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Gait abnormalities following slipped capital femoral epiphysis treated with in situ fixation

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ABSTRACT

Background: Slipped capital femoral epiphysis (SCFE) is a common disorder in adolescent for which no consensus exists regarding management. The aim of the present study was to analyze gait modifications following SCFE treated with in situ fixation (ISF) and to relate it to radiologic stage. Research question. To verify if gait biomechanics are impaired in patients with SCFE and to try to determine a degree of slippage from which gait modifications would appear.
Methods: We evaluated 16 patients treated by ISF for SCFE with slippage ranging from 11° to 61°. Gait variables were compared to normal population according to age and walking speed and were normalized in Z-scores.
Results: Spatiotemporal parameters, mechanical and energetic variables were inferior to |1.5| Z-scores and considered as normal. Kinematics showed increase of pelvic tilt and hip adduction. Kinetic variables showed modifications with increased hip extension moment. There was also a strong increase in power of hip extensor. Hip extension moment and power of hip extensors were significantly correlated to radiologic stage. Analysis of ROC curves showed a cut-off value of slippage about 25°–30° affecting kinematics of pelvis and hip and kinetic variables.
Conclusion: The gait variables were close to normal values. Main modifications were observed in kinematic and kinetic data with a significant increase in extension moment and power generated at the operated hip. This could participate to long-term joint degradation observed in SCFE, even in mild slips. The clinical message is to control regularly SCFE with initial slippage greater than > 25–30° to allow for early diagnosis of premature hip osteoarthritis.

1. Introduction

Slipped capital femoral epiphysis (SCFE) is a common disorder in adolescent with an incidence estimated between 0.33 and 24/100, 000 [1]. Epiphyseal slippage leads to a proximal femoral deformity resulting in gait disorders (external rotation walk, limp) and osteoarthritis. One of the evocated mechanisms explaining osteoarthritis is femoro-acetabular impingement (FAI) resulting from epiphyseal deformity [2–5]. Treatment of SCFE aims to stop epiphyseal slippage and to limit deformity.

In situ fixation (ISF) is the treatment of choice in stable cases with mild slippage [6,7]. Otherwise, a lot of controversies exist about management [2,7–15]. Corrective osteotomies are sometimes proposed. Dunn osteotomy [2,11,15,16] has gained in popularity because it allows for a better anatomical correction as compared to inter-trochanteric osteotomies [2,7,16,17]. However, there is no consensus concerning the degree of slippage for which this intervention should be proposed.

Nectoux et al. [5], in a retrospective study of 222 cases, suggested that FAI could be present from 35° of slippage. Song et al. [18] showed no significant gait abnormalities before 30° slippage but observed abnormalities correlated to the degree of slippage after 30°. Only four articles have evaluated gait in patients treated for SCFE. Song et al. [18] analysed gait in 30 unilateral SCFE treated by ISF with slippage from 7° to 74°. They observed more pain and decreased function with greater slippage without being significant. They also observed a decrease of

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range of motion in flexion, abduction and internal hip rotation with increasing slippage. Gait analysis (GA) showed no significant difference between control group and patients presenting with a slippage < 30°. Whereas they showed gait abnormalities correlated to the degree of slippage higher than 30°. Westhoff et al. [19,20] evaluated 39 patients treated for SCFE, 33 had been treated by ISF, 3 by sub-capital osteotomy and 3 by Imhauser osteotomy. They showed gait modifications correlated to clinical results and radiological index of Heyman and Herndon [19,20]. Caskey et al. [21] studied the gait in 8 patients who underwent Imhauser osteotomy. They found that this intervention could clinically improve hip abduction and decrease external rotation.

The purpose of our study was to verify if gait biomechanics were effectively impaired in patients with SCFE treated with ISF and to try to determine a degree of slippage from which gait modifications would appear. Gait variables were related to the radiologic stage of SCFE to find a cut-off angle in slippage generating significant gait impairments. If gait impairment is found from a certain degree of slippage, this could be an argument to propose other treatments than ISF for these patients, like corrective osteotomies.

2. Materials and methods

2.1. Patients

26 patients followed in our hospital with a history of SCFE were recruited between February 2015 and February 2017. Inclusion criteria were: unilateral SCFE treated with IFS and at least three months of postoperative follow-up. Exclusion criteria were: bilateral cases, presence of complications, other treatment than ISF, comorbidities susceptible to alter locomotion.

Sixteen patients were eligible for the study and gave their agreement for GA. Two patients have failed to come to the lab despite several reminding. The local ethics committee approved the experimental protocol and parents of each child signed an informed written consent. The trial was registered at ClinicalTrials.gov, Number NCT00825097.

The study included 16 patients (10 boys, 6 girls) with 9 right hips and 7 left hips. Mean age at surgery was 12.5 years old. Mean follow-up for GA after surgery was 23.3 months (range 4–77) (Table 1).

Every patient underwent physical exam with evaluation of pain, limp and hip range of motion (ROM) after surgical intervention.

Anteroposterior and frogleg lateral radiographs were also performed. One single senior orthopedic resident was assigned to measure the degree of slippage using the Southwick method. This was measured

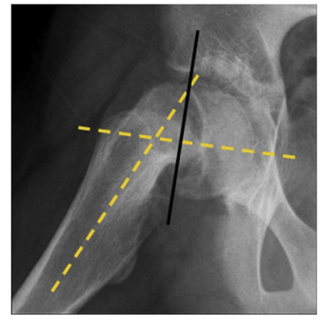

Fig. 1. Southwick method for slippage evaluation.
The Southwick angle is measured between the axis of the femoral shaft and the perpendicular to a line drawn from the anterior and posterior tips of the epiphysis on a frogleg lateral radiograph.

on the last frogleg radiograph available before GA and on which physis was still visible. Using this method, the degree of slippage is defined by the angle measured between the axis of the femoral shaft and the perpendicular to a line drawn from the anterior and posterior tips of the epiphysis on a frogleg lateral X-ray (Fig. 1). Interval between X-ray and GA ranged from 0 day to 24 months for patients who achieved skeletal maturity. For the latest, we didn't perform new X-ray, supposing that no epiphyseal remodeling occurred after the end of growth and because slippage measurement using the Southwick method is more difficult when the physis is closed. We didn't include patients who achieved skeletal maturity for more than 2 years.

2.2. Assessment

GA was performed at our 3D instrumented gait lab. Each patient was first measured, weighed and the body mass index (BMI) was calculated. Thereafter, the patient had to walk on a motor-driven treadmill at spontaneous speed assessed by the 10-m walk test. Computerized tridimensional GA including spatiotemporal, kinematic, kinetic, energetic and mechanical measurements was performed during gait on the treadmill. Twenty-one reflective landmarks, positioned on precise anatomic sites, following International Society of Biomechanics protocol, were used to compute spatiotemporal and kinematic variables. Data from landmarks were collected with 8 infra-red camera Smart DX (BTS Bioengeneering, Brooklyn, USA) at 200 Hz. From Euler angles, it allowed the computation of angular displacements of the pelvis, hip, knee and ankle in the three planes of space. Kinetic variables were

Table 1
Anthropometric and hips data.

Hip	Slippage (°)	Side	Type	Sex	BMI (kg m^{-2})	Age at surgery (yo)	Age at GA (yo)	Time between surgery and GA (months)
1	11	Left	Chronic	Boy	25.44	11	17	76
2	13	Right	Chronic	Boy	23.39	13	15	20
3	31	Left	Chronic	Boy	30.58	14.5	15.5	9
4	31	Right	Chronic	Girl	30.88	11	17	77
5	32	Right	Chronic	Boy	29.13	13	14	9
6	32	Left	Chronic	Boy	28.32	13	17	53
7	33	Right	Acute	Boy	23.7	11	12	11
8	33	Right	Chronic	Boy	22.22	10.5	12	18
9	42	Left	Chronic	Girl	50.17	11	12.5	17
10	45	Left	Chronic	Boy	24.6	12.5	13	7
11	46	Left	Chronic	Girl	15.38	10.5	11	4
12	47	Right	Chronic	Boy	34.73	14.5	16.5	24
13	51	Right	Chronic	Boy	29.07	15	15.5	4
14	51	Right	Acute	Girl	32	11	12	12
15	56	Left	Chronic	Girl	23.94	15	16.5	18
16	61	Right	Acute	Girl	32.06	12	13	12
Total		7 L/9R	3 A/13 C	6 G/10B				
Mean					28.47 [15.38; 50.17]	12.5 [10.5; 15]	14.4 [11; 17]	23.3 [4; 77]

Table 2
Gait analysis results expressed in absolute and Z-scores.

	Absolute data Mean [range]	Normalised data in Z-score Mean ± SD	p-Value
Spatiotemporal parameters			
Stance phase (%)	63.9 [61.4; 64.9]	0.88 ± 0.77	0.00036
Cadence (step min^{-1})	117.5 [101.6; 133.3]	0.38 ± 1.05	0.16
Step length (m)	0.68 [0.51; 0.81]	−0.2 ± 0.92	0.38
Segmental kinematic variables			
Frontal pelvic motion (°)	4.5 [2.3; 8.2]	0.43 ± 1.5	0.26
Sagittal pelvic motion (°)	4.4 [2.3; 7.7]	0.23 ± 0.38	0.031
Transversal pelvic motion (°)	7.7 [3.4; 15.2]	0.12 ± 0.74	0.52
Pelvic tilt (°)	13.1 [0.8; 25.5]	1.76 ± 1.11	0.000014
Frontal hip motion (°)	12 [5.5; 25.2]	0.65 ± 1.16	0.04
Sagittal hip motion (°)	42.7 [32.5; 55.1]	−0.01 ± 0.72	0.95
Transversal hip motion (°)	17 [9.2; 31.3]	0.6 ± 0.55	0.00053
Hip adduction (°)	9.1 [−3; 21.2]	1.87 ± 2.17	0.0035
Hip abduction (°)	2.8 [−8.7; 8.5]	−0.59 ± 2.42	0.34
Hip flexion (°)	33.4 [19.2; 58]	1.19 ± 1.35	0.003
Hip extension (°)	9.3 [−14.1; 21.1]	−1.36 ± 1.29	0.00072
Hip rotation (°)	−3.5 [−19.4; 10.5]	−0.53 ± 0.79	0.016
Knee ROM (°)	48.8 [28; 59.6]	−0.76 ± 1.25	0.027
Knee ROM in stance phase (°)	14.6 [7.6; 19.4]	−0.26 ± 0.64	0.12
Ankle rotation (°)	−11.3 [−24.8; 1.6]	−0.27 ± 0.62	0.13
Kinetics			
Hip extension moment (N m kg^{-1})	0.78 [0.1; 1.08]	1.83 ± 3.07	0.03
Hip flexion moment (N m kg^{-1})	−0.74 [−0.96; −0.34]	−0.81 ± 6.82	0.64
1st hip positive power peak (W kg^{-1})	1.18 [0.63; 1.74]	2.59 ± 1.6	0.00001
2nd hip negative power peak (W kg^{-1})	−0.68 [−1.13; −0.19]	−2.41 ± 1.27	0.0000016
3nd hip positive power peak (W kg^{-1})	0.56 [0.26; 0.83]	2.17 ± 0.99	0.0000003
Mechanics			
Wext (J kg m^{-1})	0.22 [0.17; 0.29]	−0.67 [−1.46 – 0.48]	0.12
Wint (J kg m^{-1})	0.28 [0.22; 0.33]	−0.44 ± 0.67	0.02
Wtot (J kg m^{-1})	0.52 [0.43; 0.68]	−0.28 ± 0.69	0.12
Recovery (%)	66.4 [39.7; 77.2]	0.49 [−0.74 – 1.31]	0.32
Energetics			
Energy cost (J kg m^{-1})	2.16 [1.22; 3.35]	−0.53 ± 1.37	0.14

Gray lines: values superior to |1.5| Z-scores.

Table 3
Kinematics data for pelvis and hip expressed in absolute values as compared to normative values.

	Absolute data Mean [range]	Norms of our lab Mean ± SD	p-Value
Frontal pelvic motion (°)	4.5 [2.3; 8.2]	3.9 ± 5.1	0.26
Sagittal pelvic motion (°)	4.4 [2.3; 7.7]	3.1 ± 7.3	0.031
Transversal pelvic motion (°)	7.7 [3.4; 15.2]	7.1 ± 5.2	0.52
Pelvic tilt (°)	13.1 [0.8; 25.5]	4 ± 7.6	0.000014
Frontal hip motion (°)	12 [5.5; 25.2]	9.3 ± 6.1	0.04
Hip adduction (°)	9.1 [−3; 21.2]	4.1 ± 6.4	0.0035
Hip abduction (°)	2.8 [−8.7; 8.5]	4.4 ± 5.8	0.34
Sagittal hip motion (°)	42.7 [32.5; 55.1]	43 ± 10.4	0.95
Hip flexion (°)	33.4 [19.2; 58]	24.1 ± 10	0.003
Hip extension (°)	9.3 [−14.1; 21.1]	18.7 ± 9.7	0.00072
Transversal hip motion (°)	17 [9.2; 31.3]	10.2 ± 12.1	0.00053
Hip rotation (°)	−3.5 [−19.4; 10.5]	2.2 ± 11.9	0.016

computed from 4 strain gauges located at the corners of the treadmill recording ground reaction force (GRF) in 3D. Using unique large force platforms emerges as a practical method to facilitate and accelerate the procedure of recording GRF data but remains a challenge to decompose force under each foot. We used an algorithm developed by Ballaz and Raison [22] and modified by Samadi et al. [23], an automatic spline method that decomposes global 3D-GRF under each foot during double support. By using an inverse dynamics approach, GRF, kinematic and anthropometrical data allowed the computation of the net joint moment of the hip, knee and ankle in the sagittal plane. The joint power of each joint was calculated as the product of the angular speed and the net joint moment. Patient was fitted with a nasal mask connected to an ergospirometer (Medisoft, Sorinnes, Belgium) to measure oxygen consumption (VO_2) and carbon dioxide production (VCO_2). The respiratory exchange ratio (RER), computed as the ratio between VCO_2 and VO_2, always remained less than one in order for the subject to remain in aerobic conditions. The Joules of energy expended per liter of oxygen consumed were computed depending on the RER. The energy cost was obtained by the ratio "walking expended minus standing" divided by speed.

Total positive mechanical work (Wtot) performed by the muscles was calculated by the sum of external work (Wext) (performed to move the body center of mass (COMb)), and internal work (Wint) (performed to move the body segments relative to the COMb) as described in Marconi et al. [22]. The 'Recovery', quantifying the percent of mechanical energy saved by a pendulum-like exchange between potential and kinetic energy of the COMb was also calculated as described in Marconi et al. [24].

Each variable was collected simultaneously during 40 s while walking at steady energetic state and were averaged on 10 successive strides. For each patient, range of motion of ankle, knee, hip and pelvis displacements were calculated in the three planes (sagittal, frontal, transverse). Moment and power parameters corresponding to maximum and minimum values were calculated as described in Marconi et al. [24].

2.3. Statistics

To eliminate the confounding variables, GA variables (x_i) were normalized in Z-scores according to our lab norms (mean, $\bar{X}$; standard deviation, SD) which have been determined by performing GA in healthy patients of different ages and at different walking speed (children aged from 9 to 15 years walking at 1– 6 km h^{-1} on treadmill).

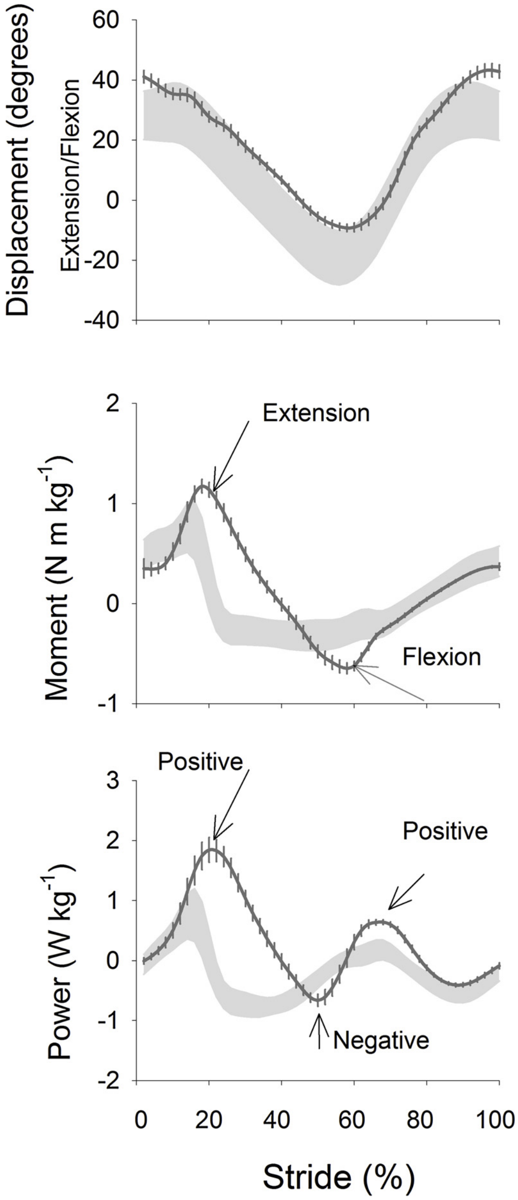

Fig. 2. Typical trace of hip kinematics and kinetics.
Top graph: Angular displacement (in degrees) of hip in sagittal (flexion-extension) plane as function of gait stride (%).
Middle graph: Muscular moment (sagittal plane) as function of gait stride (%).
Bottom graph: Hip power as function of gait stride (%).
Gray lines indicated a typical trace of one patient (average on 10 consecutive cycles). Vertical lines indicated standard errors. Gray surfaces indicated normal values (+2SD) for 6 children of 15 years walking at 5 km h^{-1} (database of our lab, not published data).

$$Z - score = \frac{(x_i - \bar{X})}{SD} \tag{1}$$

Mean and SD of normalized gait variables were extracted. Only gait variables superior to |1.5| Z-scores were selected. Pearson correlations were calculated between Southwick angle and selected gait variables. Significant correlations were used to construct receiver operation characteristic curve (ROC) used from clinical prediction rules. We focused only on gait variables greater than 1.5 Z-scores and significant area under the curve (greater than 0.7). Two variables responded to this criteria: hip extension moment and positive hip power. From these two variables, we calculated a cut-off of slippage. This cut-off value indicated that a greater slippage will generate excessive force and constraint on hip risking to deteriorate prematurely the hip. Thus, we determined a cut-off for which the radiographically measured angle will have a harmful impact on the gait.

3. Results

Anthropometric data are presented in Table 1. GA variables are summarized in Table 2 with focus on pelvis and hip kinematics in Table 3.

Spatiotemporal parameters, ROM of pelvis, knee and ankle were smaller than |1.5| Z-scores indicating no abnormalities. Pelvic tilt and hip adduction were increased. Regarding to kinetic variables (Fig. 2), hip extension moment was significantly increased. Maximal power developed at the hip was significantly increased by more than |2| Z-scores. We observed significantly increased concentric contraction of hip extensors at the beginning of gait cycle. At 50% of cycle, significantly eccentric contraction of hip extensors was observed. Significantly increased concentric contraction of hip flexors at 70% of gait cycle was also observed.

External and total mechanical work were normal. Internal work was significant slightly decreased but less than |1.5| Z-scores. Recovery, indicating the efficiency of locomotor mechanism, and energy cost were normal.

In Fig. 3, we observed a significant negative correlation between Southwick angle and hip extension moment ($r = -0.82$; $p < 0.001$). We also observed a correlation between Southwick angle and positive hip power to extend hip at 20% of stride ($r = -0.66$; $p < 0.006$). The ROC curves indicated a cut-off value from about 25.5° for hip extension moment and 29° for positive power of the hip extensors in stance phase. This means that when the Southwick angle is beyond these values, these parameters are unusually large (more than |1.5| Z-scores).

Looking to clinical data, five patients presented mild pain and two presented a clinical limp. Mean hip ROM were: 114° in flexion (range 90°–130°), 49° in abduction (range 10°–70°), 69° in external rotation (range 20°–90°) and 21° in internal rotation (range (0°–50°).

4. Discussion

We observed that gait parameters, mechanical and energetic variables were close to normal. Kinematics was disturbed for pelvis and hip (Table 3). Main modifications were observed for kinetic variables with power generated at the hip greater than |1.5| Z-scores and an increase in hip extension moment close to |1.5| Z-scores.

Regarding to global and segmental kinematics, our results were not in agreement with Westhoff et al. [19] These authors showed significant decrease in step frequency and increase of stance phase compared to control. Stance phase increased also in our study but less than 1 Z-score. However, the walking speed was also decreased that could partially explain these changes.

Westhoff et al. [19] showed a decrease in hip flexion and in sagittal hip ROM [19]. Song et al. observed increased hip extension [18]. In our study, we found no significant changes in global sagittal hip ROM with a tendency to increased hip flexion and diminished hip extension (< |1.5| Z-scores). This tendency could be explained by the increased pelvic tilt observed (> |1.5| Z-scores; $p = 0.000014$) and also described by Westhoff et al. [19].

Song et al. [18] showed a decrease in hip extension moment. On the contrary, we observed an increase of this moment. This could be secondary to potential modification of hip center of rotation following deformity induced by SCFE. Because of anterior and superior displacement of the proximal femoral metaphysis relative to epiphysis, hip center of rotation could be displaced anteriorly and superiorly. At least, this intra-articular deformity modifies the location of the hip center of rotation as compared to the femoral shaft and the whole leg, sometimes leading to leg length discrepancy. This displacement might decrease the lever arm of hip extensors, leading to the need for more strength to

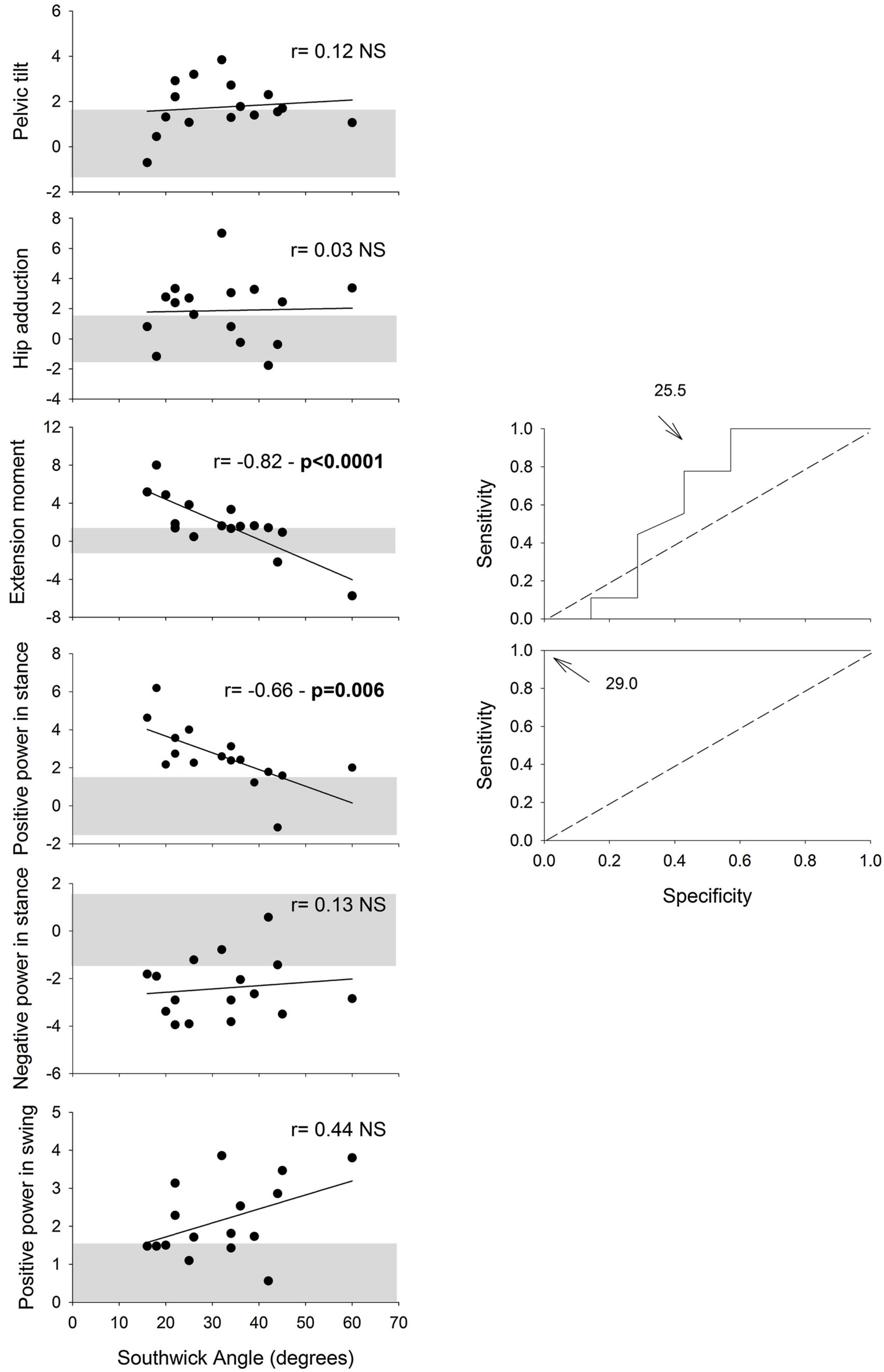

Fig. 3. Left panel: Selected gait variables (mean > |1.5| Z-scores) expressed in function of Southwick angle. Each symbol represents a patient. Gray surfaces indicated ± |1.5| Z-scores. Pearson coefficient of correlation and p-values are indicated.
Right panel: ROC curves calculated for variables significantly correlated.

create motion and thus increasing extension moment. Our results are supported by the work of Delp et al. [25] who showed that hip extension moment is increased when hip center of rotation is displaced anteriorly and superiorly.

Femoro-acetabular impingement secondary to posterior slippage of epiphysis is one of the supposed mechanisms leading to osteoarthritis in SCFE [13,14]. In our study, we observed an increase in moment and power generated by hip extensor muscles. This is even present in mild slippage (< 30°). This could be another mechanism to explain long-term cartilage degradation by increased loads applied in coxo-femoral joint.

Westhoff el al. [19] according to *Nantel et al.*'s study [26] suggested that decrease in mechanical work is linked to obesity of their patients. In GA of 10 obese patients, *Nantel et al.* showed less mechanical work and less energy cost than in GA of 10 non-obese patients [26]. In our study, a discrete decrease in internal and external mechanical works and energy cost may be linked to our patients' overweight condition. In fact, we observed a correlation between BMI and external work ($r = -0.48 - p = 0.05$). Another explanation could be in a change of the locomotive mechanism as observed in people who bear heavy weight on their heads in certain world areas like in Nepal or in Africa [27,28]. The decrease in mechanical work could be secondary to an adaptive gait mechanism to increased loads supported by their hips. We observe a discrete better pendulum gait mechanism [24[27] leading to a more economic gait.

Our main limitation is overweight condition of children. Gait variables must be interpreted with caution. Otherwise, we have only tested children with mild and moderate slippages. It would be interesting in further studies to include children with more severe slippages to see which variables of the gait could further deteriorates.

Regarding to clinical data, these have been collected in a retrospective manner because clinical evaluation was not the main purpose of this study. Thus, there were lacking data about hips ROM in a few patients. This could explain why the mean ROM is closed to normal instead of showing the attempted limitation in internal rotation and increasing in external rotation.

Otherwise, we linked slippage angles to GA variables at one point in the evolution of the disease, not considering the effect of potential remodeling of the proximal femur. It would also be interesting to perform GA at different moments in the evolution of SCFE to see if potential remodeling of the hip with remaining growth could ameliorate gait disorders or if the latest tend to increase or resolve with time.

In conclusion, the gait biomechanics variables were generally little impaired after SCFE. Only kinematic and kinetic variables were affected. We observed an increase of pelvic tilt and hip adduction. We also observed an increase in extension moment and positive power of hip extensors. This, in addition to femoro-acetabular impingement and overweight condition could be an element to explain osteoarthritis observed at medium-to-long-term. The cut-off of slippage was observed between 25 and 30° generating abnormal hip extension moment and power. Based only on our study results, it is difficult to recommend corrective osteotomies for slippage as low as 25–30°. Otherwise, the therapist should be aware that potentially deleterious gait modifications can happen for mild slippages and must therefore be attentive and propose a regular follow-up of the child to diagnose early degradation of hip joint. Further studies should evaluate gait in SCFE at a long term follow-up to determine if these abnormalities tend to worsen or improve.

Conflict of interest

Authors have no conflict of interest to disclose.

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