 36 mm (sd 21mm) behind the femoral heads. T9 was considered reflecting the position of center of gravity of the trunk. This position was assimilated to the tilt of T9 (angle between the vertical and the line between the hip-axis and the centre of the body of T9 (10.5° backwards, sd 3). This tilt has been observed correlated significantly (r = 0.62) with the projection of the center of gravity of the trunk on the femoral heads.

4.2.2.2 The tilt of L1

This angle was defined as the angle between the vertical and the line between the center of L1 and the lower plate of L5. It expressed the slope of the lumbar spine, independently of the pelvis orientation. Its value for asymptomatic subjects was -8 degrees (i.e. forwards), sd 5. It reflected the result at the lumbar level of the global balance, of an eventual correction of an upper disturbance in kyphosis by both the pelvis and the lumbar curve.

4.2.2.3 The tilt of T1

This angle was defined as the angle between the vertical and the line between the center of T1 and the lower plate of L5. It expressed the global tilt of the whole spine, but excluding the analysis of the pelvis rotation. This global slope value was reported to be of 3 degrees (sd 3).
It suffered of the same inconvenient as the overhang of C7.
Significant correlation between the tilt parameters were observed, testifying once more the harmony in the lumbo-pelvi-femoral complex in standing position. (Table 7)

Correlation	r=
Tilt T9 - Kyphosis	0.4214
Tilt L1 – Tilt T9	0.5935
Pelvic Incidence – Tilt L1	-0.1707

Table 7. Significant correlations between the “tilt parameters”

4.2.2.4 The role of the “Overhang of S1” and the “Pelvic thickness”

This “Overhang of S1” on the femoral heads was correlated with the “Pelvic Incidence” by the intermediary of the “Pelvic Tilting” (OVH S1/ PT r = 0.80, PT/ PI r = 0.54). Therefore, the overhang was the greater in case of major value of “Pelvic Incidence”, the greater were the gravity loads of the trunk projected behind the femoral heads. Also the “Pelvic Thickness” (inversely related to Pelvic Incidence r=0.334) was observed to affect the lever arm of action of the lumbo-pelvic muscles. As well, the lever arms of action of the gluteus maximus was important in case of high value of PI, PT, OVH S1 and low value of Pelvic Thickness. Contrarily, in case of low value of pelvic incidence, the gravity was projected less backwards to the femoral heads (and so the risk of disruption of the balance was greater), the values of PT and OVH S1 were lower, but the pelvic thickness was greater (the static and dynamical structures are so more vertical and such less efficient) and the lever arm of the gluteus maximus was shorter.(Figure 20) It these cases, the risk of torsion strength in the sacro-iliac joints would be greater.

5. Conclusion

In his search for the economy, the organism creates and manages moderate curves closer to the line of gravity. The lever arm of gravity remains as small as possible.
The use of the described parameters allows a functional personalized analysis of the sagittal balance of an individual.
But some questions remain:

- what is the acceptable lordosis deficit, related to the ideal value for the spine that will be able to support the age-related changes without decompensate and induce pain? We can just affirm that the lordosis (and the pelvic and spinal parameters) must be as close as possible to the ideal values

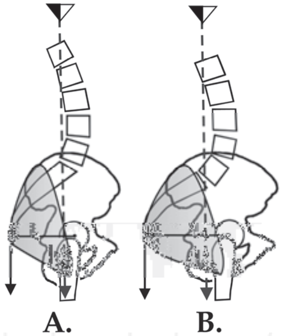

Fig. 20. Relation between Pelvic incidence (A low value, B high value) and the lever arm of gravity on the femoral heads and the lever arm of action of the gluteus maximus.

- what are the real and practical ways to restore a sufficient lordosis, either surgically or functionally? Probably, the use of a navigation device of the lumbar curve during surgery has a place for the surgical regulating. The real question is concerning a truly lordosing surgery (a vertebral osteotomy). But in this case, the correction must be complete and does not tolerate a residual deficit.
- what is the optimal ratio of benefit- risk in such serious and potentially iatrogenic procedures? Also the restoration of an adequate value according to the harmony between the parameters must be made. The global balance of the individual must be taken into account, including the cervical spine, the hips and the lower limbs including the knees and the ankles.

It can be concluded and counseled to fuse only when necessary, and in any case never lose any lordosis (by installation of the hips in extension and not in flexion, not fusing longer than indispensable, avoiding the often kyphosing surgical procedures (as inter-spinous blocks or other devices). The balancing factors take precedence over segmental lesions. Surgical procedures as inter-body fusion or disc prosthesis should not be performed in case of pre-operative loss of lordosis, because results will be unsatisfactory and involve adjacent complications. (Figure 21)

Fig. 21. Retro-listhesis in compensation to a loss of lordosis induced by the device

6. Prospects

The data reported allowed now to access an individualized functional analysis of the sagittal total balance of the lumbo-spino-pelvic complex in standing position.
However, this analysis is static and not integrated into the movement and the daily activity of the subject. The immobile bipedal station is exceptional. The acquisition of dynamic data incorporating the described parameters could assess the loads supported by the spino-pelvic structures during daily activities.
Nevertheless, actual technical devices for measuring parameters require irradiation which could become significant if the acquisitions had to be repeated, especially dynamically. For this reason, optical acquisition techniques have been developed. Currently static and repeated over time, they allowed an analytical study of the sagittal balance of a subject, its evolution and individual strategies of adaptation, after an initial radiograph using the parameters described. (Figure 22A) The simulation of the position of bony structures within the skin envelope was actually elaborated and validated. (Figure 22 B)

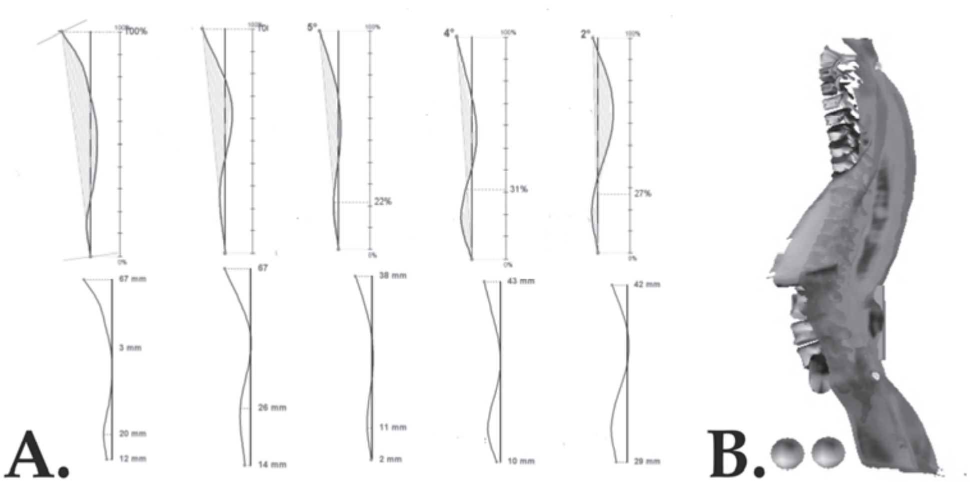

Fig. 22. Sagittal evolution of the shapes of a case during 2 years by optical assessment (A) and bony structures related to the back skin surface (B) (Biomod L® and Biomod 3S®)

Dynamic acquisitions of skin surfaces by these methods allow now an optical motion analysis, the detection of abnormal movements or segmental stiffness. The acquisition of three-dimensional envelope allows an assessment of the mass of body segments and thus the position of the centers of gravity into the body. Combined with an X-ray, real or extrapolated, this promising technology will allow a functional evaluation of all individual lumbo pelvic-femoral balance in the real life in movement.

7. References

Boulay, C. et al. (2006). Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis. *Eur Spine J,* Vol. 15, pp. 415–422

Dubousset, J. (1984). The pelvis « intercalary bone ». *Monograph of the GES*, Paris, p. 15-22

During, J. et al. (1985). Toward standards for posture. Postural characteristics of the lower back system in normal and pathologic conditions. *Spine*, Vol. 10, Issue 1, pp. 83-7

Duval-Beaupère, G. & Robain, G. (1987). Visualization on full spine radiographs of the anatomical connections of the centres of the segmental body mass supported by each vertebra and measured in vivo. *Int Orthop*, Vol 11, Issue 3, pp. 261-9

Duval-Beaupère, G.; Schmidt, C. & Cosson, P. (1992). A Barycentremetric study of the sagittal shape of spine and pelvis: the conditions required for an economic standing position. *Ann Biomed Eng*, Vol. 20, Issue 4, pp. 451-62

Duval-Beaupère, G. et al. (1998). Pelvic incidence: a fundamental parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J*, Vol. 7, pp. 99-103

Duval-Beaupère, G. (2008). Gravitational forces and sagittal shape of the spine. Clinical estimation of their relations. *Int Orthop*, Vol. 32, Issue 6, pp. 809-16

Gangnet, N. et al. (2003). Variability of the spine and pelvis location with respect to the gravity line: a three-dimensional stereoradiographic study using a force platform. *Surg Radiol Anat*, Vol. 25, pp. 424-33

Gelb, D.E. (1995). An analysis of sagittal alignment in 100 asymptomatic middle or aged volunteers. *Spine*, vol. 20, pp. 1351-8.

Gottfried, O.N. et al. (2009). Spinopelvic parameters in postfusion flatback deformity patients. *Spine J*, Vol. 9, Issue 8, pp. 639-47

Guigui, P. et al. (2003). Physiological value of pelvic and spinal parameters of sagital balance: analysis of 250 Healthy volunteers. *Rev Chir Orthop Reparatrice Appar Mot,* vol. 89, Issue 6, pp. 496-506

Hanson, D.S. et al. (2002) Correlation of pelvic incidence with low- and high-grade isthmic spondylolisthesis. *Spine*, Vol. 27, Issue 18, pp. 2026-9

Huang, R.P.; Bohlman, H.H. & Thompson, GH. (2003). Predictive value of pelvic incidence in progression of spondylolisthesis. *Spine*, Vol. 28, pp. 2381-2385

Jackson, R.P. & McManus, A.C. (1994). Radiographic analysis plane alignment and balance in standing volunteers and patients with low back an matched for age, sex and size. *Spine*, Vol. 19., Issue 14, pp. 1611-8

Jackson, R.P. & Hales, C. (2000). Congruent spinopelvic alignment on standing lateral radiographs of adult volunteers. *Spine*, Vol. 25, pp. 2808-2815

Kawakami, M. et al. (2002). Lumbar sagittal balance influences the clinical outcome after decompression and posterolateral spinal fusion for degenerative lumbar spondylolisthesis. *Spine*, Vol. 27, Issue 1, pp. 59-64

Korovessis, P.G.; Stamatakis, M.V.& Baikousis, A.G. (1998). Reciprocal angulation of vertebral bodies in the sagittal plane in an asymptomatic Greek population. *Spine*, Vol. 23, Issue 6, pp. 700-5

Kumar, M.N.; Baklanov, A. & Chopin, D. (2001). Correlation between sagittal plane changes and adjacent segment degeneration following lumbar spine fusion. *Eur Spine J*, Vol. 10, Issue 4, pp. 314-9

Labelle, H. et al. (2004). Spondylolisthesis, pelvic incidence, and spinopelvic balance: A correlation study. *Spine*, Vol. 29, Issue18, pp. 2049-2054

Labelle, H. et al. (2005). The importance of spino-pelvic balance in L5-s1 developmental spondylolisthesis: a review of pertinent radiologic measurements. Spine, Vol. 30, Issue 6, pp. S27-34

Lazennec, JY. Et al. (2000). Sagittal alignment in lumbosacral fusion: relations between radiological parameters and pain. *Eur Spine J*, Vol. 9, Issue 1, pp.47-55

Marty, C. et al. (2002). The sagittal anatomy of the sacrum among young adults, infants and spondylolisthesis patients. *Eur Spine J*, Vol. 11, pp. 119-25

Morel, E. et al. (2005). Sagittal balance of the spine and degenerative spondylolisthesis. *Rev Chir Orthop Reparatrice Appar Mot*, Vol. 91, Issue 7, pp. 615-26

Nachemson, A.L. (1981). Disc pressure measurements. *Spine*, Vol. 6, Issue 1, pp. 93-7

Schultz, A. & Andersson, G. (1981). Analysis of loads on the lumbar spine. Spine, Vol.6, Issue 1, pp. 76–82

Schultz, A.; Andersson, G. et al. (1982). Loads on the lumbar spine. Validation of a biomechanical analysis by measurements of intradiscal pressures and myoelectric signals. *J Bone Joint Surg Am*, Vol. 64, Issue 5, pp. 713-20

Vaz, G. et al. (2002). Sagittal morphology and equilibrium of pelvis and spine. *Eur Spine J*, Vol. 11, pp. 80–87

Vedantam, R. et al. (1998). Comparison of standing sagittal spinal alignment in asymptomatic adolescents and adults. *Spine*, vol. 23, pp. 211-5

Vedantam, R. et al. (2000). The effect of the variation in arm position on sagittal spnal alignment. *Spine*, Vol. 25, Issue 17, pp. 2204-9

Vialle, R. et al. (2005). Radiographic Analysis of the Sagittal Alignment and Balance of the Spine in Asymptomatic Subjects. *J Bone Joint Surg (Am),* Vol. 87, Issue 2, pp. 260-267

Vialle, R. et al. (2005). Radiological assessment of lumbosacral dystrophic changes in high-grade spondylolisthesis. *Skeletal Radiol*, Vol. 34, Issue 9, pp. 528-35

Vialle, R. et al. (2007) Sacral and lumbar-pelvic morphology in high-grade spondylolisthesis. *Orthopedics*, Vol. 30, Issue 8, pp. 642-9

Vialle, R. et al. (2007). Is there a sagittal imbalance of the spine in isthmic spondylolisthesis? A correlation study. Eur Spine J, Vol. 16, Issue 10, pp. 1641-9

Wodecki,P. et al. (2002). Sagittal alignment of the spine: comparison between soccer players and subjects without sports activities. *Rev Chir Orthop Reparatrice Appar Mot*, Vol. 88, Issue 4, pp. 328-36

Biomechanics in Applications
Edited by Dr Vaclav Klika

ISBN 978-953-307-969-1
Hard cover, 408 pages
Publisher InTech
Published online 09, September, 2011
Published in print edition September, 2011

During last couple of years there has been an increasing recognition that problems arising in biology or related to medicine really need a multidisciplinary approach. For this reason some special branches of both applied theoretical physics and mathematics have recently emerged such as biomechanics, mechanobiology, mathematical biology, biothermodynamics. The Biomechanics in Application is focusing on experimental praxis and clinical findings. The first section is devoted to Injury and clinical biomechanics including overview of the biomechanics of musculoskeletal injury, distraction osteogenesis in mandible, or consequences of drilling. The next section is on Spine biomechanics with biomechanical models for upper limb after spinal cord injury and an animal model looking at changes occurring as a consequence of spinal cord injury. Section Musculoskeletal Biomechanics includes the chapter which is devoted to dynamical stability of lumbo-pelvi-femoral complex which involves analysis of relationship among appropriate anatomical structures in this region. The fourth section is on Human and Animal Biomechanics with contributions from foot biomechanics and chewing rhythms in mammals, or adaptations of bats. The last section, Sport Biomechanics, is discussing various measurement techniques for assessment and analysis of movement and two applications in swimming.