Children with lower limb length inequality

The measurement of inequality,

the timing of physiodesis

and gait analysis

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Kinderen met een beenlengteverschil

Het meten van verschillen, het tijdstip van physiodese en gangbeeldanalyse.

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voor mijn ouders en Jorianne

Contents

Chapter 1

Limb length inequality, the problems facing patient and doctor.

Review of literature and aims of the studies

Introduction

The symmetry of the human locomotion apparatus makes inequality of the limbs an aberrant finding for both patient and doctor. 4-15% Of the healthy, adult population, has a limb length inequality (LLI) of one cm or more (Table 1.1). A minor discrepancy of less than one cm is therefore common and many people are not even aware of it. More often the tailor makes the diagnosis than the 'patient' (Morscher 1972a).

The discomfort of LLI will increase with greater inequality of the limbs. However, the same LLI can give rise to different degrees of discomfort: LLI which is slowly acquired during the growth period is much better tolerated than LLI which is suddenly acquired in adulthood (e.g. by trauma). In developing countries, elderly adults with LLI of even more than 10 cm performed heavy manual work throughout their lifes. Sports activities don't have to be limited either: people were described who became a twohundred meter dash-champion in spite of 2.9 cm LLI and who skied on water and snow with 7.4 cm inequality (Gross 1978, Menelaus 1991).

Table 1.1 Incidence of limb length inequality.
Radiographic studies done in healthy subjects, without complaints that could be related to their LLI.

Authors, total number of patients	LLI (mm)	n	(%)
Rush and Steiner 1946	0	29	29
100 young soldiers	0-5	38	38
	6-10	29	29
	11-20	4	4
	> 20	0	0
Giles and Taylor 1981	0-9	46	92
50 patients with headache	> 9	4	8
Friberg 1983	0-4	203	57
359 young soldiers	5-9	100	28
	10-14	48	13
	> 15	8	2

It is up to the patient and his doctor to evaluate the problem of the inequality of the limbs and to select from a wide variety of treatment modalities (Amstutz and Sakai 1978, Scott 1983, Menelaus 1991).

To better manage the problem of LLI, the Sophia Children's Hospital in Rotterdam started a limb length clinic in 1979 in which children with LLI or with suspected LLI are seen at regular intervals. The studies described in the next chapters are based on patients who were seen in this clinic since 1979.

1.1 Etiology, developmental patterns and prediction of LLI

1.1.1 Etiology and developmental pattern

The disorders that may result in LLI are summarized in table 1.2 (Morscher 1972, Moseley 1987, Torode 1991). 218 Patients seen from 1979 to 1995 in the limb length clinic at the Sophia Children's Hospital are classified accordingly.

Table 1.2 Etiology of limb length inequality in 218 patients.

Congenital		*Trauma*	
congenital longitudinal deficiency of the femur		fractured femur	8
proximal femoral focal deficiency	1	fractured tibia	5
congenital short femur	11	fractured femur and tibia	4
coxa vara	2	epiphyseal injuries	2
congenital longitudinal deficiency of the fibula	4	avascular necrosis	
congenital longitudinal deficiency of the tibia	1		
posteromedial angulation of the tibia and fibula	7	*Tumor and tumor-like conditions*	
congenital pseudarthrosis of the tibia	3	Ewing sarcoma in femur	1
skeletal dysplasia	4	Ewing sarcoma in fibula	1
congenital dislocated hip	10	multiple exostosis	1
neurofibromatosis	2	unicameral bone cyst	
clubfoot	2	fibrous dysplasia and related disorders	
congenital constriction band syndrome	1	Ollier's disease and related disorders	4
Vascular malformations		*Thermal injuries*	
femoral stenosis	1	cold and heat injuries	
popliteal stenosis	1		
		Radiation injury	1
Infections			
metaphyseal osteomyelitis of the femur	1	*Anisomelia*	
metaphyseal osteomyelitis of the tibia	1	hemihypertrophy	15
septic arthritis of the hip	10	Klippel Trénaunay syndrome	12
septic arthritis of the knee	4	Beckwith Wiedemann	2
septic arthritis of the hip and knee	1	Proteus syndrome	
		Russell-Silver	
Non-septic inflammatory conditions		hemiatrophy	16
juvenile chronic arthritis			
haemophilia		*Miscellaneous*	
stimulation from other chronic inflammations		Legg-Calvé-Perthes	2
		COPS syndrome	2
Neurological disorders		Goltz syndrome	1
cerebral palsy	22	arthrogryposis	1
poliomyelitis	14	slipped capital femoral epiphysis	
myelocele	2	iatrogenic	
thetered cord	1		
		Idiopathic	34

Several causes of LLI can be distinguished: those that cause a difference in length but not in growth rate; those that cause a difference in growth rate but not initially in length; and those that do both. For example, fractures that heal with shortening produce an immediate LLI, but not a long term difference in growth rate; radiation may affect the growth plate with a change in the growth rate of the leg but does not result in immediate shortening. Conversely, the congenital short femur not only starts with a difference in length, but also causes a difference in growth rate with growth inhibition (Moseley 1987). One measurement in a child is of little value. Repeated measurements are necessary to obtain insight in the developmental pattern and in the quantity of LLI at maturity (van Linge 1985).

To get insight in etiology and this developmental pattern Shapiro (1982) studied 803 children with various disorders and at least a 5 years follow up. He described 5 patterns (Figure 1.1):

- Type 1, upward slope pattern: LLI develops and increases continuously with time, at the same rate;
- Type 2, upward slope-deceleration pattern: LLI increases at a constant rate for a variable period of time, and then shows diminishing rate, independent of skeletal maturation;
- Type 3, upward slope-plateau pattern: LLI first increases with time, but then stabilizes and remains unchanged throughout the remaining period of growth;
- Type 3A, downward slope-plateau pattern: LLI decreases with time, but then stabilizes and remains unchanged throughout the period of growth;
- Type 3B, plateau pattern: LLI, detected initially after it has developed, remains unchanged throughout the remaining period of growth;
- Type 4, upward slope-plateau-upward slope pattern: LLI first increases, then stabilizes for a variable but considerable period of time, and then increases again toward the end of the growth period;
- Type 5, upward slope-plateau-downward slope pattern: LLI increases with time, stabilizes, and then decreases in the absence of surgery.

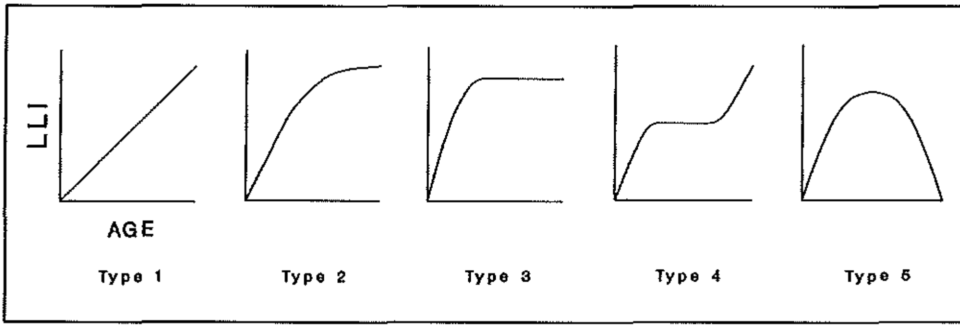


Figure 1.1 Developmental patterns of LLI.

A certain disorder is not always committed to one of these patterns. Table 1.3 illustrates the distribution of developmental patterns in the various disorders of the children from Shapiro's study.

Table 1.3 Distribution of developmental patterns in the various diseases causing LLI. Reproduced from: Shapiro F. Developmental patterns in lower extremity length discrepancies. J Bone Joint Surg 1982; 64-A: 639-51.

DISTRIBUTION OF DEVELOPMENTAL PATTERNS IN THE VARIOUS DISEASES IN EIGHT HUNDRED AND THREE PATIENTS

Condition	No. of Patients	Pattern Type				
		I	II	III	IV	V
Proximal femoral focal deficiency	18	18	0	0	0	0
Congenitally short femur, including congenital coxa vara (with some associated leg and foot anomalies)	102	65	29	8	0	0
Ollier's disease	17	17	0	0	0	0
Destroyed epiphyseal growth plates	21	21	0	0	0	0
Poliomyelitis	115	64	25	17	9	0
Septic arthritis (hip)	33	14	4	12	3	0
Fractured femoral shaft	116	0	8	108*	0	0
Cerebral palsy (hemiparetic)	46	15	5	24†	0	2
Anisomelia						
Hemihypertrophy	86	48	20	18	0	0
Hemiatrophy	27	17	4	6	0	0
Hemangiomas	29	9	8	10	1	1
Neurofibromatosis	17	11	2	3	0	1
Juvenile rheumatoid arthritis	36	7	0	16	0	13
Legg-Perthes disease	140	21	8	52	10	49

* Both type-III and type-IIIA discrepancies.
† Many of these discrepancies were detected in the plateau phase (type IIIB).

1.1.2 Prediction of 'remaining growth' and LLI

The prediction of LLI at maturity, which is important for the timing of treatment, can be performed by several methods. When Phemister (1933) described his method for arresting physeal growth, the contribution of the epiphysis to longitudinal growth at a specific age became particular important. Digby (1916) had measured the contribution of the proximal and distal epiphysis in several long bones with reference to the nutrient canal. The estimated proximal growth of the femur was 31%, its estimated distal growth was 69%. For the tibia these percentages were 57% and 43% respectively. Gill and Abbott (1942) measured this growth with reference to growth arrest lines in two patients and with vitallium markers in one patient. They estimated proximal growth of the femur to be 30% and 70% for its distal part. For the tibia these percentages were 55% and 45% respectively. Anderson et al. (1963) also measured growth with use of the growth arrest lines. Their study consisted of 206 boys and girls. Its result was an average of 71% of total femoral increment at the distal metaphysis and 57% of total tibial growth at the proximal metaphysis.

With knowledge of the remaining growth one could predict final LLI and determine the moment of physeal arrest. A simple method for the timing of epiphyseal arrest ('rule of the thumb') was first mentioned by White and Warner (1938) but later described in more detail by White and Stubbins (1944), Menelaus (1966) and Westh and Menelaus (1981). This method assumed that the lower femoral growth plate provides three-eights of an inch (1.0 cm) of growth per year and the upper tibial growth plate one-quarter of an inch (0.6 cm) per year. It further assumed that boys fuse both these growth plates at the calendar age of 16 years and girls at the age of 14 years. It was advised not to use this method under the age of 8½ in girls and under the age of 10½ in boys, and not in case of discrepancy between skeletal and calendar age.

The studies from Anderson et al. (1963 and 1964) provided data which have become 'classic' (Amstutz and Sakai 1978). The purpose of the study from Anderson et al. (1963) was to predict remaining growth in the lower extremities. They designed a growth remaining chart (Figure 1.2) in which they considered mean length of femur and tibia at any skeletal age, femoral increment at the distal metaphysis and tibial increment at the proximal metaphysis. Thus, physeal arrest is done when the remaining growth in one or both growth plates equals LLI.

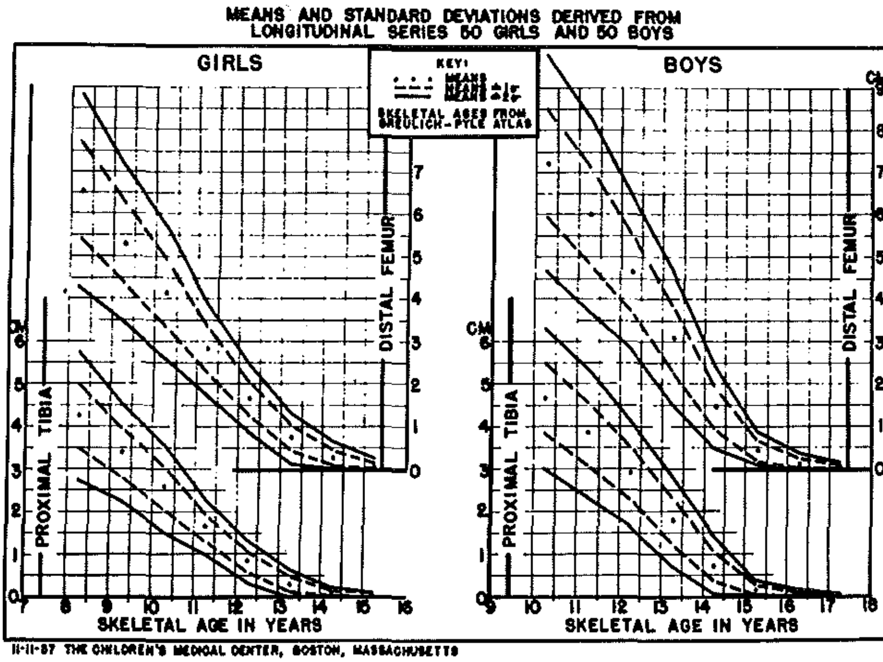


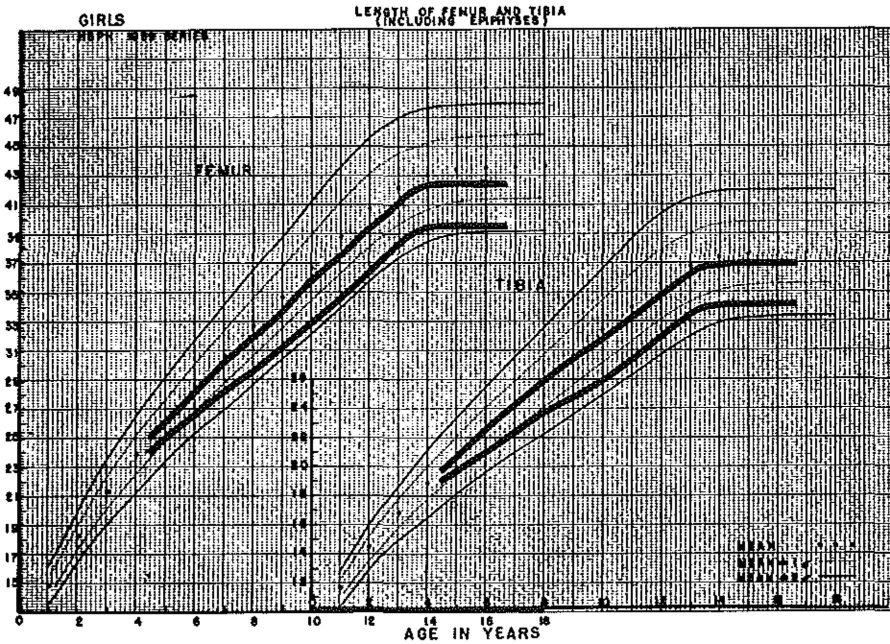
Figure 1.2 Growth remaining chart.
Reproduced from: Anderson M, Green WT, Messner MB. Growth and predictions of growth in the lower extremities. J Bone Joint Surg 1963; 45-A: 1-14.

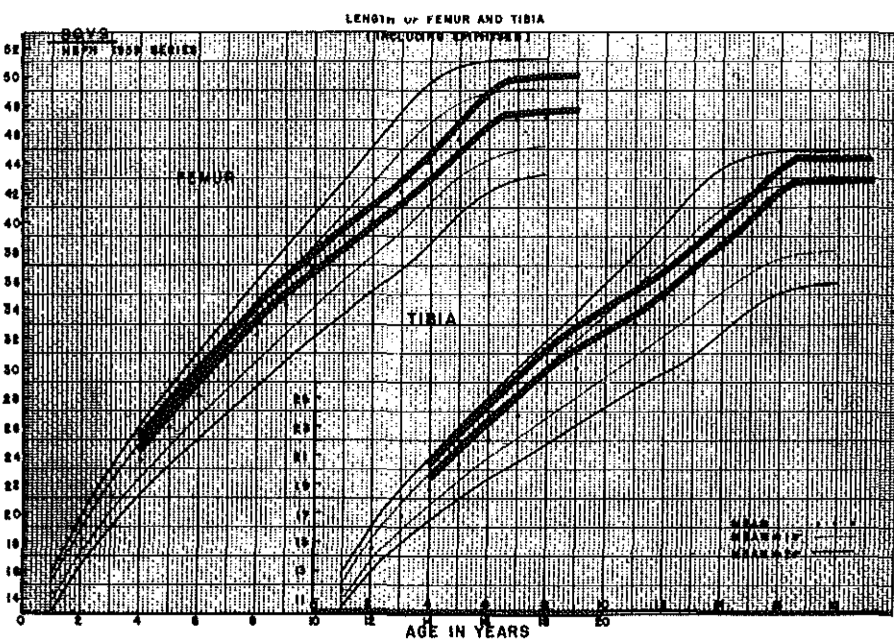
The data used for the growth remaining chart were derived from a study of 100 boys and girls. 50 Of these children were affected by poliomyelitis on the lower extremity opposite the one used for this chart. The other 50 had enrolled in the study of Stuart and Reed (1959). This was a comprehensive study of normal children of the Harvard School of Public Health, performed in the period 1930 until 1956. With respect to the pattern of maturation or the average quantity of growth that occurred after specific skeletal ages, no significant statistical differences were found between the two groups. Only the girls in the normal series were found to be somewhat taller than those of the group with poliomyelitis. The study of Anderson et al. (1964) presented the lengths of normal femur and tibia in 134 of the children from the study of Stuart and Reed (1959), from 1 to 18 years of calendar age (Figure 1.3).

Moseley (1977) tried to facilitate the use of the growth remaining chart and developed a straight line graph (Figure 1.4). Its advantage is the possibility to plot the measurements of the legs on a straight line and take the growth percentile of the child into account. For the construction of this graph, Moseley used the data from Anderson et al. (1964). The results of timing physiodesis with Moseley's Straight Line Graph are described in chapter 4.

Eastwood and Cole (1995) stressed the importance of the developmental pattern of LLI. They felt that the growth remaining method and the Straight Line Graph lacked insight in this pattern. Therefore they developed a graph in which LLI is only depicted against chronological age. Reference slopes for tibial and femoral physiodesis can be added, to estimate the age for physiodesis. With the method of Eastwood and Cole, the insight in developmental pattern of LLI may indeed be better than with any other method, however several drawbacks can be made. At first, the reference slopes are based on the 'rule of the thumb'. This is a less accurate slope - especially in the last years before cessation of growth - than the reference slopes from the straight line graph, which are based on growth versus skeletal (biological) age. At second, the graph does not present information on the skeletal maturity pattern of the patient, as does the straight line graph. At third, the results of this method as reported by Eastwood and Cole are, probably partly, based on measurements of LLI with wooden boards. As explained in chapter 2, this measurement method is not accurate enough for scientific purposes. One should therefore be sceptical about its results.

Page 19: Figure 1.3 Normal lengths of femur and tibia, chart 1 and 2.
Reproduced from: Anderson M, Messner MB, Green WT. Distribution of lengths of the normal femur and tibia in children from one to eighteen years of age. J Bone Joint Surg 1964; 46-A: 1197-1202.


GIRLS
LENGTH OF FEMUR AND TIBIA
(INCLUDING EPIPHYSES)
FEMUR
TIBIA
AGE IN YEARS


LENGTH OF FEMUR AND TIBIA
FEMUR
TIBIA
AGE IN YEARS

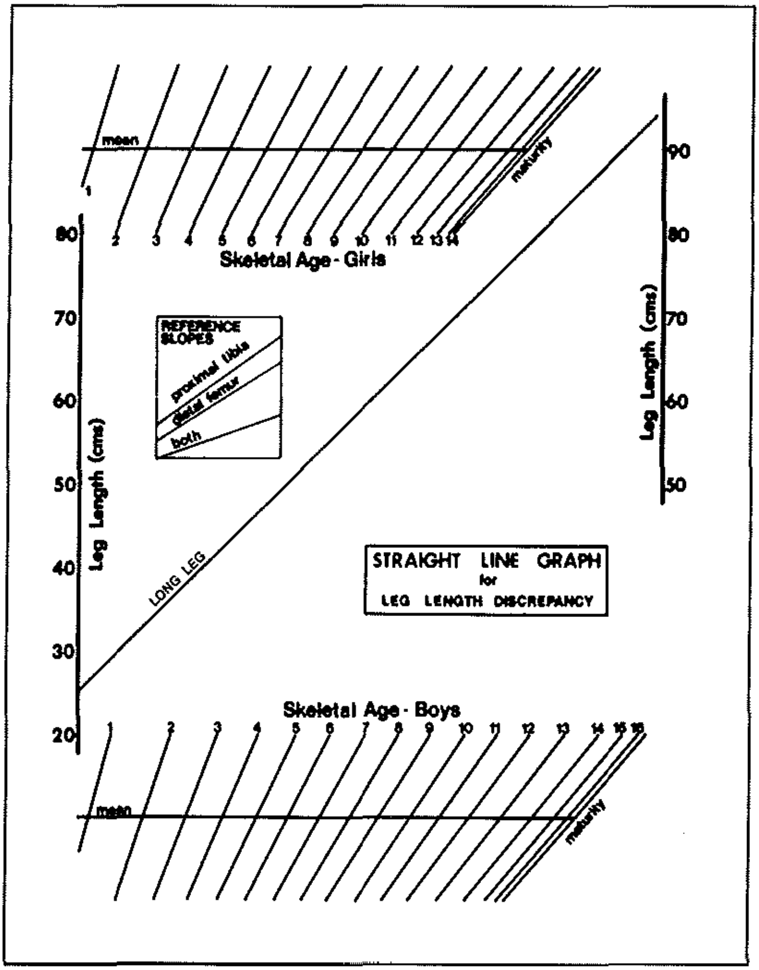


Figure 1.4 Moseley's Straight Line Graph.
Reproduced from: Moseley CF. A straight line graph for leg length discrepancies. Clin Orthop 1978: 136; 33-40, with permission.

In our continuous attempt to improve timing of physiodesis, we found arguments to update Moseley's Straight Line Graph. The data used by Moseley are subject to the so called 'secular trend'. They are outdated nowadays and ready for renewal. To reconstruct the straight line graph, we used the measurements from the limb length clinic of Sophia Children's Hospital since 1979. This study is further presented in chapter 5.

1.2 Measurement of LLI

The management of LLI starts with the measurement of the difference in leg length. It is not always necessary to measure LLI with the highest possible accuracy. However when the rate of growth of femur and tibia is to be measured for scientific or therapeutic purposes, a highly accurate method is desirable. If measurement of LLI is done on a more general basis (e.g. in a routine examination), a less accurate method will suffice. Depending on the desired accuracy there are several options to choose from. A survey of the different methods is given in the next paragraphs.

1.2.1 Clinical methods

Wooden boards and a tape measure are mostly used in daily practice.

Only the tape measure is suitable for the measurement of the length of one limb. In these measurements the patient is in supine position. Various landmarks can be used, from anterior superior iliac spine to medial or lateral malleolus. The position of the umbilicus varies too much to be of use as a reliable proximal reference. A tape measure is also of use in the estimation of thigh length and the localization of the main LLI, above or below the knee. In this case, the measurement is done from the anterior superior iliac spine to the lateral or medial interarticular space at the knee. Inaccuracies are caused by failure to use similar bony landmarks, fixed joint deformities, atrophy of the thigh muscles and pelvic tilt in the sagittal plane (Eichler 1972, Morscher 1972b).

By placing wooden boards under the short limb until the pelvis is level and by using boards of 0.5, 1, 2, 3 and 5 cm. thickness, every LLI from 0.5 to 11.5 cm can be measured with 0.5 cm increments. The difference only exists between both limbs and can also be called 'functional LLI' since LLI caused by fixed deformity of knee or ankle is measured as well. Wooden boards are not of use in case of adduction contracture of the hip because the pelvis can not be made level.

1.2.2 Radiographic methods

Radiographic measurements were first done by so called 'teleradiography' (Hickey 1924). The patient was in an erect position and both limbs were totally exposed on long films. Disadvantages of this method were the high radiation dosage and the use of long films. Its inaccuracy was due to the diverging beam, with an enlargement factor of about 3-8%, depending on the distance from object to film (Green, Wyatt and Anderson 1946, Oest and Sieberg 1971). Merrill (1942) also used teleradiography but, to lower film cost, only exposed hip-, knee- and ankle joints together with a ruler.

X-ray scanography led to orthoradiography with full exposure of the extremities (Milwee 1937 and Green, Wyatt and Anderson 1946) and to 'modified spot scanography' with exposure of just the joints and a ruler (Bell and Thompson, 1950). The essence of those methods was the use of a central X-ray beam perpendicular to the film at the joint spaces. The latter method is described in detail by Taillard (1956). This is the method we use in our limb length clinic. Deviation from the real length of the bones is 0-3 mm. (Green, Wyatt and Anderson 1946, Taillard 1956 and Huurman et al. 1987).

Digitized radiographs obtained with a CT-scanner have several advantages. Measurements are done from the anteroposterior scoutview of femora and tibiae with placement of a cursor. Errors because of angulation of the bones and joints are eliminated in this way. If necessary, heel height can easily be included. This technique is very accurate. Its radiation dose is less than half of the radiation dose of orthoradiography (Helms and McCarthy 1984, Carey 1987, Huurman et al. 1987 and Aaron et al. 1992). The radiation dose of orthoradiography is much dependent on the devices used. It is reported to be 504 mrad for the hips (Kogut 1987), 150 mrad for the skin over the reproductive organs and 60 mrad for CT-scan obtained digitized radiographs (Huurman et al. 1987). In our limb length clinic a difference in radiation dose between orthoradiographs and CT-scan obtained radiographs was not measured.

Microdose digital radiography, compared with computerized tomography, has the main advantage of further reducing radiation dosage to 1-10 mrad. Its accuracy is similar or slightly better than orthoradiography (Altongy et al. 1987, Kogutt 1987 and Wilson and Ramsby 1987).

Ultrasonography can also be used in the assessment of LLI. A transducer is used to identify the joint space and can be moved vertically in a special rack. Compared to radiographic methods, its accuracy is less, with a maximum measuring fault of 1 cm. The advantage of absence of radiation but the disadvantage of limited accuracy, made the authors to advise this technique in screening situations only (Holst and Thomas (1989), Terjesen et al. (1991), Konermann et al. (1995).

1.2.3 Conclusions

In conclusion, radiographic methods - especially orthoradiography and computerized tomography - are currently the most accurate methods for measurement of LLI and, therefore, the 'gold standard.' In daily practice, however, wooden boards or a tape measure are commonly used. Depending on the quantity of LLI that is considered important, errors inherent to these methods may lead to unintentional diagnosis or underdiagnosis of LLI. Wooden boards are considered to be more precise than a tape measure, but direct comparison of both methods with radiographs is poorly documented and statistics don't clearly illustrate the consequences for the clinician (Clarke 1972, Eichler 1972, Friberg et al. 1988). Therefore we did the study as presented in chapter 2.

1.3 Treatment

1.3.1 Non operative

Depending on the patient's requirements every LLI can be treated without an operation. If, after cessation of growth, LLI is mild or moderate, non operative treatment may be continued. For the child waiting for an operative correction, non operative treatment is obligatory.

A large range of shoe lifts is available and can be applied on both the outside and inside of the shoe. Shoe lifts are appropriate for discrepancies up to 3 cm. Further raising of sole and heel may be limited by ankle instability, which can be stabilized by a booth or ankle-foot-orthosis (Kolb and Marquardt 1972, Meyer and Petersen 1972).

1.3.2 Shortening

Femoral and tibial shortenings are seldom performed before growth has ceased. Both techniques bypass the uncertainties in prediction of final LLI and can accurately correct length, angular and rotational deformities. Shortening may be less favourable in short individuals, but is ideal in case of overgrowth of one limb. Femoral shortening is mostly preferred because the femur is better concealed and better protected by muscles than the tibia and a compartment syndrome - as reported by Hellinger and Teschner (1983) - is therefore less likely to occur (Siffert 1987). Complications as delayed union and loss of fixation occur more often in the tibia than in the femur. As much as 7.5 cm shortening in the femur and 5.1 cm shortening in the tibia has been described. Both procedures are limited by bulging of soft tissues (difficulties in closure of the wound and cosmetic appearance), which is most apparent in the tibia (Broughton et al. 1989, Kenwright and Albinana 1991). Muscle weakness due to shortening is common and may last up to 8-9 months, but is not reported to be permanent (Winquist et al. 1978, Blair et al. 1989, Broughton et al. 1989, Kenwright and Albinana 1991).

Rizzoli (1847) was the first to report on a femoral osteotomy with overriding of the fragments for correcting LLI (cited after Howorth, 1942). Later, femoral shortenings were done at the diaphyseal level with, compared to todays standards, little fixation. Calvé and Galland (1918) used remaining cortex after an oblique osteotomy as an intramedullary peg. White (1935) performed a transverse osteotomy in the mid-shaft of the femur and fixated the overriding fragments with pins. An oblique osteotomy of the entire femoral shaft fixed with screws was preferred to Küntscher nail fixation by Thompson, Straub and Campbell (1954). They noted less secure fixation and more delayed union with the Küntscher-nail. These earlier methods are illustrated in Figure 1.5.

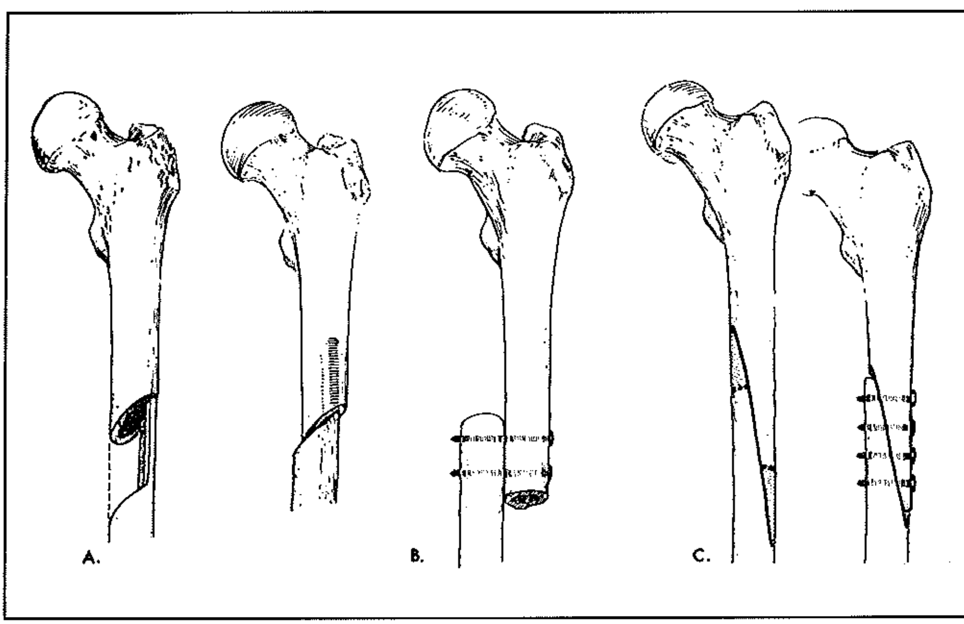


Figure 1.5 Shortening of the femur.
A. Calvé and Galland (1918), B. White (1935), C. Thompson, Straub and Campbell (1954). Reproduced from: Tachdjian MO. Pediatric Orthopedics. W.B. Saunders Co. Philadelphia 1972, with permission.

Plate fixation, probably resulting in better fixation, was done by Howorth (1942) after a step-cut osteotomy at diaphyseal level. Blount (1943) and Thornton (1949) described subtrochanteric shortening with a hooked plate of 130^0. Cameron (1957) developed a chevron type midshaft femoral osteotomy with Küntscher nail fixation. He acquired additional fixation with the removed bone segment by screwing it on the osteotomy as an onlay graft. Diaphyseal shortening can also be performed in a closed procedure with an intramedullary saw (Küntscher 1964, Fischer 1972, Winquist et al. 1978, Oppenheim and Namba 1988, Blair et al. 1989) and can, if desired, be modified by a step-cut osteotomy (Johansson and Barrington 1983). Wagner (1972) obtained compression on the osteotomy by the use of 90^0 and 95^0 blade plates in case of femoral shortening at the subtrochanteric and distal metaphyseal level.

Todate, subtrochanteric osteotomy is the preferred procedure, mainly because of its high potential for bone union. Problems encountered with stability when using intramedullary nails may be solved by locking (Hellinger and Teschner 1983, Blair et al. 1989, Kenwright and Albinana 1991). Compression is probably better with a 90^0 blade plate: no delayed consolidation was reported (Besselaar 1988). Distal metaphyseal shortening is reserved for simultaneous correction of deformities in the mechanical axis caused by the knee joint (Wagner 1972).

Tibial shortening can be performed by diaphyseal shortening and fixation with either an intramedullary nail or plate. Shortening in metaphyses is preserved for simultaneous correction of varus, valgus or rotational deformities since wound closure may be more difficult in this area (Wagner 1972). Broughton et al. (1989) described a step-cut method with fixation of just two screws. Both the diaphyseal shortening with plate fixation and the step-cut method are preferred in the patient with open growth plates.

1.3.3 Amputation

Amputation is not mentioned as a treatment of LLI but as a treatment for certain lower extremity congenital abnormalities with accompanying LLI (Aitken 1959). Syme amputation is the recommended therapy in selected cases of congenital longitudinal deficiency of the fibula. Patients who have had an amputation function well, have fewer complications and need less additional surgery than patients who were treated by lengthening. (Hootnick et al. 1977, Achterman and Kalamchi 1979, Fulp et al. 1996, Naudie et al. 1997). Through knee amputation is an alternative in congenital longitudinal deficiency of the tibia (Jones, Barnes and Lloyd-Roberts 1978). A rotationplasty or a Syme amputation, combined with an arthrodesis of the knee, may be indicated for proximal femoral focal deficiency to provide a stump that is easier to fit into a prothesis (Epps 1983, Alman et al. 1995).

1.3.4 Inhibition of physeal growth

Phemister (1933) introduced 'epiphyseodiaphyseal fusion' (today called physiodesis) to 'arrest longitudinal growth of bones and to treat deformities' (by 'deformities' Phemister meant angular joint deformities). For instance, Phemister excised the epiphyses of the proximal radius to correct a varus deformity of the elbow in a child with dyschondroplasia. The epiphyseodiaphyseal fusion is a real fusion: after partial excision of the growth plate, reversed bone blocks fuse the epiphyses to the diaphyses (Figure 1.6). White and Stubbins (1944) introduced a small modification, to ensure physiodesis, with more rigorous excision of the bone blocks and a 90^0 twist instead of 180^0. In the Sophia Children's Hospital, until 1997, a complete excision of the growth plate is performed and additional curls are made in the spongious part of the bone to secure physiodesis. Nowadays, 'percutaneous epiphysiodesis' (Bowen and Johnson 1984) is probably the preferred therapy. It allows physiodesis through smaller incisions and so

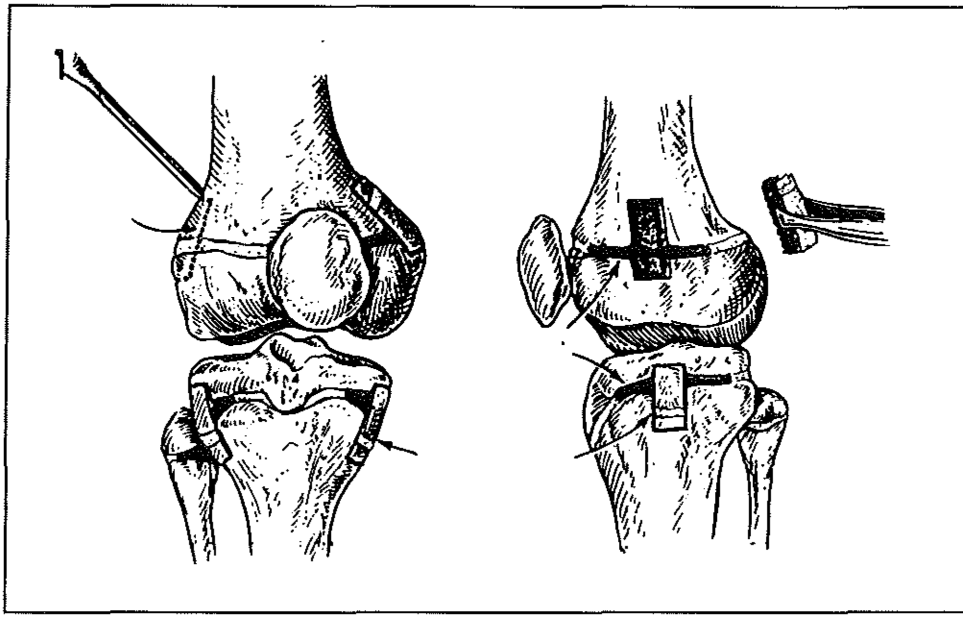


Figure 1.6 Epiphyseodiaphyseal fusion according to Phemister (1933).
Reproduced from: Phemister DB. Operative arrestment of longitudinal growth of bones in the treatment of deformities. J Bone Joint Surg 1933; 15: 1-15.

decreases complaints of dysesthesia, has better cosmesis and permits early rehabilitation. This technique proved to be safe and resulted in less postoperative hospital stay and less postoperative knee stiffness than the original procedure (Ogilvie and King 1990, Atar 1991, Liotta, Ambrose and Eilert 1992, Horton and Olney 1996). Results with respect to final LLI are similar (Porat et al. 1991, Timperlake et al. 1991).

An attempt to control bone growth was also made by placing staples over the medial and lateral side of the growth plate. The problem of computing the remaining growth was thought to be relieved by this temporary inhibition of growth (Hodgen and Frantz 1946, Blount and Clarke 1949). Although stapling is useful in correction of LLI (especially in correction of angular deformities) problems in timing, reoperation because of broken and migrated staples, angular deformities and unpredictable growth after removal of the staples, have not made it popular (Trias, Mueller and Ray 1961, Høstrup and Pilgaard 1969, Blount 1971, Sifert 1987).

1.3.5 Bone growth stimulation

Several attempts were made to stimulate the growth of a short limb (see Table 1.4). None of the methods resulting from these attempts proved to be reliable and predictable enough for the treatment of LLI in man.

Table 1.4 Investigations done to the stimulation of bone growth.

Method of stimulation	Authors	year
Introduction of foreign body into the bone	Chapchal and Zeldenrust	1948
	Pease	1952
periostal stripping and periostal division	Langenskiold	1957
	Khoury, Silberman and Cabrini	1963
	Crilly	1972
	Houghton and Rooker	1979
	Wilde, Baker	1987
	Lynch, Taylor	1987
arteriovenous fistula	Janes and Musgrove	1959
internal heating	Richards and Strofer	1959
electrical stimulation	Armstrong and Brighton	1986
lumbar sympathectomy	Barr, Stindfield and Reidy	1950

1.3.6 Limb lengthening

The opportunity and challenge offered by an operation to 'cure' the short, diseased limb by lengthening, is very attractive to both patient and doctor. In case of a considerable LLI lengthening may be used in combination with shortening or with growth inhibiting procedures to achieve equal limb length.

Codivilla (1905) was the first to report on a limb lengthening procedure. After having performed a diaphyseal osteotomy, he applied traction. First in a plaster and later by wire traction through the calcaneus. Putti (1921) modified this method by using an apparatus similar to the current external fixator, with one pin proximal and one pin distal from the ostetomy. Traction was obtained by the use of a spring controlled telescoping tube. Abbott (1927) developed a more stable bilateral frame and reported an impressing list of complications in 1939. To permit walking at an earlier stage, this frame was made even more stable through modifications by Anderson (1952), Judet (1971) and Wagner (1971).

The external fixation device is ideal for gradual distraction but the role for internal fixation seems limited to 'one stage procedures'. Plates can so be used for fixation after a z-osteotomy (Cauchoix and Morel 1978). A combination of shortening and lengthening can correct even greater LLI. After resection and transplantation of the femoral fragment, both limbs can be fixated with either a nail (Lezius 1946, Merle d'Aubigné and Dubousset 1971) or a hook plate (Heidensohn et al. 1972). Lengthening in one procedure after a femoral osteotomy and fixation with an intramedullary rod, but without bone transplant, has not become very popular because of problems with delayed union (Fischer 1972). Transiliac lengthening (a modified innominate osteotomy) is best preserved for a selected group of patients in which LLI is (also) located in the hemipelvis (Millis and Hall 1979).

Ilizarov's frame (1990) has to be mentioned separately. His frame is an external fixation device that, because of its highly modular design, is appropriate for both limb lengthening and (simultaneous) correction of multidirectional deformities. Its use is not common but may be indicated for selected cases.

Originally, lengthening with an external fixator was achieved after a diaphyseal osteotomy. Later, lengthening by distraction epiphysiolysis - to produce a closed fracture in the growth plate region - was performed with an apparatus similar to Ilizarov's (Monticelli 1981). Compared to diaphyseal or metaphyseal corticotomy, its theoretical advantage is that lengthening at the side where normal growth occurs, can be done without surgical damage to periost and vascular supply. De Bastiani et al. (1987) performed corticotomy in the proximal area of the diaphysis, because of supposedly better bone healing. Distraction was done after callus formation (10-15 days after operation). The method of De Bastiani et al. was therefore called 'callotasis'. Its main disadvantage is the technically more demanding fixation in the proximal diaphysis.

Complications due to the various lengthening procedures are numerous. These include vascular disturbance, nerve complication, delayed-union and non-union, deformities of the foot, muscular weakness, malposition of the bone fragments, infection, hypertension, fracture, dislocation of the hip, knee deformity and subluxation. Major complications such as severe restricted joint motion, severe angular deviation and fracture occurred in 28 out of 56 lengthening procedures (Tjernström et al. 1994). In the same study minor and moderate complications made up a total of 118. In van Roermund's review (1994) of 55 reports on tibial lengthening procedures, bony complications as axial deviation and refractures occurred in 17%, loss of ankle and knee joint motion in 17 to 28%, pin tract infections in 13 to 26%, nerve and vessel damage varying from 1 to 12% and osteomyelitis in less than 3% of the patients. In 43 femoral and 20 tibial lengthenings, Mosca and Moseley (1987) report 60 complications that compromised the final outcome of the lengthenings. Limited joint motion was noted by Glorion et al. (1996) to be the most commonly encountered difficulty during lengthening of the femur. They mentioned 15 of these complications in 70 of their lengthenings to be serious.

To prevent angular deformation the latest modification in limb lengthening with an external fixator is distraction over an intramedullary nail. This method also allows early removal of the fixator because it is only necessary for distraction itself (Baumgart et al. 1996, Guichet and Lascombes 1996, Kristiansen et al. 1996, Lin et al. 1996).

Ninety years after its introduction, limb lengthening is still a very complicated procedure with a high rate of complications. In operative treatment of LLI, a shortening procedure or physiodesis should therefore be the first choice.

1.4 The influence of LLI on gait and stance and its subsequent consequences.

As stated in the introduction of this chapter the discomfort of LLI will increase with greater inequality of the limbs. The degree of discomfort however, is little documented. The basic problem is tilt of the pelvis in the frontal plane in stance. Subsequently, a curvature of the spine develops which is most often convex to the short side in the lumbar part, although convex to the long side also occurs (Ingelmark and Lindström, 1963). This lateral curvature may be present only when the individual is standing or walking and may disappear in the sitting or recumbent position. It should therefore not be classified as a structural scoliosis (Kleinberg 1951).

In gait, LLI is mentioned to cause excessive expenditure of energy due to the increased vertical movements of the pelvis. This is best understood when walking with LLI is compared to the children's game of walking with one limb on the curb. Adaptation to these increased vertical movements of the pelvis and to pelvic sway (the alternating swinging to the left and right) probably occur with increased flexion of the knee of the long leg and, especially in young patients, with toe walking (Steindler 1964, Morscher 1965 and Moseley 1987).

These descriptions gave rise to the assumption that LLI might lead to low back pain and osteoarthritis of hip and knee. Low back pain as a result of (mild) LLI is not likely (Horal 1969, Grundy and Roberts 1984, Hellsing 1988, Soukka et al. 1991 and 1992) but is still being discussed by some authors (Friberg 1992). The relation between ostearthrosis of the hip and LLI was documented in only one report (Gofton and Trueman 1971). The relation between osteoarthrosis of the knee and LLI is still theory (McCaw and Bates 1991).

The direct effect of LLI on pelvic bones, muscles and on gait was reported in a number of studies. In stance an artificial LLI was shown to cause posterior rotation of the innominate bone from the long leg, up to 1.5 degree with 7/8 inch LLI (Cummings et al. 1993). The electromyographic study done by Morscher and Taillard (1965) revealed no changes in muscle activity with (artificial) LLI less than 1 cm, for both stance and gait.

Vink and Huson (1987) measured pelvic sway in gait with potentiometers. Artificial LLI up to 4.0 cm had only minor influence on pelvic sway. Kaufman et al. (1996) measured the influence of LLI on gait in patients with force plates. In general LLI >2.0 cm resulted in gait asymmetry, greater than observed in the non-affected population.

To quantify the relationship between LLI and pelvic sway in gait, together with the adaptations in lower limb movement, we performed the study described in chapter 3.

1.5 Aims of the studies.

Nearly twenty years of experience with the management of LLI in the limb length clinic of the Sophia Children's Hospital is base of this thesis. Shortcomings and drawbacks encountered in measuring techniques and applicability of Moseley's Straight Line Graph, as reviewed in this chapter, were studied prospectively from the beginning of the limb length clinic.

The department of Biomedical Physics and Technology of the Erasmus University Rotterdam offered the opportunity to make use of their gait analysis laboratory. With this facility insight could be obtained in the described lack of knowledge in kinematics of gait with LLI.

The studies in the following chapters were done to answer the following questions:

What is the accuracy of clinical methods in measuring LLI?

How does LLI influence pelvic sway and movements of hip, knee and ankle in gait?

What are the results of physiodesis, when timing is done with Moseley's Straight Line Graph?

Can Moseley's Straight Line Graph be improved with current growth data?

Chapter 2

Measurement of limb length inequality.

Comparison of clinical methods with orthoradiography in 190 children

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2.1 Abstract

We studied the agreement in measuring limb length inequality with orthoradiograms and clinical methods.

In 190 children attending our limb length clinic for the first time, 95% of the measurements with wooden boards was within -1.4 and +1.6 cm of the results of the orthoradiograms. A tape measure had significant less agreement.

The predictive value of a localization of the main limb length inequality above the knee, as found with a tape measure, was 64% and for a localization of the main limb length inequality below the knee 75%.

A Wooden Board Reliability Graph is presented, which can be helpful in the decision to perform orthoradiographic measurements of limb length inequality in e.g. evaluation of impairment.

2.2 Introduction

Radiographic methods for measuring limb length inequality (LLI) are most accurate but, in daily practice, measurements with wooden boards or a tape measure are commonly used.

Wooden boards are considered to be more precise than a tape measure, but a direct comparison of both methods is poorly documented (Clarke 1972, Eichler 1972, Friberg et al. 1988). The purpose of a tape measure seems primarily to be the assesment of the localization of the main LLI, i.e. above or below the knee.

In this study, we compared both clinical methods with orthoradiograms in 190 children attending our limb length clinic.

2.3 Patients and methods

We used the data from the first visit of 190 children to our limb length clinic between 1981 and 1994.

All clinical measurements were done by one person (A.D.), who was not informed by the results of the orthoradiograms.

159 Patients were examined in the standing position, with straight knees. Wooden boards of different thicknesses were placed under the short limb until the iliac crests were level, according to Morscher (1972) and Carey (1991). In the remaining 31 patients, such measurements were not made because they could not stand or they had lower limb contractures or equinus deformity of the feet. With a tape measure, the distances from the anterior superior iliac spine to the medial knee jointline, and from the medial knee jointline to the tip of the medial malleolus, were determined to the nearest 0.5 cm, while the patient was in supine position.

Total LLI and lengths of femur and tibia were measured by orthoradiography, also in supine position, as described by Taillard (1956). These measurements were performed by one of two authors.

In each patient comparison between the various methods was done by subtracting the outcome of the clinical measurement from the LLI found with the orthoradiogram, and thereafter analysed with the variance ratio test (F-test, SPSS software).The significance level was set at 0.05. The mean difference and the 95% limits of agreement (mean $\pm$ 2 SD) were calculated according to Bland and Altman (1986). Regression analysis was used to design a reliability graph, which makes it possible to estimate intervals of the real LLI, if measured radiographically.

The predictive value of the tape measure in localizing the main LLI above or below the knee was also calculated.

2.4 Results

The measurements with tape showed less agreement than those with wooden boards and they were less precise (Table 2.1).

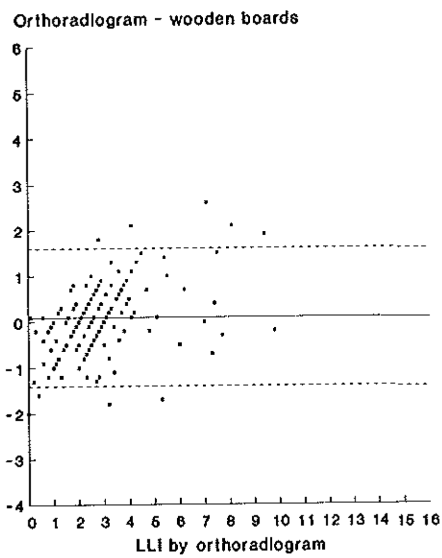
Table 2.1 Agreement of clinical methods with orthoradiograms.
Mean *SD* difference and 95% limits of agreement.

	Difference (cm)		95% limits
wooden boards, n 159	0.09	*0.78*	-1.4 / 1.6
tape measure, n 190	0.14	*0.97*	-1.8 / 2.1

p = 0.002, F-test.

The accuracy of the clinical methods appeared to be independent of the magnitude of the LLI (Figures 2.1 and 2.2).

The predictive value for localization of the main LLI above the knee, as found with a tape measure, was 64% and for localization below the knee 75% (Table 2.2).



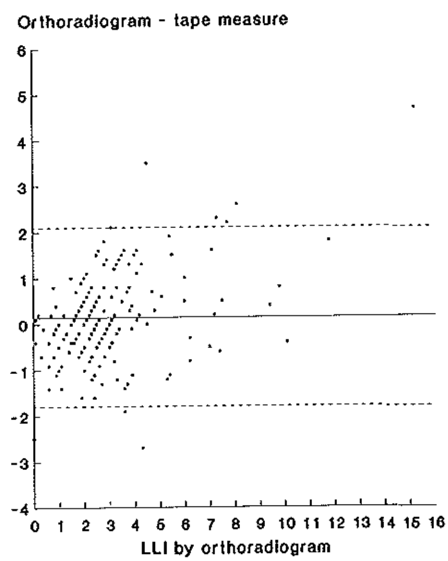


Figure 2.1 The differences in measurement of LLI between orthoradiogram and wooden boards (n 159). Figure 2.2 The differences in measurement of LLI between orthoradiogram and tape measure (n 190). ------- 95% limits of agreement

Table 2.2 Localization of the main limb length inequality.

	Tape measure		
	Below the knee[1]	Above the knee[2]	No difference
Orthoradiograms			
Below the knee	60	28	17
Above the knee	19	53	10
No difference	1	2	0

[1] Predictive value for LLI below the knee 60/80 = 0.75
[2] Predictive value for LLI above the knee 53/83 = 0.64.

2.5 Discussion

The use of a tape measure to assess the localization of the main LLI had a limited value. In measuring the total amount of LLI, tape measures could perhaps have been more precise, if the measurements had been done directly from anterior iliac spine to medial malleolus, instead of adding the distances above and below the knee.

According to our study, 95% of the measurements of LLI with wooden boards will be within about 1.5 cm of the measurements made with orthoradiograms. From a study on 21 adults with low back pain (Friberg et al. 1988), the same agreement for wooden boards can be calculated.

Individual skills and experience influence the reliability of clinical methods considerably. The interobserver variation has been reported to result in 60% disagreement among four doctors when 0.6 cm was the criterion for 'short leg' (Nichols and Bailey 1955). For our study, with one experienced examiner, this is of minor interest.

To illustrate the clinical implications of our study, the Wooden Board Reliability Graph (Figure 2.3) was designed. With help of this graph, the reliability of a certain measurement with wooden boards can be estimated, after which the clinician can decide to perform an orthoradiogram as well.

There is no consensus on the amount of LLI that is clinically important (Menelaus 1991). In any case, in posttraumatic LLI of 2 cm or more, some impairment is thought to be present according to the widely used Guides to the Evaluation of Permanent Impairment (American Medical Association 1993). The consequences of our study for the diagnosis of such impairment are shown by the Reliability Graph (fig 3). It appears that only if a LLI found with wooden boards is less than 0.5 cm, the possibility that the real LLI is more than 2.0 cm does become acceptably small. Therefore in examinations for insurance matters during which a clinical LLI greater than 0.5 cm is found, the recommendation by the AMA guides to perform an orthoradiogram is supported by our findings.

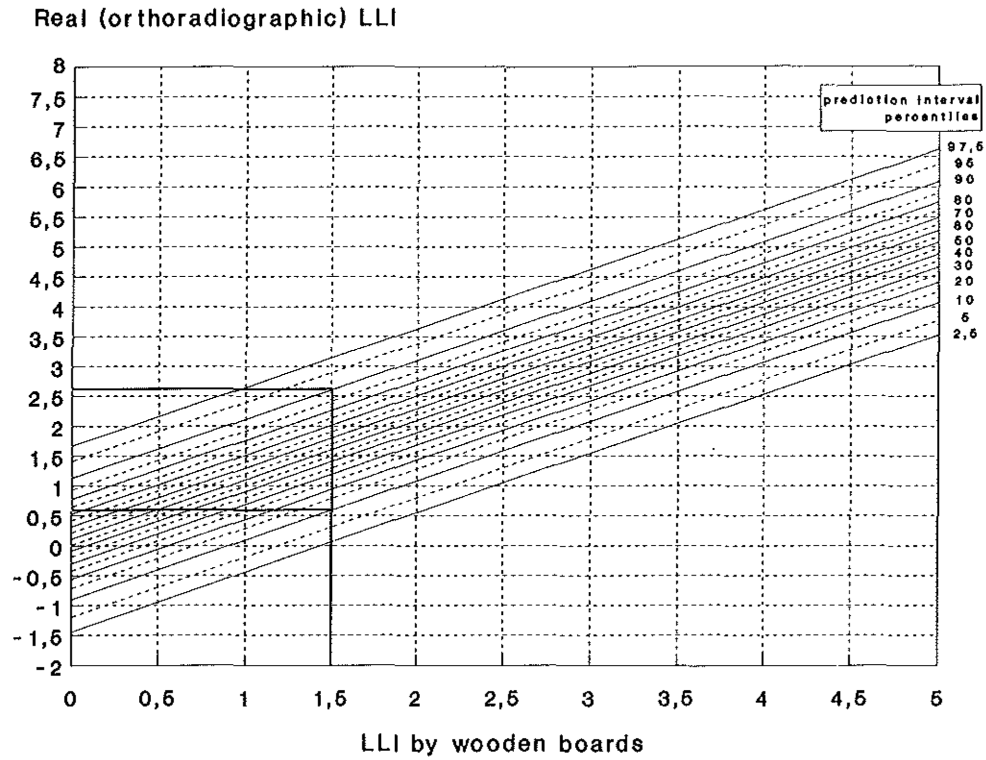


Figure 2.3 Wooden Board Reliability Graph.

The graph predicts real (orthoradiographic) LLI, based on knowledge of the LLI obtained with wooden boards. Various intervals, indicated by percentiles, can be estimated. Example. During clinical examination a LLI of 1.5 cm is found with the use of wooden boards. In the graph the vertical line at 1.5 cm on the x-axis crosses the 10- and 90% lines at about 0.6 cm and 2.6 cm on the y-axis. This means an 80% chance that the real (orthoradiographic) LLI is between 0.6 and 2.6 cm. In the same way a 20% chance can be found that the real LLI is about 1.0 cm or less.

Chapter 3

Gait in children with Limb Length Inequality.

A kinematical analysis of pelvic sway and lower extremities

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This study is submitted for publication.

3.1 Abstract

We describe the results of gait analysis, with a three camera video system, in 18 children with limb length inequality (LLI) and in 5 children without LLI. 5 Children had a severe hip deformity due to a coxitis and one child had a hemiplegia. Measured were the movements of the pelvis in the frontal plane (i.e. pelvic sway in gait and pelvic tilt in stance), flexion of hip, knee and ankle. LLI ranged from 0.2-4.3 cm.

Greater LLI led to increased pelvic sway and in the long leg with an increased flexion of the knee at heelcontact (linear regression analysis, respectively $p=0.01$ and $p=0.05$). Less strong were the relations found with increased flexion of the knee of the long leg at midstance ($p=0.04$, correlation analysis) and with increased flexion of the hip of the long leg ($p=0.03$, correlation analysis after ranking). The vertical amplitude of the pelvis did not increase with LLI. Pelvic sway proved to be less than pelvic tilt ($p=0.005$). Compared with the control group, the movements of the pelvis remained within normal limits unless LLI exceeded 3 cm. Consequently, correction of LLI only reduced pelvic sway if LLI exceeded 3.0 cm. In patients with abductor muscle weakness due to coxitis or hemiplegia pelvic sway trendelenburg gait predominated. In those patients pelvic sway did not lessen with a correction, pelvic sway might even become more than pelvic tilt in stance.

3.2 Introduction

The inconvenience of limb length inequality (LLI) increases with greater inequality of the limbs. In stance this inequality causes tilting of the pelvis in the frontal plane. As far as treatment of LLI is based on correcting pelvic tilt, note that this tilt is only observed in standing posture with straight legs. In gait LLI is mentioned to cause excessive expenditure of energy due to the increased vertical movements of the pelvis. A comparison can be made with the child's game of walking with one limb on the curb. Adaptation is supposed to occur with flexion of the knee and, especially in young patients, with toe walking (Steindler 1964, Morscher 1965 and Moseley 1987). The discomfort experienced by LLI is therefore not a static phenomenon, but a dynamic process subject to one's position and gait. Treatment and treatment goal may so vary in different patients (Moseley and Bowen, 1989). The presumed (later) consequences of LLI as low back pain - although much subject to debate (Soukka et al. 1991 and 1992, Friberg 1992) - and osteoarthritis of the hip and knee (Gofton and Trueman 1971, McCaw and Bates 1991) contribute to the considerations in treatment of LLI.

We found kinematic measurements with respect to stance and gait restricted to artificial LLI in healthy persons. An artificial LLI, up to 4 cm, was shown to have little effect on pelvic sway when walking on a treadmill (Vink and Huson, 1987). By a force plate study, Kaufman, Miller and Sutherland (1996) showed gait asymmetry in patients with LLI greater than 2.0 cm.

It was the aim of our study to measure, in patients with LLI, the effect on pelvic sway and the pattern of lower limb movement, with and without a shoe lift.

3.3 Patients and methods

Gait was studied in a group of 23 children. Subgroups were: 5 children without LLI (control group), 13 children with LLI and 5 children with LLI due to coxitis. LLI in patients was measured within 3 months from gait analysis, with orthoradiographs as described by Taillard (1956). Age, etiology and LLI are shown in table 3.1.

A three camera video system was used for kinematic analysis (Keemink and Hoek van Dijke, 1991). Cameras were placed on the left and right side, and in front of the patient. Recordings were made simultaneously. Infrared reflecting markers were directly applied on the limbs (Figure 3.1). Data were stored on video-tape, and later transmitted to hard disc after visual inspection. The sampling frequency of 50 Hz was appropriate for this type of research (Begg, Wytch and Major 1989, Whittle 1982, Oonpu, Gage and Davis 1991). Heel contact was registered with a force-sensing resistor (FSR, Interlink Electronics, diameter 1.5 cm, thickness 0.32 mm). Registration was done on a treadmill (Enraf Nonius, Delft, the Netherlands TR 4009) during one minute. The patient's gait was registered during one minute. From the strides in this minute, the parameters mentioned in table 3.2 were calculated.

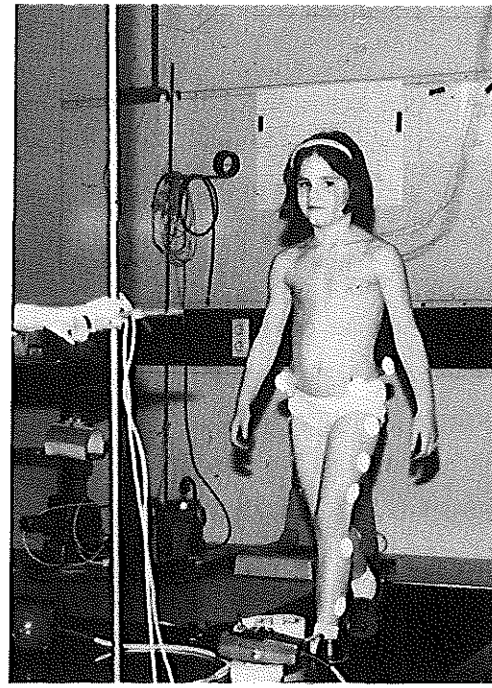

Figure 3.1
A child with infrared reflecting markers on the tredmill, with permission.

A pilot study was done in healthy persons with respect to pelvic sway. The results were comparable to those found in literature: if high speed movies were used with pins

Page 49: Table 3.1 Patients and individual results.
Two measurements are given for each child, without a correction for LLI and with a correction or extra heel raise.
LLI = amount of inequality and the shortest limb, listed in ascending order
AGE in years and months
PTS = pelvic tilt in stance, PSG = pelvic sway in gait, - sign means tilt to the left
FKHS = flexion of the knee at heelstrike, FKMS = flexion of the knee at midstance;
L = for the left side, R = for the right side, - sign is extension compared to stance.
all angles are in degrees

CASE	LLI	ETIOLOGY	AGE	PTS	PSG	FKHS-L	FKHS-R	FKMS-L	FKMS-R
Control group, without (A) and with (B) a heel raise									
1 A	0.0	control	6.10	0.0	1.1	-3.6	-12.6	20.3	14.1
B	2.0 L			-1.9	0.9	-4.4	-5.7	21.5	18.2
2 A	0.0	control	10.11	0.0	0.7	-1.2	3.0	26.9	30.7
B	2.0 L			-2.3	1.1	-5.5	10.7	21.0	29.2
3 A	0.0	control	9.4	0.0	-1.8	-8.8	-5.4	22.6	29.9
B	2.0 L			-4.0	-2.4	-11.7	1.5	19.5	31.2
4 A	0.0	control	5.11	0.0	-1.5	-14.3	-11.7	16.6	20.7
B	2.0 L			-6.3	-3.2	-12.1	-7.2	19.9	21.4
5 A	0.0	control	12.9	0.0	-2.4	-2.7	-4.2	19.8	20.6
B	2.0 L			-6.2	-2.8	1.0	4.3	26.0	26.8
Patients, without a correction (A) and with an extra heel raise (B)									
6 A	0.2 R	hemihypertrophy	16.1	0.3	1.4	-7.9	-1.8	15.5	21.9
B	2.7 R			4.8	3.7	-4.2	-8.3	18.7	16.4
7 A	0.4 L	hemiatrophy	15.1	-0.7	0.9	3.9	2.8	25.6	23.1
B	2.9 L			-5.6	-0.6	4.7	7.1	26.1	27.5
8 A	0.6 L	mult cart exostosis	14.11	-0.2	-0.5	-3.7	0.6	15.3	23.7
B	1.4 R			0.6	0.4	2.7	6.5	21.6	29.0
9 A	2.0 R	coxitis, cox varum	14.9	2.7	-1.6	11.9	-3.6	29.3	18.0
B	4.5 R			6.1	-1.2	17.2	-7.9	34.7	15.6
Patients, without (A) and with a correction (B) for LLI									
10 B	0.4 L	hemihypertrophy	12.10	-1.0	-1.0	-4.7	6.5	31.8	37.3
B	1.6 R			3.9	1.1	-7.8	-4.2	30.0	28.6
11 B	0.6 L	coxitis	15.4	-1.4	1.2	-6.3	3.0	42.6	49.0
A	1.6 L			-3.7	-.1	-4.6	4.7	24.4	34.6
12 B	0.7 R	coxitis	11.9	0.6	-5.2	13.1	-5.9	30.8	10.9
A	2.2 R			2.6	-4.8	12.4	-4.2	29.4	13.0
13 B	0.1 R	idiopathic	9.0	0.3	-2.9	9.6	9.7	30.3	31.6
A	2.4 L			-7.7	-3.2	-11.6	5.7	12.3	25.0
14 B	0.5 L	coxitis	7.2	-2.3	-4.3	-9.8	2.1	10.4	26.3
A	2.5 L			-11.5	-5.7	-10.6	5.7	15.5	28.2
15 B	0.0 L	Klippel Trenaunay	12.8	0.0	0.5	-2.2	0.6	28.4	19.3
A	2.5 L			-3.5	0.1	-3.7	-2.9	24.4	16.2
16 B	0.2 L	lower limb paresis	15.11	-0.4	1.1	4.5	-1.6	25.8	23.1
A	2.7 L			-5.4	-0.3	1.9	-1.6	16.5	23.8
17 B	0.7 R	asymmetric diplegia	13.1	0.6	5.3	-4.3	7.8	13.1	29.3
A	2.8 L			-2.4	4.3	-0.1	-3.1	16.0	16.0
18 B	0.0	idiopathic	11.4	0.0	-0.6	-4.8	-1.9	28.8	28.4
A	3.0 L			-6.8	-2.3	-1.0	0.2	29.2	26.3
19 B	0.2 R	hemiatrophy	11.8	0.3	0.1	-2.9	2.2	20.4	26.1
A	3.2 R			4.4	3.5	-0.6	-2.6	21.2	24.4
20 B	0.5 L	coxitis	16.2	-0.6	6.6	-2.1	6.9	15.2	29.7
A	3.5 L			-4.5	6.1	-5.2	7.4	10.4	28.3
21 B	0.5 L	idiopathic	15.3	-0.8	-1.4	-2.1	-5.2	12.6	20.3
A	3.5 L			-5.3	-3.9	-5.1	4.9	11.2	25.7
22 B	0.6 L	hemiatrophy	9.2	-1.3	-4.1	3.6	-3.0	28.9	30.9
A	3.6 L			-8.0	-6.4	1.0	-4.5	30.2	30.2
23 B	1.3 R	physeal fracture	12.7	2.9	1.3	-8.0	4.5	20.9	33.7
A	4.3 R	distal femur		9.7	3.7	1.7	2.3	29.0	31.4

Table 3.2 Parameters measured in gait.

pelvic sway (in gait)
mean, minimum, maximum, amplitude
pelvic tilt (in stance)
mean vertical amplitude of:
center, left and right side of the pelvis
mean flexion of the hip
mean extension of the hip
mean flexion of the knee at:
heelstrike, midstance and swing
mean flexion of the ankle joint at heel off
moment of heel off as a percentage of the stride

fixed into the bone (Eberhart, Inman and Bresler, 1954) or with use of a pelvic belt (Sutherland 1984) or if an opto-electronic system like ours was used together with a pelvic belt (Thurston and Harris 1982 and Oonpuu, Gage and Davis 1991). In the present study no obese persons were included.

Each subject walked with various LLI: without a shoe lift (except for patient 10) and with the shoe lift mostly used by the patient or with a shoe lift supplied with us. The shoe lift did not always equalize LLI completely. Children from the control group (1-5), patients with little LLI (6-8) and patient 9 who did not tolerate a shoe lift on the short limb, also walked with an extra heel lift to compare gait in LLI with gait and artificial (increased) LLI. The treadmill's walking speed was set at 5 km/h if found comfortable and was otherwise, especially in the younger children, adjusted to a comfortable lower speed.

Statistical analysis was done with paired t-test, correlation and regression analysis (extended with a quadratic term if significant) and SPSS/PC+ software. Significance level was set at 0.05.

3.4 Results

In the children without a hip deformity, without hemiplegia and without a correction for LLI (n=16) increase of LLI was associated with increase of mean pelvic sway in gait (PSG) and with more flexion of the knee in the long leg at heelstrike (FKHS), p=0.01, respectively p=0.05 with linear regression analysis. The increase of flexion of the knee of the long leg at midstance and mean flexion of the hip of the long leg were also associated with increase of LLI, but could only be demonstrated with respectively correlation analysis (p=0.04) and correlation analysis after ranking (p=0.03). The patients in this group with LLI (n=11) had less PSG than pelvic tilt in stance (PTS), p= 0.005 with paired t-test, Figure 3.2. Correlation between LLI and all other parameters measured was not found. Individual results are presented in table 3.1.

Most exceptions were found in the children with coxitis or hemiplegia (9, 11,12,14,17,20). Firstly, in 3 children (12,17,20), PSG was marked more than PTS (Figure 3.2). Secondly, in stance and gait the pelvis always tilted towards the short limb in all children but 6 (7,9,12,15,17,20), in whom the pelvis, in gait, tilted towards the long limb (Figure 3.2).

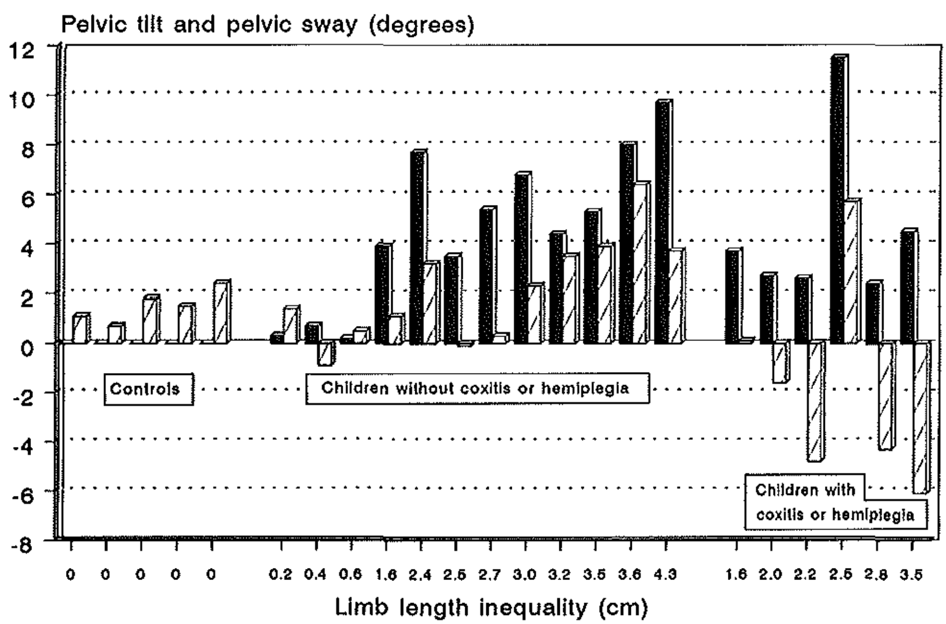

Figure 3.2
Pelvic tilt in stance (▬) and pelvic sway in gait (▱), negative value for tilt to the long limb.

The application of a correction for LLI in 14 children (10-23), resulted in marked less pelvic sway towards the short leg in 5 children with 3,0 cm or more (18,19,21,22,23). PSG before and after correction differed less than PTS for all children, except for case 8 with 0,1 degree more difference in PSG after correction. Changes in flexion of hip, knee and ankle varied greatly individually and no trend could be identified.

The application of 2 cm artificial LLI in the control group led to similar changes as in children with LLI. PSG increased in 4 children (2-5) but less than PTS. FKHS of the long (right) limb was increased in all children. Flexion of the knee at midstance (FKMS) increased in the long leg in all but 1 child (2).

The artificial increase of LLI in 4 children with little LLI (6,7,8,9) did not result in more PSG, except for 1 child (6), and PSG was always less then PTS. In the long leg at heelstrike, flexion of the knee increased (7,8,9) or extension decreased (8). In the same leg at midstance flexion of the knee increased in all.

3.5 Individual registrations

Table 3.1 shows the results of parameters in which we expected or observed marked changes and which were used for the statistical analysis. Our registrations however, were continuously. To illustrate the changes at every moment of the stride, these registrations are shown for 3 children: 1 without LLI (case 2), 1 with 2,5 cm LLI and no change in pelvic sway (case 15) and 1 with 3,0 cm LLI with changed pelvic sway (case 18). Registrations of these children with shoe lifts are also shown.

Figure 3.3 presents the recordings of case 2, a child from the control group without LLI. It is worth noting that even without LLI, kinematics of the legs are not exactly symmetric. Figure 3.4 presents recordings of the same child with a 2.0 cm shoe lift on the right side. Pelvic sway did not alter despite the raise by the shoe lift. Adaptation to LLI occurred through overall decreased flexion of the left knee and increased flexion of the right knee at heelstrike, followed by overall decreased flexion of the left hip and decreased dorsiflexion of the right ankle. The latter might have been be

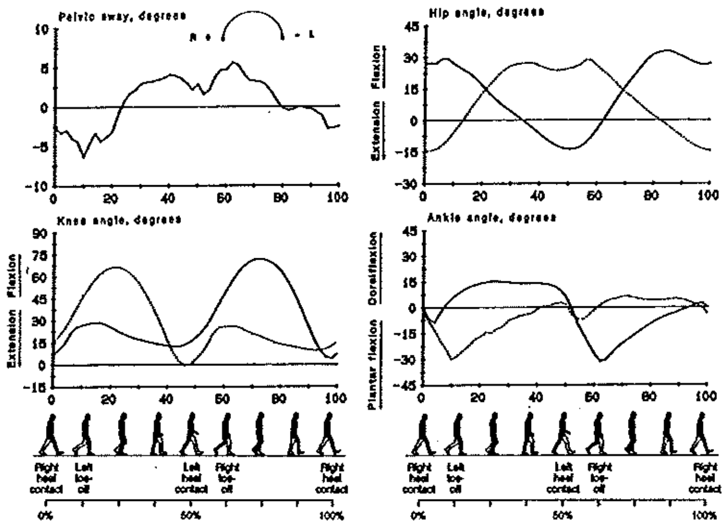

Figure 3.3 Gait recording of case 2, equal legs.
—— = right leg, ------= left leg, horizontally % of stride cycle.

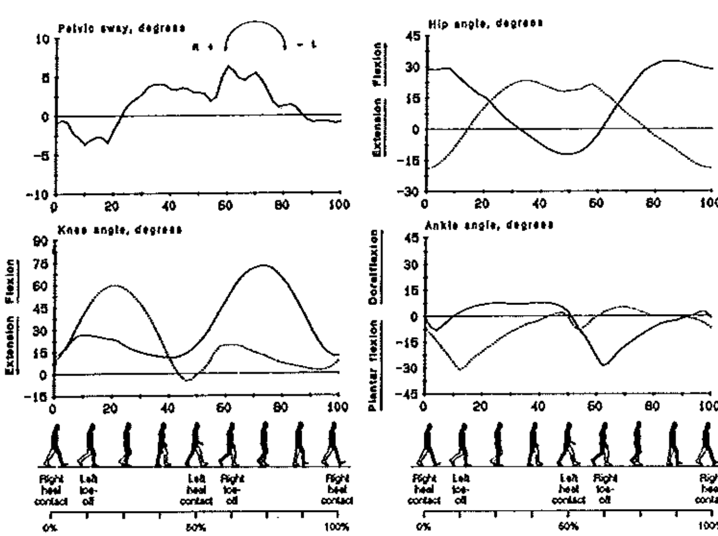

Figure 3.4 Gait recording of case 2, 2.0 cm long right leg.
—— = right leg, ------= left leg, horizontally % of stride cycle.

the result of our artificial LLI, as the heel was raised with 2.0 cm and the forefoot with 1.0 cm.

In case 2, adaptation to artificial LLI with a shoe lift thus occurred through increased flexion of the long leg and decreased flexion of the short leg with an almost identical pelvic sway as a result.

Figure 3.5 presents the recordings of case 15, a boy with 2.5 cm LLI, in whom the left leg was the short one. Figure 3.6 shows his LLI, corrected by a heel lift of 2.5 cm and a forefoot lift of 0.75 cm. In both situations pelvic sway appears similar to pelvic sway in case 2. Figure 3.5 shows that only small differences between the left and right leg can be seen. The left knee flexes more during stance than the right one, which is contradictory to what we would expect: increased flexion of the right, long leg. Furthermore, the left hip extends more than the right one at toe off, while at that same moment the left ankle increases its plantar flexion to the same proportion as the right ankle. After correction with a shoe lift (Figure 3.6) pelvic sway was in the same (normal) range as before correction. Differences between Figure 3.5 and 3.6 are found in slightly increased flexion of the left knee after heelstrike and in stance, and decreased plantar flexion of the left ankle. A full correction for LLI did not result in more symmetric kinematics of both legs as might have been expected.

In short, although walking with 2,5 cm LLI, pelvic sway remained normal. This could not be explained completely from the graphs. Only increased extension of the short left leg at toe off was found. Pelvic sway did not alter after correction (it was already normal). It therefore seemed as if adaptation occurred to the correction by increased flexion of the left leg and less equinus of the ankle on that side.

In Figure 3.7 the recordings of case 18, a boy with 3.0 cm LLI of whom the left leg was the short one, are presented. In Figure 3.8 his LLI was corrected with a heel lift of 3.0 cm and the forefoot with a 1.0 cm lift, partly as an orthopedic shoe. Figure 3.7 shows his unability to maintain normal pelvic sway. The most striking differences in this figure between left and right leg, are seen in hip angle and ankle angle. Flexion of the left hip was a bit less than of the right hip, and plantar flexion of the left ankle decreased at the moment of toe off. The first might be an attempt to maintain the pelvis level but

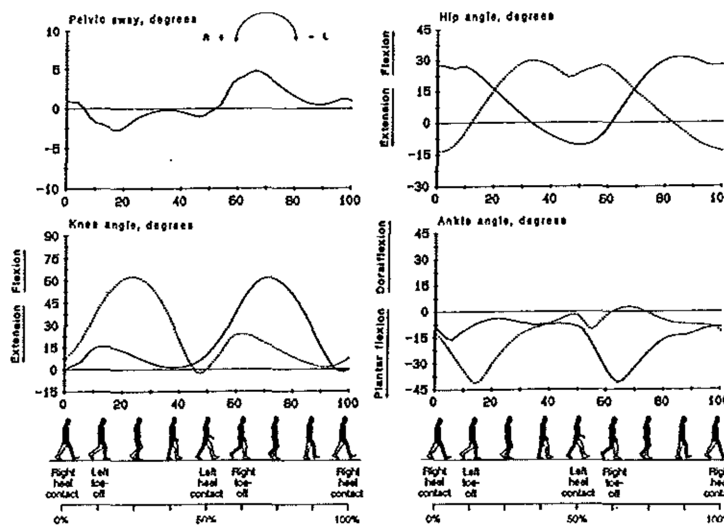

Figure 3.5 Gait recording of case 15, 2.5 cm short left leg.
—— = right leg, ------ = left leg, horizontally % of stride cycle.

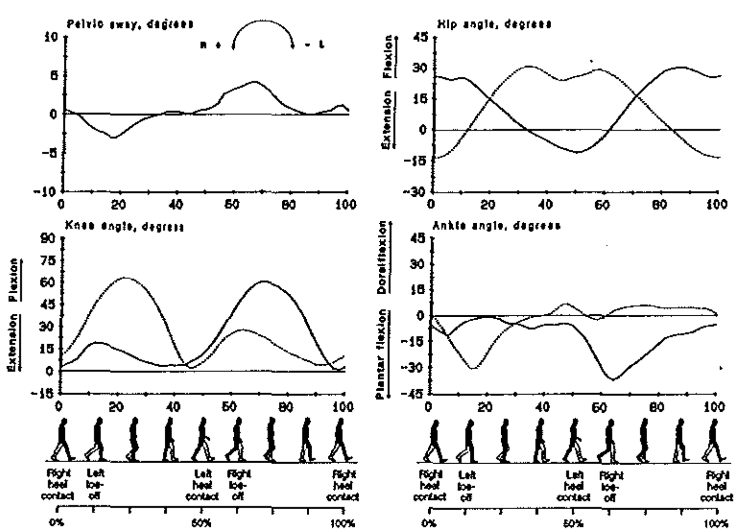

Figure 3.6 Gait recording of case 15, equal legs.
—— = right leg, ------ = left leg, horizontally % of stride cycle.

the latter is of no use. After correction (Figure 3.8) pelvic sway was within normal range. The pattern of flexion of hip and knee did not differ much from the pattern before correction. Most apparent is decreased plantar flexion of the left ankle at the moment of toe off when walking with a correction. One may conclude that the patient tried to compensate for his LLI by increased equinus of the ankle of the short leg, but his LLI was too large to allow full compensation. It is also possible that the differences in ankle flexion are just a result of the correction we provided, because symmetry in ankle flexion was not achieved by correction but increased after correction. The effect of the shoe lift was therefore a 'push up' of the left side of the pelvis and was subsequently followed with adaptation, that is decreased plantar flexion, of the left ankle.

The graphs in the Figures 3.3-3.8 illustrate the individual consequences of LLI. Although they are not suitable for statistical analysis, they can be helpful in the study of individual adaptations to LLI. Kinematics of the ankle could therefore not be shown to have a fixed relation with LLI. The individual examples however, do demonstrate intra-individual changes because of LLI.

3.6 Discussion

In this study it was shown that pelvic sway increased with greater LLI and that pelvic sway in gait (PSG) was less than pelvic tilt in stance (PTS), as illustrated in Figure 3.2.

The comparison made in the introduction with the child's game of walking with one limb on the curb does not hold for gait and LLI. The fatigue experienced in this game is caused by spending energy on increased vertical amplitude of the pelvis. This increase of amplitude because of LLI was not found by us. By using a compass model, Saunders, Inman and Eberhart (1953) theoretically explained the adaptations that occur in gait to save energy. Amongst others, they showed pelvic tilt and flexion of the knee to be of aid in the conservation of energy by translating the center of gravity through a smooth undulating pathway of low amplitude. Our study confirmed this adaptation and we found

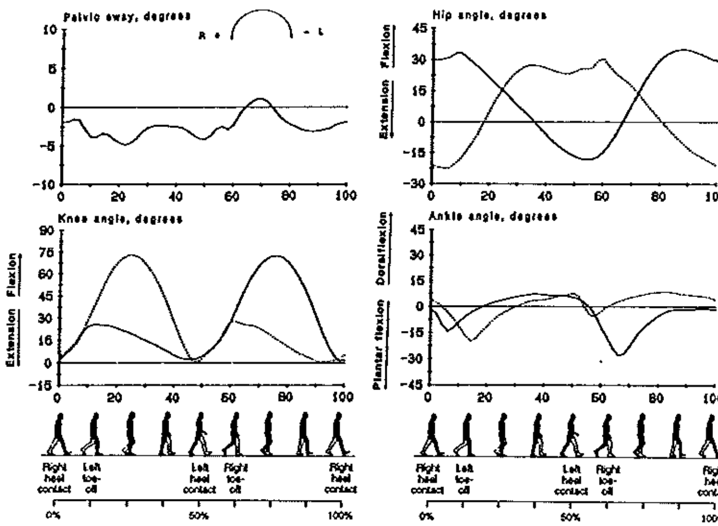

Figure 3.7 Gait recording of case 18, 3.0 cm short left leg.
—— = right leg, ------= left leg, horizontally % of stride cycle.

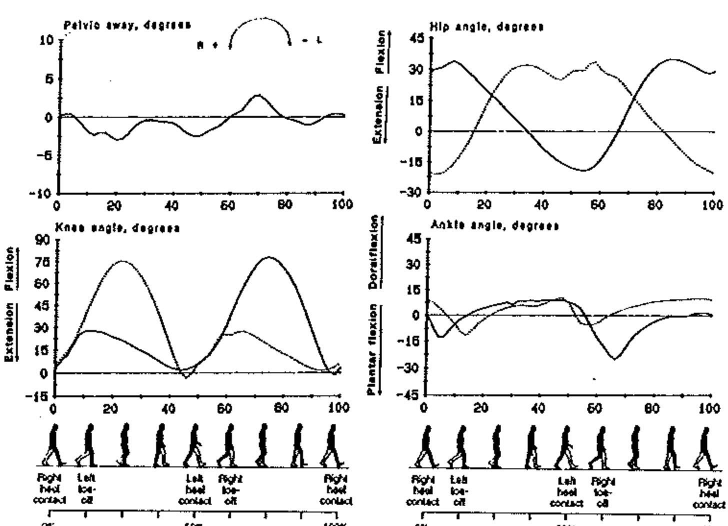

Figure 3.8 Gait recording of case 18, equal legs.
—— = right leg, ------= left leg, horizontally % of stride cycle.

increased pelvic sway and increased flexion of the knee at heelstrike and midstance with greater LLI.

PSG was found to be less than PTS which is easily explained by flexion of the knee of the long leg. This is underlined by its relation with greater LLI. The relation between greater LLI and hip movement was weaker than the relation between greater LLI and knee movement. The relation between greater LLI and with ankle movement could not be demonstrated, although its existence is theoretically very likely and much in line with clinical observations. The individual recordings however, did indicate adaptations in ankle kinematics. The reason for a lack of a statistical relationship between LLI and kinematics of the ankle could be the limited size of our studygroup, other relevant parameters in gait (such as abduction of the hip) or the existence of great interindividual differences.

PSG was within the range of the control group (-2.4-1.1 degrees) up to an LLI of 3.0 cm, excluding the patients with a coxitis or a hemiplegia and patient 13. Also, an artificial LLI (2.0 cm) in the control group only led to minor changes in PSG. The same holds truth if existing LLI (patients 6,7,8,9) was increased up to 4.5 cm LLI, except for patient 6. If one considers a correction for LLI with the intention to reduce PSG, PSG has to be out of normal range. In our study a correction for LLI was therefore only of use in 5 children (18,19,21,22,23), who had 3.0 cm LLI or more. Another intention of treatment with a correction for LLI could be the restoration of more symmetrical kinematics of both legs. However from the individual data only in a small number of patients could such an effect be found (13,20,21).

Patients with a hip deformity due to coxitis or with a hemiplegia differed from the other children with LLI in a number of ways. In 4 of these patients (9,12,17,20), pelvic sway seemed to be influenced more by their hip pathology than by LLI. This could result in pelvic sway opposite to the side expected with LLI (9,12,17,20). PSG was sometimes even more than PTS (12,17,20). Abductor muscle weakness causing this Trendelenburg gait could clearly be diagnosed by physical examination in 2 of the patients (17,20) with a hip deformity due to coxitis or with a hemiplegia. Trendelenburg gait of patient 9 was also likely because of a painful right hip at the moment of investigation. Correction for

LLI in these patients did not lessen pelvic sway (except case 14). Even if LLI reached up to 3.5 cm (patient 20), a correction could not influence pelvic sway, simply because the abductor muscles could not keep the pelvis level. The advice of Moseley and Bowen (1989) and Menelaus (1991) not to correct LLI completely in patients with an asymmetric diplegia is confirmed by our findings. The presence of a deformed hip as in coxitis with accompanying abductor muscle weakness can be added to this advice.

The treatment of LLI aims at facilitating gait and posture. When a child stands erect with straight legs there is an obligatory pelvic tilt, an anatomic deformity because of a static examination. In gait functional adaptations are likely to occur. This was also stated by Kaufman, Miller and Sutherland (1996), who based their opinion on their force plate study. When walking, we found the child to compensate the LLI by increasing flexion and extension of the knee joint of the long leg, while the movements of the pelvis remained within normal limits, unless the LLI was in excess of 3 cm.

Chapter 4

Timing of physiodesis in lower limb length inequality with the straight line graph.

Results and recommendations after 51 patients

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4.1 Abstract

In a prospective study 51 children underwent 56 physiodeses for lower limb length inequality (LLI). Timing of surgery was based on (bi)annual orthoradiographic measurements and skeletal age, and in accordance with Moseley's Straight Line Graph. The mean predicted LLI was 5.0 (3.0-11.0) cm and the mean LLI at the end of growth was 1.5 (0.0-4.3) cm. Treatment was considered as a failure in 19 patients. This was due to LLI exceeding 1.5 cm (n=14), the need to perform a secondary operation (n=4), or the combination of both (n=1).

After analysis of the failures it is concluded that the accuracy of the straight line graph is mainly limited by the pattern of skeletal maturation. Recommendations to prevent failures by other causes are given.

4.2 Introduction

Equalization of the lower limbs may be performed by 'epiphyseodiaphyseal fusion' (Phemister 1933), or physiodesis. The outcome of treatment for lower limb length inequality (LLI) depends mainly on the timing of surgery. Reported problems encountered with this exact timing are growth prediction (Anderson et al. 1963) developmental pattern of LLI (Shapiro 1982) and skeletal age estimation (Cundy et al. 1988).

We report our experiences and results in a consecutive series of children with LLI, in all of whom the timing of physiodesis was based on the Straight Line Graph (Moseley 1977).

4.3 Patients and methods

Since 1979 all children who were presented with LLI exceeding 2 cm at the Orthopedic Department of the University Hospital Rotterdam were followed-up in a special limb length clinic. Between 1980 and 1992 56 physiodeses were performed in 51 children (20 boys). All these children were followed until the end of growth.

Once (sometimes twice) a year LLI was measured by orthoradiography (Taillard 1956) and skeletal age was determined by comparing the radiograph of the hand with the atlas of Greulich and Pyle (1959). These data were plotted in the straight line graph (Moseley 1977). Timing of physiodesis of the lower femoral and or the proximal tibial physis was determined accordingly when predicted LLI at the end of growth will exceeded 3 cm.

Statistical analysis was done with Mann-Whitney U test.

4.4 Results

The clinical data are shown in table 4.1.

The predicted mean LLI without treatment, was 5.0 (3.0-11.0) cm. The final mean LLI after physiodesis was 1.5 (0-4.3) cm.

The result of treatment in nineteen patients was considered as a failure: fourteen children had a final LLI exceeding 1.5 cm, four patients had to be operated on twice and one patient ended with a final LLI exceeding 1.5 cm despite two operations. In patient 42 and 51 severe hip deformity changed our treatment goal. We tried to obtain a shorter leg on the affected side, about one to two cm. The reasons for failure are shown in table 4.2.

The influence of skeletal maturation was analyzed further. Delay in maturation caused overcorrection exceeding 1.5 cm in three patients (9,12,48) and necessitated a second operation in three patients (29,31,32). In another six patients (3,10,11,15,16,23) this phenomenon caused overcorrection of less than 1.5 cm. Acceleration of skeletal maturation occurred before operation in two patients (7,13) and could therefore be taken into account in the timing of epiphysiodesis. The observed changes in skeletal maturation always led towards corresponding changes in growth as could be calculated with the tables of Anderson and Green (Anderson et al. 1963).

The period from operation until skeletal maturity was related to the chance of overcorrection (p-value 0.01) and final LLI exceeding 1.5 cm (p-value 0.04). The predicted final LLI without treatment, the number of preoperative measurements, calendar and skeletal age at operation could not be related to overcorrection or final LLI exceeding 1.5 cm.

The mean difference between predicted and final LLI was 1.3 (0.0-4.3) cm for all fifty-one patients and 0.6 (0.0-1.5) cm after exclusion of the nineteen failures.

Table 4.1 Clinical data for 51 patients with limb length inequality

A	B	C	D	E	F	G	H	I	J	K	L
1	M	facio acro dysostose	13/9	13/0	7	TF	4.4	4.5	0.0	2.1	2.1
2	M	congenital short femur	13/10	14/6	2	TF	4.1	4.0	0.0	2.7	2.7
3	M	hemiatrophy	14/8	13/0	7	TF	3.5	4.0	0.0	0.9	-0.9
4	F	fractured tibia	12/10	12/6	2	TF	2.7	3.0	0.0	0.5	0.5
5	F	hemiatrophy	11/1	10/0	7	F	4.3	5.0	0.0	0.5	0.5
6	F	Klippel Trenaunay	12/0	11/6	6	TF	3.1	3.1	0.0	0.1	0.1
7	M	Streeter syndrome	14/9	13/0	5	TF	3.7	5.0	0.0	0.5	0.5
8	F	osteomyelitis proximal tibia	10/9	11/0	3	TF	3.9	7.0	0.0	0.1	0.1
9	M	arthrogryposis	13/8	14/0	6	TF	3.8	5.0	1.5	4.2	-2.7
10	F	hemiatrophy	10/9	11/0	5	TF	3.8	5.0	0.0	1.4	-1.4
11	M	hemihypertrophy	13/7	12/6	9	TF	3.3	4.0	0.0	1.4	-1.4
12	M	fractured femur and tibia	11/2	12/0	5	F	3.1	3.1	0.0	4.0	-4.0
13	F	posterior medial bowing tibia	11/10	12/6	4	TF	3.1	4.0	0.5	0.1	0.6
14	F	posterior medial bowing tibia	11/6	11/6	7	TF	5.2	6.0	0.0	0.1	0.1
15	M	Klippel Trenaunay	12/7	13/0	6	TF	3.2	3.5	0.0	1.3	-1.3
16	F	idiopathic	12/7	12/0	6	TF	3.2	3.5	1.0	2.5	-1.5
17	F	cerebral palsy	13/3	13/0	3	TF	2.8	3.5	1.5	0.4	1.1
18	F	skeletal dysplasia	11/0	12/0	3	TF	4.6	5.0	0.0	4.3	4.3
19	M	poliomyelitis	12/9	12/6	5	TF	3.9	5.0	1.0	0.7	0.3
20	M	fibula aplasia type 3	11/5	12/0	4	TF	7.2	8.0	0.0	0.1	-0.1
21	M	osteomyelitis distal femur	11/5	12/4	4	F+Fh	5.0	6.0	0.0	4.0	4.0
22	M	M Ollier	12/7	13/6	1	TF+Th	5.5	5.5	0.0	0.3	-0.3
23	F	hemihypertrophy	10/11	10/6	2	F	4.5	11.0	0.0	0.5	-0.5
24	F	hemihypertrophy	11/5	10/6	1	TF	8.1	8.1	1.0	1.1	-0.1
25	M	M Ehlers Danlos	14/5	13/6	1	TF	3.1	4.0	1.0	0.7	0.3
26	F	M Ollier	10/11	11/0	1	F	3.2	8.0	1.0	1.3	-0.3
27	F	poliomyelitis	12/4	13/0	1	TF	3.7	4.0	2.0	1.6	3.6
28	M	septic hip	13/5	13/6	2	TF	6.5	6.0	2.0	0.9	2.9
29	M	septic hip	11/9	12/0	3	F+Fc	3.3	4.5	2.0	2.0	0.0
30	F	septic hip	11/2	10/6	4	TF	7.4	7.5	0.0	3.2	3.2
31	M	cerebral palsy	14/2	13/0	3	TF+TFc	3.2	3.2	0.0	0.4	0.4
32	F	hemihypertrophy	11/2	12/4	3	TF+TFc	3.0	3.5	0.0	0.6	-0.6
33	M	septic hip	11/1	11/0	5	F	4.1	6.5	0.0	1.0	1.0
34	M	hemihypertrophy	13/10	13/6	3	TF	3.1	4.0	0.0	1.5	1.5
35	M	hemihypertrophy	13/11	13/4	2	TF	3.2	3.5	0.5	0.2	0.7
36	M	hemiatrophy	9/6	9/6	4	T	4.6	6.0	0.0	1.5	1.5
37	M	cerebral palsy	14/10	13/6	4	TF	3.6	4.0	0.0	0.3	0.3
38	M	septic hip	13/3	13/9	3	TF	3.8	4.5	0.0	0.3	1.1
39	M	hemihypertrophy	13/1	14/0	8	TF	4.1	5.0	0.0	0.3	0.3
40	M	poliomyelitis	11/8	11/6	4	TF	6.3	9.5	1.0	0.4	1.4
41	M	hemiatrophy	13/0	13/10	6	TF	3.5	4.0	0.5	0.3	0.8
42	F	septic hip	11/11	12/0	8	TF	3.7	4.5	1.0	1.0	2.0
43	M	fractured femur	14/4	14/0	3	TF	3.4	4.0	2.5	0.0	2.5
44	F	cerebral palsy	11/11	14/0	3	TF	3.1	3.1	1.0	0.0	1.0
45	F	fractured distal femur	13/1	13/0	6	TF	3.4	4.0	1.5	1.9	3.4
46	M	multiple osteochondromas	12/9	13/0	3	TF	6.0	6.5	0.0	0.5	-0.5
47	M	septic hip	13/2	13/4	5	TF	4.7	5.0	0.5	3.0	3.5
48	M	fractured femur and tibia	15/1	13/0	5	TF	2.6	3.7	0.0	3.3	-3.3
49	F	congenital pseudarthrosis tbia	12/1	11/6	5	TF	7.1	7.1	0.0	3.5	3.5
50	F	idiopathic	14/3	12/6	8	TF	3.8	4.0	0.5	1.7	2.2
51	M	poliomyelitis	13/2	15/0	3	TF	3.2	3.5	2.0	0.5	2.5

A Patient number
B Sex
C Etiology
D Age at operation; year/months
E Skeletal age at operation; year/months
F Number of preoperative orthoradiographic measurements

G Site of physiodesis
- T tibia
- F femur
- TF tibia and femur
- \+ second operation
- c contralateral
- h homolateral

H LLI at operation (cm)

I Predicted inequality without physiodesis
J Predicted inequality with physiodesis
K Difference between predicted and realized LLI
L Final LLI at maturity, minus sign means overcorrection

Table 4.2 Failures

Cause	Patient number
Insufficient pre-operative measurements	2, 27, 28
Premature fusion of damaged growth plate	18, 21, 30, 47
Delay in skeletal maturation	9, 12, 29, 31, 32, 48
Unpredicted growth stop	
Due to disease	49
Due to rapid maturation	50
Surgeon's failures	
Operation failure	22
Underestimated growth before physiodesis	1
Physiodesis done too late	
Due to doctor's delay	45
Due to patients delay	43

4.5 discussion

Two studies have been done using the straight line graph in all patients. Timperlake et al. (1991) reported a mean final LLI of 1.5 (0.2-4.0) cm, while seventeen out of thirty-five patients ended with a final LLI of 1.5 cm or less and no secondary operations were performed. The study of Dewaele et al. (1992) achieved a mean final LLI of 1.48 cm in 36 patients.

Analysis of our failures has led to a number of recommendations. A sufficient number of pre-operative measurements will provide better understanding of development of LLI and skeletal maturation. For that reason early referral to a limb length clinic and physiodesis of both femur and tibia, instead of only one of them at an earlier stage, is preferable. This can, however, result in the disadvantage of knees at uneven heights. Premature closure of damaged growth plates in the short limb may be foreseen by comparison with the contralateral side. Prevention of surgeon's failures is inherent to the experience obtained. With the help of these recommendations a better final result could theoretically have been obtained in seven patients.

The failures due to a delay in skeletal maturation do not seem to be preventable;

they all occurred after the operation.

In treatment of LLI the problem of changes in skeletal age in relation to a child's calendar age has been noted before (Green and Anderson 1957, Blair et al. 1982). Variation in radiographic determination of skeletal age is also a source of inaccuracies (Cundy et al. 1988). Furthermore, the observed changes in skeletal maturation can represent differences between the children of our study and the children from which the original data of the straight line graph and the atlas of Greulich and Pyle were derived. Normal skeletal changes in puberty (Buckler 1984), delayed or premature onset of puberty, illness and operation may also attribute to a change of the skeletal age related to the calendar age. Our study shows that the straight line graph can be accurate in predicting LLI after treatment by physiodesis but this accuracy is limited by the pattern of skeletal maturation.

The advantage of physiodesis as the least traumatic procedure to correct a LLI is tempered by the disadvantages of repeated radiographic measurements and the risk of significant residual LLI or overcorrection. Our study suggests, that even with the recommendations mentioned above, almost one of every four patients would not have obtained a satisfactory result. An alternative treatment for moderate LLI is shortening of the long leg after the end of growth, although these operations have their problems too (Kenwright and Albinana 1991).

Chapter 5

The straight line graph in limb length inequality.

A new design based on 182 Dutch children

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5.1 Abstract

Moseley's Straight Line Graph (M-SLG), which is based on growth data obtained in the 1940s and 1950s, is helpful for the timing of physiodesis. We investigated whether current growth data could improve this graph. We estimated growth curves, based on recent data on 182 Dutch children, collected between 1979 and 1994, using repeated measure analysis of variance. In both boys and girls the mean femur and tibia length had increased when compared to the data collected by Anderson et al. (1964).

Based on our growth data, a new straight line graph (Rotterdam Straight Line Graph; R-SLG) was created. Its value was assessed by comparing the difference between the predicted length of the short (i.e., not operated) limb at maturity with the final limb length. In a group of 34 children who underwent physiodesis up to 10 years ago, the R-SLG gave better prediction of limb length at maturity than the M-SLG did in 22 out of 34 cases and equal results were obtained in 5 cases.

We conclude that our updated SLG can improve the prediction of final limb length and thus also the timing of physiodesis.

5.2 Introduction

The result of physiodesis for inequality of limb length (LLI) is determined by the timing of the operation. For that purpose Moseley (1977) developed a straight line graph (M-SLG). The use of M-SLG has been reported by several authors (Timperlake et al. 1991, Dewaele and Fabry 1992, Lampe et al. 1992). Apart from failures not related to the use of M-SLG itself, discussion on the accuracy of this method focuses on the data about which M-SLG was based-i.e., measurements of North American children in the 1940s and 1950s (Anderson et al. 1964). Regional and present-day differences in skeletal maturation (Porat et al. 1991) as well as the tendency of people in industrialized countries to become taller (van Wieringen 1987) affect the use of M-SLG.

We actualized the straight line graph with recent growth data on Dutch children acquired in our limb length clinic and evaluated it.

5.3 Patients and methods

Between 1979 and 1994, 226 children (94 girls) were (bi-)annually seen at our limb length clinic. Most of them were followed until maturity. 44 Children (12 girls) were excluded from this study for various reasons, such as systemic disease or treatment affecting both limbs, abnormalities or operations on both limbs and incomplete measurements. Etiology of LLI of the 182 children included is given in table 5.1. In every child, length of the normal limb was measured. For example in case of hemihypertrophy we measured the short limb, and in case of hemihypotrophy we measured the long limb. Measurements were done with orthoradiographs, as described by Taillard (1956). In all children, the femur was measured from the most cranial point of the femoral head to the most distal point of the medial condyle. The tibia was measured from the eminentia intercondylaris medialis to the most proximal point of the talus. Total limb length was measured from the head of the femur to the talus. In total, we performed 596 measurements (280 in girls), mean per child 3.3 (2-14). Skeletal age was determined according to the atlas of Greulich and Pyle (1959), by one of two available radiologists. The limb length was considered as a function of calendar age and skeletal age. Growth curves were estimated with the help of multivariate regression analysis, using Biomedical Computer Programs (BMDP) software (module 5V: unbalanced repeated measure models with the covariance matrix defined as first-order autoregressive). Using these data we constructed a new straight line graph (Rotterdam Straight Line Graph, R-SLG), similar to Moseley's method (Moseley 1977).

The construction of the straight line graph can be explained by the following model. The way in which the mean limb length (L) increases with age (a) is described as:

$L(a) = L_o + s\,F(a)$, with $L(a)$ = mean limb length at a certain age,

L_o = mean limb length at birth

$F(a)$ = a monotonically increasing function of age.

s = slope

The formula above represents a straight line (slope s) of the mean limb length with F(a). Hence F(.) can be considered a transformation of the age-axis that distorts distances between adjacent ages on this axis, whilst keeping the order intact. This transformation may be nonparametric. (Moseley has chosen $s=1$ in M-SLG. For practical reasons, we have chosen $s = 0.6$ in the R-SLG).

The growth curve of an individual (i) child's limb is denoted as $L_i(a)$ which is defined as: $L_i(a) = C_i L(a)$ with C_i a positive factor typical for an individual child. The mean of the C_i's for all children in a population is 1, describing the mean growth curve L(a). For the individual child, the growth curve ($L_i(a)$) is also drawn as a straight line with a slope of 0.6 but drawn against the $C_i\,F(a)$-axis. This $C_i\,F(a)$-axis applies to the individual child and is parallel to the mean skeletal age axis (F (a)-axis). This $C_i\,F(a)$-axis is stretched out compared to the F (a)-axis when C_i is larger than 1 (i.e., when the child's normal limb is longer than the mean limb length at that skeletal age), the axis becomes shorter when C_i is smaller than 1. The former gives a $C_i\,F(a)$-axis that is drawn above the F (a)-axis, whereas the latter is drawn below the F (a)-axis. Hence, for an individual child, the age-axis, which already is transformed by transformation F(.) is also rescaled by a factor C_i (Figure 5.1).

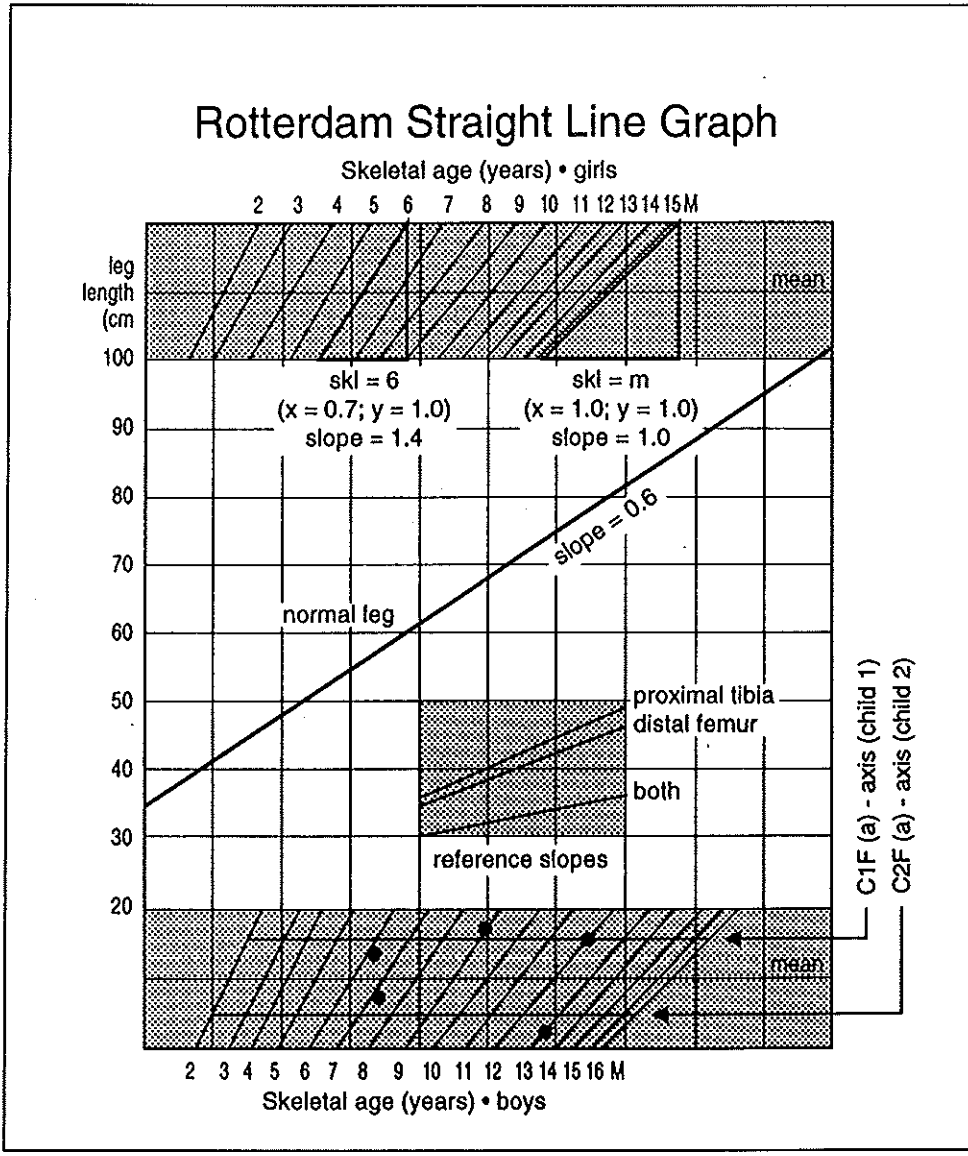


Figure 5.1 The Rotterdam Straight Line Graph, for explanation see text.

The actual slope of the skeletal age lines in the nomogram is unimportant, it is the relative slope of these lines to the others that is important. The line that is located most to the right is the maturity line. This line is placed at a slope of 1 to reduce errors in drawing both horizontal and vertical lines to it. The other lines are placed in a way that the ratio of its X-co-ordinate to the X-co-ordinate of the maturity line at the same Y-co-ordinate is equal to the proportion of adult growth achieved by that skeletal age as derived from the mean values in the tables of Anderson et al. (1964) for boys and girls. In other words, if the maturity line slope is 1 ($X = 1$, $Y = 1$), then a skeletal age line with a slope of 1.4 ($X = 0.7$, $Y = 1$) shows that given a specific skeletal age, 70% of the total growth of the limb is achieved.

The mean differences in skeletal lengths between the Dutch population and that described by Anderson et al. (1964) were compared by means of a t-test ($p < 0.05$ significant). The differences in skeletal age at the various calendar ages were compared with a Z-test having the same significance.

To compare the value of the R-SLG with M-SLG, the length of the short limb (not always a normal limb) at maturity was predicted with help of both R-SLG and M-SLG in 34 of the 182 patients. These 34 patients (14 girls) underwent physiodesis up to 10 years ago (Table 5.1). 17 patients were also included in a former study (Lampe et al. 1992). The time of the prediction was just after the last measurement before physiodesis. Measurements were always done with orthoradiographs. When using M-SLG, total limb length was calculated by adding lengths of femur and tibia; when using R-SLG, total limb length was calculated by measuring the length from the femoral head to the talus. The mean number of radiographic measurements was 4 (2-8). The two methods were compared by calculating the difference between predicted and final limb lengths (paired t-test).

5.4 Results

At most ages Dutch children had longer femora and tibiae than in the data of Anderson et al. (1964). This increase was statistically significant for the femur in girls

Table 5.1 Etiology of limb length inequality.

	All children (n 182)	M-SLG compared to R-SLG (n 34)
Congenital		
congenital longitudinal deficiency of the femur:		
proximal femoral focal deficiency	1	
congenital short femur	9	
coxa vara	2	
congenital longitudinal deficiency of the fibula	4	1
congenital longitudinal deficiency of the tibia	1	
posteromedial angulation of the tibia and fibula	7	3
congenital pseudarthrosis of the tibia	1	1
skeletal dysplasia	4	1
congenital dislocated hip	9	3
clubfoot	2	
congenital constriction band syndrome	1	1
Vascular malformations		
popliteal stenosis	1	
Infections		
metaphyseal osteomyelitis of the femur	1	
metaphyseal osteomyelitis of the tibia	1	
septic arthritis of the hip	10	1
septic arthritis of the knee	4	
septic arthritis of the hip and knee	1	
Neurological disorders		
hemiplegia	17	
poliomyelitis	8	
myelocele	1	
Trauma		
fractured femur	6	1
fractured tibia	4	1
fractured femur and tibia	4	3
epiphyseal injuries	2	
Tumor and tumor-like conditions		
multiple exostosis	1	1
Ollier's disease and related disorders	4	
Anisomelia		
hemihypertrophy	11	1
Klippel Trénaunay syndrome	11	3
Beckwith Wiedemann hemiatrophy	2	1
hemiatrophy	16	
Miscellaneous		
Legg-Calvé-Perthes	1	
arthrogryposis	1	
Idiopathic	34	12

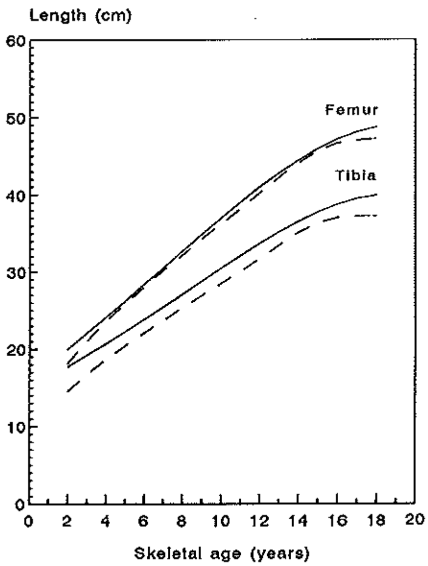
aged 8-9 years and in boys aged 10-15 years, and for the tibia in girls aged 6-16 years and in boys aged 6-16 years. In both sexes, the length of the tibia increased more than that of the femur (Figures 5.2 and 5.3). Although not significant, in general the mean skeletal age was slightly lower than the mean calendar age, except for girls between 9 and 11 years (Figures 5.4 and 5.5). With these data, we created the R-SLG, as shown in Figure 5.1.

Prediction of the short limb length at maturity with the R-SLG was statistically significant better than with M-SLG. The mean difference between M-SLG and R-SLG was 1.0 cm (95% confidence interval 0.5/1.5 cm). Better results were obtained in 8 out of 14 girls and 14 out of 20 boys, equal results were obtained in 2 girls and 3 boys (Figure 5.6).

5.5 Discussion

The consequences of the secular trend are illustrated by the differences we found in the length of the femur and tibia of Dutch children and those measured by Anderson et al. (1964). Some differences exist in measurement technique, the most important is the use of teleroentgenography by Anderson et al. (1964) in younger children. The enlargement factor caused by teleroentgenography (although used with mathematical correction) might have led to overestimation, and in any case less accurate measurement of length of the tibia and femur in younger children. The differences in limb length in young children, as found in our study and that of Anderson et al., are therefore underlined. Furthermore, small differences exist as regards the points of reference with use of orthoradiography. We believe that these do not explain the differences found in length of the femur and tibia but are a result of the secular trend. Therefore we created a new straight line graph. The problem of points of reference will probably also be encountered by future investigators, who choose other measurement techniques, such as computer tomography or ultrasound.

The graphic method, the straight line graph, created by Moseley (1977), was



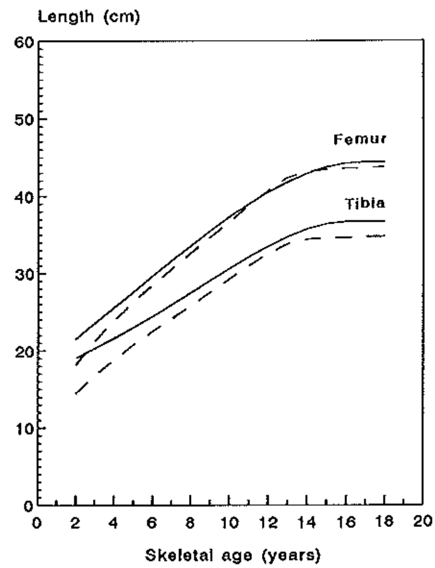


Figure 5.2 Lengths of femur and tibia in boys. Figure 5.3 Lengths of femur and tibia in girls.
Dutch data (——) compared to those of Anderson et al. (----); 1964).

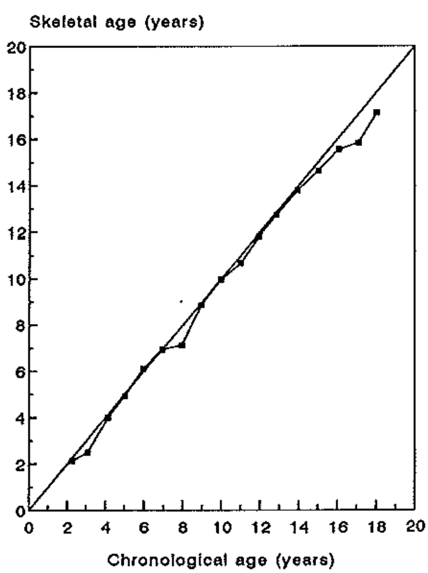


Figure 5.4 Mean skeletal age versus age in Dutch boys.

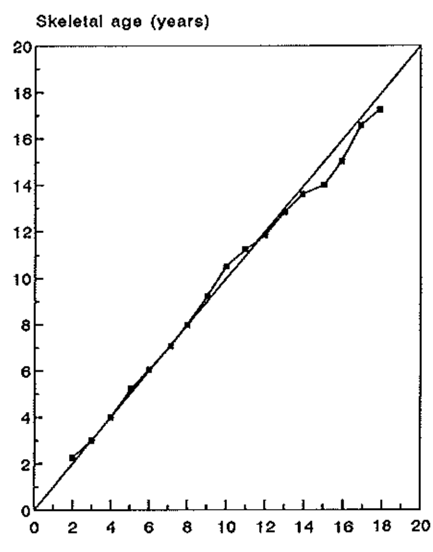


Figure 5.5 Mean skeletal age versuscalendar calendar age in Dutch girls.

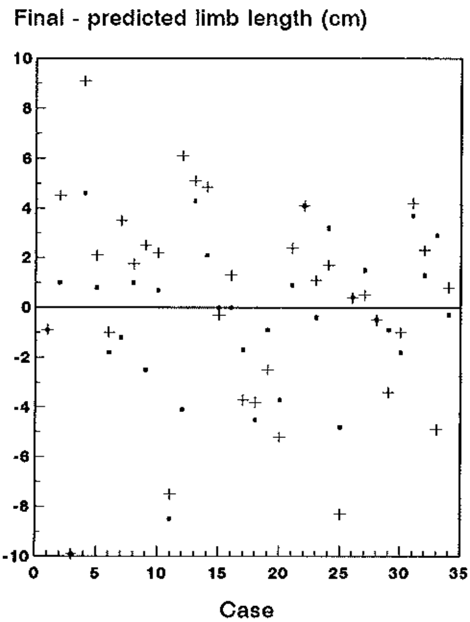


Figure 5.6 Difference (cm) between final and predicted length of the short limb at maturity for + M-SLG and ■ R-SLG.

based on the growth data of Anderson et al. (1964), to predict final LLI and to determine the limb length at which physiodesis should be performed. This method is based on two concepts. First, growth of the limb is represented by a straight line after rescaling the abscissa by means of an 'empiric transformation', a nonparametric transformation independent of the nature of the data involved. Secondly, the growth percentile of the child is taken into account in determining limb length at maturity, by means of an age nomogram.

There are several differences between the R-SLG and M-SLG. In the R-SLG, total limb length is measured from the femoral head to the talus, instead of the sum of the femur and tibia lengths, as in M-SLG. In M-SLG this results in relatively longer limb length at younger ages than at older ages, because there is an overlap between the femur and tibia on radiographs at older ages. M-SLG therefore tends to predict limb length longer than that achieved. Because the overlap is the same for both limbs, it does not affect the prediction of LLI by either M-SLG or R-SLG.

Another difference is the primary use of skeletal age in the R-SLG, as mean skeletal age seemed to differ from mean calendar age in our population, although not significantly. When Anderson et al. presented their data in 1964, calendar age might have been considered the same as skeletal age. Some differences already existed in those days and were also noted by Little et al. (1996). The assumption made in the construction of M-SLG, which is based on the data of Anderson et al. (1964), of calendar age being equal to skeletal age might thus be a possible source of error. With the primary use of skeletal age in the R-SLG, we further eliminated age-related errors in M-SLG.

Finally, in the R-SLG, a different slope (0.6) was chosen than in M-SLG (1.0) for the straight line, presenting growth of the long limb. This was done by an adaptation of the abscissa to facilitate its use. The reference lines, representing growth after physiodesis, have been adjusted accordingly.

The better results in the prediction of final limb length with R-SLG, as compared to M-SLG, reflect the necessity to update the growth data on which M-SLG is based. It may thus help to the improve timing of physiodesis.

With the adaptations mentioned above, we believe we have improved M-SLG for use in our clinic. However this method may not be superior in a population different from ours. The same is probably true of M-SLG, but this did not prevent its widespread use. However, despite the use of an 'optimal straight line graph', changes in the pattern of maturation, due to increasing deceleration of growth, inaccuracy in determining skeletal age or manual drawing of the lines in a straight line graph, may reduce the accuracy of this method (Green and Anderson 1957, Blair et al. 1982, Cundy et al. 1988, Lampe et al. 1992).

Chapter 6

Summary and discussion

Almost 20 years of experience with the management of limb length inequality (LLI) in the limb length clinic of the Sophia Children's Hospital gave rise to the studies described in this thesis. At first, the measurement of LLI and the applicability of physiodesis with use of Moseley's Straight Line Graph (M-SLG) were studied prospectively from the beginning of the limb length clinic. After having collected new data, M-SLG was updated and redesigned. In the gait laboratory of the department of Biomedical Physics and Technology of the Erasmus University Rotterdam, kinematics in gait with LLI were measured.

In **chapter 1**, entitled 'Limb length inequality, the problems facing patient and doctor', a review of literature and the aim of the study are presented. In the review of the literature attention is given to etiology, prediction and developmental pattern of LLI, measurement techniques, various kind of treatment, the influence of LLI on gait and stance and its late consequences.

In **chapter 2** the agreement in the measurement of LLI by orthoradiograms and clinical methods is compared. In daily practice measurement of LLI is commonly done with clinical methods as wooden boards and a tape measure. From literature no satisfying accuracy of these methods could be found. Because management of LLI starts with knowledge of LLI, this study was undertaken to provide better insight in the accuracy of clinical methods.

95% Of the measurements with wooden boards in 190 children who attended our limb length clinic for the first time, was within -1.4 and +1.6 cm of the results measured by orthoradiograms. A tape measure had significant less agreement. If a tape measure was used, the predictive value was low for a localization of the main LLI above the knee 64% and for a localization of the main LLI below the knee 75%.

A Wooden Board Reliability Graph is presented, which can be helpful in the decision whether or not to perform orthoradiographic measurements of LLI.

From this study follows that, if one suspects LLI to be relevant in the treatment of the patients complaints, clinical measurements are not always accurate enough. Radiographic measurements should then be performed. Financial consequences (for example in the evaluation of impairment) can also be a reason to perform a more accurate radiographic measurement. The use of clinical measurements is so limited to screening for which its inaccuracy is more acceptable.

In **chapter 3** the results of gait analysis in children with LLI are presented. In the standing position one is most aware of his or her's LLI while in supine or sitting position LLI does not matter. Gait is an intermediate situation in which pelvic sway can be compensated for by flexion of the hip, knee and ankle. Our knowledge of pelvic sway due to LLI, in gait, is almost limited to a comparison with the child's game of walking with one limb on the curb. The gait analysis was therefore done to quantify the kinematics of pelvis, hip, knee and ankle.

A three camera video system was used in 18 children with, and in 5 children without LLI. The movements of the pelvis in the frontal plane (i.e. pelvic sway in gait and pelvic tilt in stance), flexion of hip, knee and ankle were measured during one minute on a treadmill. LLI ranged from 0.2 to 4.3 cm.

Greater LLI led to increased pelvic sway, and in the long leg to an increased flexion of the knee at heelcontact (respectively $p=0.01$ and $p=0.05$ with linear regression analysis). Less strong were the relations found between the quantity of LLI and the increase of flexion of the knee of the long leg at midstance ($p=0.04$, correlation analysis) and between the quantity of LLI and the increase of flexion of the hip of the long leg ($p=0.03$, correlation analysis after ranking). The vertical amplitude of the pelvis did not increase with LLI. Pelvic sway was less than pelvic tilt ($p=0.02$). Compared to the children without LLI, pelvic sway remained within normal limits, unless LLI exceeded 3 cm. Consequently, correction of LLI with a heel raise only reduced pelvic sway if LLI exceeded 3.0 cm. In patients with abductor muscle weakness due to coxitis or hemiplegia pelvic sway did not decrease through correction. After correction, pelvic sway could than be even more than pelvic tilt.

In this study LLI of 3 cm was a limit with respect to pelvic movements and to the benefit from a shoe lift. Neutralizing pelvic tilt and pelvic sway, in LLI less than 3 cm, was not appropriate due to the dynamic process of gait. One should therefore be reluctant and careful in the selection of patients for (operative) treatment if LLI is less than 3 cm.

In **chapter 4** a prospective study is described in which the results are presented of physiodesis timed with M-SLG. In 1977 Moseley presented 'A straight line graph for leg length discrepancies'. This method appeared promising for the timing of physiodesis and was subsequently used in the limb length clinic of the Sophia Children's Hospital Rotterdam.

51 Children underwent 56 physiodeses for LLI. Timing of surgery was based on (bi)annual orthoradiographic measurements and skeletal age, and was in accordance with M-SLG. The mean predicted LLI was 5.0 (3.0-11.0) cm and the mean LLI at the end of growth was 1.5 (0.0-4.3) cm. Treatment was considered to have failed in 19 patients. This was due to LLI exceeding 1.5 cm (n=14), the need to perform a secondary operation (n=4), or the combination of both (n=1).

After analysis of the causes of failures it is concluded that the accuracy of M-SLG is not only influenced by etiology of LLI, technical skills and accuracy in determining skeletal age, but also and most unforeseeable, by the pattern of skeletal maturation. Recommendations to prevent failures by other causes are given. These recommendations might have led to better results in 7 patients.

Physiodesis as a treatment for LLI in children is the least traumatic operative procedure. Because the operation is performed during growth, LLI will on average be less than if the child had not been operated on until maturity. However, shortening at the end of growth however, can be done very precisely. This is contradictory to physiodesis which, despite the use of M-SLG, failed in almost one of four of our patients.

In **chapter 5** the update of M-SLG is described. One of its limitations is that the data on which M-SLG is based, are probably outdated. The measurements were obtained in the thirties, forties and fifties of this century and are subject to the so called 'secular trend': the tendency of people in the industrialized countries to become taller.

At first growth curves were estimated. The growth curves were based on data of 182 Dutch children who were seen between 1979 and 1994 and estimated with use of repeated measures analysis of variance. Compared to the data used by Moseley, the mean femur and tibia length had increased significantly in both boys and girls.

Then, with these new growth data, a new straight line graph (Rotterdam Straight Line Graph; R-SLG) was created. Its value was ascertained by comparing the difference between the predicted length of the short (i.e. not operated) limb at maturity to the final limb length. In a group of 34 children who underwent physiodesis up to 10 years ago, R-SLG better predicted limb length at maturity in 22 children than M-SLG. Equal results were obtained in 5 children.

It is concluded that R-SLG can improve the prediction of final limb length and thus can improve the timing of physiodesis. The R-SLG will not correct for the potential sources of error as pointed out in the previous chapter, but will only correct for the consequences of the secular trend and regional differences. The fact that R-SLG is able to better predict the final limb length is due to the use of current growth data.

Samenvatting

Dit proefschrift gaat over beenlengteverschillen (BLV) bij kinderen. Bijna 20 jaar ervaring met de behandeling van BLV op het beenlengtespreekuur van het Sophia Kinderziekenhuis Rotterdam vormde de basis van de beschreven studies. Vanaf het begin werd het meten van BLV en de toepasbaarheid van de physiodese met gebruikmaking van 'Moseley's Straight Line Graph' (M-SLG), prospectief onderzocht. Later werd met nieuwe gegevens M-SLG vernieuwd. In het gangbeeld laboratorium van de afdeling Biomedische Natuurkunde en Technologie van de Erasmus Universiteit Rotterdam konden de veranderingen door BLV in de kinematica van het gangbeeld worden gemeten.

Hoofdstuk 1 getiteld: 'Limb Length Inequality, the problems facing patient and doctor,' biedt een overzicht van de literatuur en het doel van de studie. In het literatuuroverzicht wordt aandacht gegeven aan etiologie, voorspelling en het ontwikkelingspatroon van BLV, meetmethoden, de verschillende behandelingsmethoden, de invloed van het BLV op gangbeeld en stand en de latere gevolgen van BLV.

Hoofdstuk 2 beschrijft de nauwkeurigheid waarmee met plankjes of een meetlint het BLV kan worden gemeten. Alhoewel röntgenologische methoden het meest nauwkeurig zijn, worden de eerstgenoemden in de dagelijkse praktijk echter meer gebruikt. In de literatuur kon geen bevredigende beschrijving van de nauwkeurigheid van beide methoden worden gevonden. Het onderzoek in dit hoofdstuk werd verricht om hierin een beter inzicht te verkrijgen.

Bij 190 kinderen, die het beenlengtespreekuur voor de eerste keer bezochten, werd het BLV achtereenvolgens gemeten met plankjes, een meetlint en orthoröntgenologisch. Van de metingen verricht met plankjes, viel 95% binnen -1,4 en +1,6 cm van de röntgenologische metingen. Dit was nauwkeuriger dan de metingen die verricht waren met een meetlint. Het gebruik van een meetlint voor de lokalisatie van het grootste BLV (boven of onder de knie) had een lage voorspellende waarde, respectievelijk 64 en 75%. Een figuur werd ontworpen waarin gemakkelijk de betrouwbaarheid van een meting met plankjes kan worden afgelezen.

Geconcludeerd werd dat niet-röntgenologische methoden het BLV onnauwkeurig meten. Als een nauwkeurige meting gewenst is (bijvoorbeeld in wetenschappelijk onderzoek) of als het BLV financiële gevolgen kan hebben (bijvoorbeeld bij beoordeling van invaliditeit door een BLV) is een röntgenologische meting dan ook noodzakelijk.

Hoofdstuk 3 beschrijft het looponderzoek bij kinderen met een BLV. In stand is men zich het meest bewust van een BLV omdat een scheefstand ontstaat van het bekken in het vooraanzicht, bij zitten of liggen is dit niet het geval. Tijdens lopen kan de scheefstand van het bekken gecompenseerd worden door buiging in heup, knie en enkel. Onze kennis van bekkenscheefstand tijdens lopen met BLV is vrijwel beperkt tot een vergelijking met het kinderspel waarbij met één been wordt gelopen op een stoeprand. De gangbeeldanalyse werd verricht om de kinematica van bekken, heup, knie en enkel, door BLV, te meten.

Voor het onderzoek werd een videosysteem met drie camera's gebruikt, waarmee gelijktijdig het lopen in het vooraanzicht en het linker- en rechter zijaanzicht kon worden vastgelegd. Gemeten werden de scheefstand van het bekken in het vooraanzicht en de buiging van heup, knie en enkel. 18 Kinderen met en 5 kinderen zonder BLV werden op deze manier gefilmd. Het lopen vond plaats op een lopende band. Het BLV varieerde van 0,2 tot 4,3 cm.

Tijdens het lopen werd bij toename van het BLV een grotere bekkenscheefstand gevonden en een vergrote buiging van de knie van het lange been op het moment dat de hak de grond raakte. In mindere mate werd ook een vergrote buiging van de knie gevonden in het midden van de standfase. De vertikale, op- en neer gaande, beweging van het bekken bleek niet toe te nemen met een groter BLV. Verder bleek dat tijdens lopen de scheefstand van het bekken minder was dan in stand. Soortgelijke bevindingen werden gedaan bij de vijf kinderen zonder BLV, nadat bij hen kunstmatig een BLV werd gecreëerd met een hakverhoging van 2 cm. Vergeleken met de kinderen zonder BLV bleef de bekkenscheefstand tijdens lopen binnen normale waarden, tenzij het BLV groter was dan 3,0 cm. Een correctie van het BLV verminderde de bekkenscheefstand tijdens het lopen dan ook alleen, als het BLV meer dan 3,0 cm bedroeg. Patiënten met een zwakte van de abductoren door coxitis of een hemiplegie hadden geen baat bij een correctie van het verschil, de bekkenscheefstand tijdens lopen kon dan zelfs groter zijn dan in stand.

Hoofdstuk 4 beschrijft een prospectieve studie waarbij de resultaten van een groeiremmende ingreep door middel van een physiodese met behulp van M-SLG worden beschreven en geanalyseerd. In 1977 publiceerde Moseley 'A straight line graph for leg length discrepancies'. Zijn methode leek veelbelovend voor het bepalen van het moment van een physiodese en werd vervolgens gebruikt op het beenlengtespreekuur van het Sophia Kinderziekenhuis Rotterdam.

Bij 51 kinderen werd 56 maal een physiodese verricht vanwege BLV. Het tijdstip van operatie werd bepaald aan de hand van (half-)jaarlijks verrichte orthoröntgenologische beenlengtemetingen met gelijktijdig bepalen van de skeletleeftijd, overeenkomend met M-SLG. Het gemiddelde voorspelde BLV, aan het einde van de groei, was 5,0 (3,0-11,0) cm. Na physiodese was het gemiddelde BLV aan het einde van de groei 1,5 (0,0-4,3) cm. De behandeling van 19 patiënten werd als mislukt beschouwd omdat het uiteindelijke BLV meer was dan 1,5 cm (n=14), omdat een tweede operatie noodzakelijk was geweest voor het uiteindelijke resultaat (n=4), of vanwege een combinatie van beide (n=1).

Na analyse van de niet succesvolle behandelingen werd geconcludeerd dat de nauwkeurigheid van de M-SLG niet alleen wordt beperkt door de etiologie van het BLV, door technische vaardigheden en door de nauwkeurigheid waarmee de skeletleeftijd kan worden vastgesteld, maar ook door het patroon van de individuele biologische rijping dat het meest onvoorspelbaar is. Aanbevelingen worden gedaan om teleurstellende resultaten, als gevolg van deze en andere oorzaken, te voorkomen. Deze aanbevelingen hadden tot betere resultaten kunnen leiden bij 7 patiënten.

Physiodese als behandeling voor BLV bij kinderen heeft als voordeel dat het de minst traumatische operatieve procedure is. Omdat de operatie wordt uitgevoerd tijdens de groei, zal het BLV bovendien gemiddeld minder zijn dan bij het kind dat pas aan het einde van de groei wordt geopereerd. Een subtrochantere verkorting aan het einde van de groei heeft deze voordelen niet, maar kan wel zeer nauwkeurig gebeuren. Dit in tegenstelling tot de physiodese, die in bijna een kwart van de patiënten tot een onbevredigend resultaat leidde.

Hoofdstuk 5 beschrijft het onderzoek dat werd uitgevoerd om de M-SLG verder te verbeteren. De gegevens waarop Moseley zijn 'rechte lijn grafiek' baseerde, zijn metingen uit de jaren dertig, veertig en vijftig bij Noord-Amerikaanse kinderen. In de loop der tijd is de bevolking van de geïndustrialiseerde landen echter langer geworden. Onderzocht werd of met het gebruik van recente beenlengtemetingen een rechte lijn grafiek kon worden geconstrueerd, waarmee meer nauwkeurig het moment van physiodese kon worden bepaald.

Met behulp van beenlengtemetingen bij 182 Nederlandse kinderen, verricht in de periode van 1979 tot en met 1994, werden nieuwe groeicurven berekend. Bij jongens en bij meisjes is de gemiddelde lengte van femur en tibia toegenomen, vergeleken met de gegevens die Moseley gebruikte. Met de nieuwe metingen werd een nieuwe rechte lijn grafiek (de 'Rotterdam Straight Line Graph', R-SLG) ontworpen. De waarde van de R-SLG werd bepaald door beenlengte op volwassen leeftijd te vergelijken met de door de R-SLG en M-SLG voorspelde lengte. Deze vergelijking vond plaats in een groep van 34 kinderen waarbij, tot 10 jaar geleden, een physiodese was verricht. De R-SLG gaf een betere voorspelling van de lengte van het niet geopereerde been dan M-SLG bij 22 kinderen en een gelijke voorspelling bij 5 kinderen.

De conclusie was dat de nieuwe R-SLG de uiteindelijke beenlengte nauwkeuriger voorspelt, waardoor het moment waarop een physiodese verricht moet worden nauwkeuriger bepaald kan worden. De R-SLG corrigeert echter niet voor de oorzaken van onnauwkeurigheid die in het vorige hoofdstuk aangegeven werden, alleen voor de consequenties van de langer geworden bevolking en regionale verschillen. De betere voorspellingsmogelijkheden met R-SLG zijn daarmee het gevolg van het gebruik van recente groeigegevens uit de eigen groep patiënten.

List of abbreviations

LLI	Limb length inequality
BLV	Beenlengteverschil
M-SLG	Moseley's Straight Line Graph
R-SLG	Rotterdam Straight Line Graph
PSG	Pelvic sway in gait
PTS	Pelvic tilt in stance

References

Aaron A, Weinstein D, Thickman D, Eilert R. Comparison of orthoroentgenographyand computed tomography in the measurement of limb-length discrepancy. J Bone Joint Surg (Am) 1992; 74: 897-902.
Abbott LC. The operative lengthening of the tibia and fibula. J Bone Joint Surg 1927; 9: 128-52.
Abbott LC, Saunders JBCM. The operative lengthening of tibia and fibula. Ann Surg 1939; 110: 961-91.
Achterman C, Kalamchi A. Congenital deficiency of the fibula. J Bone Joint Surg (Br) 1979; 61: 133-7.
Aitken GT. Amputation as a treatment for certain lower-extremity congenital abnormalities. J Bone Joint Surg (Am) 1959; 41: 1267-85.
Alman BA, Krajbich JI, Hubbard S. Proximal femoral focal deficiency: Results of rotationplasty and syme amputation. J Bone Joint Surg (Am) 1995; 77: 1876-82.
Altongy JF, Harcke HT, Bowen JR. Measurement of leg length inequalities by micro-dose digital radiographs. J Pediatr Orthop 1987; 7: 311-6.
American Medical Association. The musculoskeletal system. In: Guides to the evaluation of permanent impairment. American Medical Association. Chicago 1993: 75.
Amstutz HC, Sakai DN. Equalization of leg length. Clin Orthop 1978; 136: 2-6.
Anderson M, Green WT, Messner MB. Growth and predictions of growth in the lower extremities. J Bone Joint Surg (Am) 1963; 45: 1-14.
Anderson M, Messner MB, Green WT. Distribution of lengths of the normal femur and tibia in children from one to eighteen years of age. J Bone Joint Surg (Am) 1964; 46: 1197-1202.
Anderson WV. Leg-lengthening. J Bone Joint Surg 1952 (Br); 34: 150.
Armstrong PF, Brighton CT. Failure of the rabbit tibial growth plate to respond to the long-term application of a capacitively-coupled electric field. J Orthop Res 1986; 4: 446-51.
Atar D, Grant A, Strongwater A. Percutaneous epiphysiodesis. J Bone Joint Surg (Br) 1991; 73: 173.
Barr JS, Stindfield AJ, Reidy JA. Sympathetic ganglionectomy and limb length in poliomyelitis. J Bone Joint Surg (Am) 1950; 32: 793-802.
Baumgart R, Betz A, Kettler M, Scweiberer, L. Limb Lengthening - External and fully implantable systems. Results of 52 cases. Read at the 20th SICOT world congress, Amsterdam, the Netherlands 1996.
Begg RK, Wytch R, Major RE. Instrumentation used in clinical gait studies: a review. J Med Eng & Tech 1989; 13: 290-5.
Bell JS, Thompson WAL. Modified spot scanography. Am J Roentgenol 1950; 63: 915-6.
Besselaar PP. Beenlengteverschil. Diafysaire verlenging en subtrochantere verkorting. Thesis, Universiteit van Amsterdam, Amsterdam 1988.
Blair VP, Schoenecker PL, Sheridan JJ, Capelli AM. Closed shortening of the femur. J Bone Joint Surg (Am) 1989; 71: 1440-7.
Blair VP, Walker SJ, Sheridan JJ, Schoenecker PL. Epiphysiodesis: A problem of timing. J Pediatr Orthop 1982; 2: 281-4.
Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1(8476): 307-10.
Blount WP. Blade-Plate internal fixation for high femoral ostetomies. J Bone Joint Surg 1943; 25: 319-39.
Blount WP, Clarke GR. Control of bone growth by epiphyseal stapling. J Bone Joint Surg (Am) 1949; 31: 464-77.
Blount WP. A mature look at epiphyseal stapling. Clin Orthop 1971; 77: 158-63.
Bowen JR, Johnson WJ. Percutaneous epiphysiodesis. Clin Orthop 1984; 190: 170-3.
Broughton NS, Olney BW, Menelaus MB. Tibial shortening for leg length discrepancy. J Bone Joint Surg (Br) 1989; 71: 242-5.
Buckler JMH. Skeletal age changes in puberty. Arch Dis Child 1984; 59: 115-9.
Calvé J, Galland M. A new procedure for compensatory shortening of the unaffected femur in case of considerable asymmetry of the lower limbs, fractures of the femur, coxalgia. Amer J Orthop Surg 1918; 16: 211-235.
Cameron BM. A technique for femoral shaft shortening. J Bone Joint Surg (Am) 1957; 39: 1309-13.
Carey RPL. Clinical examination and measurement of limb length inequality. In: The management of limb inequality (Ed. Menelaus MB). Churchill Livingstone, Edinburgh 1991; 4: 50-2.

Carey JPL, de Campo JF, Menelaus MB. Measurement of leg length by computerised tomographic scanography: brief report. J Bone Joint Surg (Br) 1987; 69: 846-7.
Cauchoix J, Morel G. One stage femoral lengthening. Clin Orthop 1978; 136: 66-73.
Chapchal G Zeldenrust J. Experimental research for promoting longitudinal growth of lower extremities by irrigation of growth region of femur and tibia. Acta Orthop Scand 1948: 17: 371-96.
Clarke GR. Unequal leg length: An accurate method of detection and some clinical results. Rheum Phys Med 1972; 11: 385-9.
Codivilla A. On the means of lengthening of in the lower limbs, the muscles and tissues which are shortened through deformity. Am J Orthop Surg 1905; 2: 353-69.
Crilly RG. Longitudinal overgrowth of the chicken radius. Journal of Anatomy 1972; 112: 11-8.
Cummings G, Scholz JP, Barnes K. The effect of imposed leg length difference on pelvic bone symmetry. Spine; 1993: 368-73.
Cundy P, Paterson D, Morris L, Foster B. Skeletal age estimation in leg length discrepancy. J Pediatr Orthop 1988; 8: 513-5.
De Bastiani G, Aldegheri R, Renzi Brivio L, Trivella G. Limb lengthening by callus distraction (callotasis). J Pediatr Orthop 1987; 7: 129-34
Dewaele J, Fabry G. The timing of epiphysiodesis. A comparative study between the use of the method of Anderson and Green and the Moseley chart. Acta Orthopaedica Belgica 1992; 58: 43-7.
Digby KH. The measurement of diaphyseal growth in proximal and distal directions. J Anat Physiol 1916; 50: 187-8.
Eastwood DM, Cole WG. A graphic method for timing the correction of leg-length discrepancy. J Bone Joint (Br) 1995; 77: 743-7.
Eberhart HD, Inman VT Bresler B. The principal elements in human locomotion. In: Human limbs and their substitutes (Eds. Klopsteg PE, Wilson PD). New York: McCraw-Hill Book Company Inc, 1954: 437-71.
Eichler J. Methodologische Fehler bei der Feststellung der Beinlänge und der Beinlängedifferenzen. Orthopäde 1972; 1: 14-20.
Epps CH. Current concepts review. Proximal femoral focal deficiency. J Bone Joint Surg (Am) 1983; 65: 867-70.
Fischer S. Operative Beinverkürzung und Beinverlängerung nach dem Verfahren von Küntscher. Orthopäde 1972; 1: 50-56.
Friberg O. Clinical symptoms and biomechanics of lumbar spine and hip joint in leg length inequality. Spine 1983; 8: 643-51.
Friberg O, Nurminen M, Korhonen K, Soininen E, Manttari T. Accuracy and precision of clinical estimation of leg length inequality and lumbar scoliosis: comparision of clinical and radiological measurements. Int Disabil Studies 1988; 10: 49-53.
Friberg O. Letter to the editor. Spine 1992; 17: 458-9.
Fulp T, Davids JR, Meyer LC, Blackhurst DW. Longitudinal deficiency of the fibula. operative treatment. J Bone Joint Surg (Am) 1996; 78: 674-82.
Giles LGF, Taylor JR. Low-back pain associated with leg length inequality. Spine 1981; 6: 510-21.
Gill GG, Abbott LC. Practical method of predicting the growth of the femur and tibia in the child. Arch Surg 1942; 45: 286-315.
Glorion C, Pouliquen JC, Langlais J, Ceolin JL, Kassis B. Femoral lengthening using the callotasis method: Study of the complications in a series of 70 cases in children and adolescents. J Pediatr Orthop 1996; 16: 161-7.
Gofton JP, Trueman GE. Studies in osteoarthritis of the hip: Part II. Osteoarthritis of the hip and leg-length disparity. Can Med Assoc J 1971; 104: 791-9.
Green WT, Anderson M. Epiphyseal arrest for the correction of discrepancies in length of the lower extremities. J Bone Joint Surg (Am) 1957; 39: 853-72.
Green WT, Wyatt GM, Anderson M. Orthoroentgenography as a method of measuring the bones of the lower extremities. J Bone Joint Surg 1946; 28: 60-5.
Greulich WW, Pyle SI. Radiographic atlas of skeletal development of the hand and wrist. 2th ed. Stanford: Stanford University press, 1959.
Gross RH. Leg length discrepancy: How much is too much? Orthopedics 1978; 1: 307-10.

Grundy PF, Roberts CJ. Does unequal leg length cause back pain? Lancet 1984; 2(8397): 256-8.
Guichet J, Lascombes P. Gradual elongation intramedullary nail for femur (Albizzia). Results of the 52 first cases in 48 patients. Read at the 20th SICOT world congress, Amsterdam, the Netherlands 1996.
Heidensohn P, Hohmann D, Weigert M. Subtrochantere Verkürzungs- und Verlängerungsosteotomie. Orthopäde 1972; 1: 46-9.
Hellinger J, Teschner W. Beinlängeausgleich durch Verkürzungsosteotomie. Beitr Orthop Traumatol 1983; 30: 210-9.
Helms CA, McCarthy S. CT scanograms for measuring leg length discrepancy. Radiology 1984; 151: 802.
Hellsing A-L. Leg length inequality. A prospective study of young men during their military service. Upsala J med Sci 1988; 93: 245-53.
Hickey PM. Teleoroentgeography as an aid in orthopedic measurements. Am J Roentgenol & Rad Therapy, 1924; 11: 232-3.
Hodgen JT, Frantz CH. Arrest of growth of the epiphyses. Arch Surg 1946; 53: 664-74.
Holst A, Thomas W. Die sonographische Beinlängenmessung. Röntgen-Bl 1989; 42: 134-8.
Hootnick D, Boyd NA, Fixsen JA, Lloyd-Roberts GC. The natural history and management of congenital short tibia with dysplasia or absence of the fibula. J Bone Joint Surg (Br) 1977; 59: 267-71.
Horal J. The clinical appearance of low back disorders in the city of Gothenborg. Acta Orthop Scand 1969; suppl 118.
Horton GA, Olney BW. Epiphysiodesis of the lower extremity: Results of the percutaneous technique. J Pediatr Orthop 1996; 16: 180-2.
Høstrup H, Pilgaard S. Epiphyseodesis and epiphyseal stapling on the lower limbs. Acta Orthop Scand 1969; 40: 130-6.
Houghton GR, Rooker GD. The role of the periosteum in the growth of long bones. An experimental study in the rabbit. J Bone Joint Surg (Br) 1979; 61: 218-20.
Howorth MB. Leg-Shortening operation for equalizing leg length. Arch Surg 1942; 44: 543-55.
Huurman WW, Jacobsen FS, Anderson JC, Chu WK. Limb-length discrepancy measured with computerized axial tomographic equipment. J Bone Joint Surg (Am) 1987; 69: 699-705.
Ingelmark BE, Lindström J. Asymmetries of the lower extremities and pelvis and their relations to lumbar scoliosis. Acta Morph Neerl Scand 1963; 5: 221-34.
Ilizarov GA. Clinical application of the tension-stress effect for limb lengthening. Clin Orthop 1990; 250: 8-26.
Janes JM, Musgrove JE. Effect of arteriovenous fistula on the growth of bone. Surg Clin North Am 1950; 30: 1191-1200.
Johansson JE, Barrington TW. Femoral shortening by a step-cut osteotomy for leg length discrepancy in adults. Clin Orthop 1983; 181: 132-6.
Jones D, Barnes J, Lloyd-Roberts GC. Congenital aplasia and dysplasia of the tibia with intact fibula. J Bone Joint Surg (Br) 1978; 60: 31-39.
Judet R. Présentation du distracteur pour allongement des os des membres. Chirurgie 1971; 97: 777-8.
Kaufman KR, Miller LS, Sutherland DH. Gait asymmetry in patients with limb-length inequality. J Pediatr Orthop 1996; 16: 144-150.
Keemink CJ, Hoek van Dijke GA, Snijders CJ. Upgrading of efficiency in the tracking of body markers with video techniques. Med Biol Eng Comput 1991; 29: 70-4.
Kenwright J, Albinana J. Problems encountered in leg shortening. J Bone Joint Surg (Br) 1991; 73: 671-5.
Khoury SC, Silberman FS, Cabrini RL. Stimulation of the longitudinal growth of long bones by periostal stripping. J Bone Joint (Am) 1963; 45: 1679-84.
Kleinberg S. Scoliosis. Baltimore: the Williams & Wilkins company, 1951: 114-5.
Kogutt MS. Computed radigraphic imaging: use in low-dose leg length radiography. AJR 1987; 148: 1205-6.
Kolb G. Marquardt E. Beinlängenausgleich mit orthopädischen Apparaten und Prothesen. Orthopäde 1972; 1: 35-9.
Konermann W, Malländer W, Gruber G, Hettfleisch J, Bettin D, Klein D, Güth V. Die Sonographische Beinlängen- und Beinlängendifferenz messung. Z Orthop 1995; 133: 442-52.

Kristiansen LP, Steen H, Bjerkreim I. Tibial lengthening over an intramedullary nail by callutasis using the Ilizarov external apparatus. Read at the 20th SICOT world congress, Amsterdam, the Netherlands 1996.
Küntscher G. Die geschlossene Verkürzungs-osteotomie. Z Orthopedie 1964; 98: 123-9.
Lampe HIH, Swierstra BA, Diepstraten AFM. Timing of physiodesis in limb length inequality. Acta Orthop Scand 1992; 63: 672-4.
Langenskiöld A. Inhibition and stimulation of growth. Acta Orthop Scand 1957; 26: 308-16.
Lezius A. Der stabile osteoplastische Ersatz großer Knochendefekte der unteren Gliedmaßen. Chirurg 1946; 17/18: 162-8.
Lin C-C, Huang S-C, Liu T-K, Chapman MW. Limb lengthening over an intramedullary nail. An animal study and clinical report. Clin Orthop 1996: 330; 208-16.
Linge B van. Preventie en correctie van beenlengteverschillen. In: Het Medisch Jaar. Utrecht:Bohn, Scheltema & Holkema, 1985: 127-37.
Liotta FJ, Ambrose TA, Eilert RE. Fluoroscopic technique versus Phemister technique for epiphysiodesis. J Pediatr Orthop 1992; 12: 248-51.
Little DG, Nigo L, Aiona MD. Deficiencies of current methods for the timing of epiphysiodesis. J Pediatr Orthop 1996; 16: 173-9.
Lynch MC, Taylor JF. Periostal devision and longitudinal growth in the tibia of the rat. J Bone Joint (Br) 1987; 69: 812-6.
McCaw ST, Bates BT. Biomechanical implications of mild leg length inequality. Br J Sp Med 1991; 25: 10-3.
Menelaus MB. Correction of leg length discrepancy by epiphyseal arrest. J Bone Joint Surg (Br) 1966; 48: 336-9.
Menelaus MB. An attitude to the management of limb inequality. In: The management of limb inequality (Ed. Menelaus MB). Churchill Livingstone. Edinburgh 1991; 1: 1-8.
Merle d'Aubigné R, Dubousset J. Surgical correction of large length discrepancies in the lower extremities of children and adults. J Bone Joint (Am) 1971; 53: 411-30.
Merrill OE. A method for the roentgen measurement of the long bones. Am J Roentgenol 1942; 48: 405-6.
Meyer E, Petersen D. Beinlängenausgleich mit othopädieschutechnischen Maßnahmen. Orthopäde 1972; 1: 21-35.
Millwee RH. Slit scanography. Radiology 1937; 28: 483-6.
Millis MB, Hall JE. Transiliac lengthening of the lower extremity. J Bone Joint Surg (Am) 1979; 61: 1182-94.
Monticelli G, Spinelli R. Distraction epiphysiolysis as a method for limb lengthening. III. Clinical applications. Clin Orthop 1981; 154: 274-85.
Morscher E, Taillard W. Beinlängenunterschiede. Basel: S Karger, 1965: 20-42.
Morscher E. Aetiologie und klinik der Beinlängeunterschiede. Orthopäde 1972a; 1: 1-8.
Morscher E. Die Messung der Beinlängen. Orthopäde 1972b; 9-13.
Mosca V, Moseley CF. Results of limb lengthening using the Wagner device. Orthop Trans 1987; 11: 52-3.
Moseley CF. A straight line graph for leg length discrepancies. J Bone Joint Surg (Am) 1977; 59: 174-8.
Moseley CF. Leg length discrepancy. Orthop Clin North Am 1987; 18: 529-35.
Moseley CF, Bowen JR. Leg Length Discrepancy. In: Dee R, ed. Principals of orthopaedic practice. New York: McGraw-Hill Book Company, 1989; 67: 1186-91.
Naudie D, Hamdy RC, Fassier F, Morin B, Duhaime M. Management of fibular hemimelia. Amputation or limb lengthening. J Bone Joint Surg (Br) 1997; 79: 58-65.
Nichols PJR, Bailey NTJ. The accuracy of measuring leg-length differences. Br Med J 1955; 2: 1247-8.
Oest O, Sieberg HJ. Die Röntgenganzaufname der unteren Extremitäten. Z Orthop 1971; 109: 54-72.
Ogilvie JW, King K. Epiphysiodesis: Two-year results using a new technique. J Pediatr Orthop 1990; 10: 809-11.
Oonpuu S, Gage JR, Davis RB. Three-dimensional lower joint kinetics in normal pediatric gait. J Pediatr Orthop 1991; 11: 341-9.
Oppenheim WL, Namba R. Closed femoral shortening modification using an internal splint. J Pediatr Orthop 1988; 8: 609-12.

Pease CN. Local stimulation of growth of long bones, a preliminary report. J Bone Joint (Am) 1952; 34: 1-24.

Phemister DB. Operative arrestment of longitudinal growth of bones in the treatment of deformities. J Bone Joint Surg 1933; 15: 1-15.

Porat S, Peyser A, Robin GC. Equalization of lower limbs by epiphysiodesis: results of treatment. J Pediatr Orthop 1991; 11: 442-8.

Putti V. The operative lengthening of the femur. JAMA 1921; 77: 934-5.

Reichelt A, Mohtashami M. Erfahrungen mit der temporären Epiphyseodese nach Blount. Orthopäde 1972; 1: 40-5.

Richards V, Strofer R. The stimulation of bone growth by internal heating. Surgery 1959; 46: 84-96.

Roermund PM van. Tibial lengthening by distraction epiphysiolysis. Thesis, Universiteit Utrecht, Utrecht 1994.

Rush WA, Steiner HA. A study of lower extremity length inequality. Am J Roentgenol 1946; 56: 616-23.

Saunders JBdeCM, Inman VT, Eberhart HD. The major determinants in normal and pathological gait. J Bone Joint Surg (Am) 1953; 35: 543-58.

Scott JH. Leg length inequality. In: Postgraduate textbook of clinical orthopaedics (Ed. Harris NH). John Wright & Sons Ltd. Bristol 1983; 282-91.

Shapiro F. Developmental patterns in lower extremity length discrepancies. J Bone Joint Surg (Am) 1982; 64: 639-51.

Siffert RS. Current concepts review: Lower limb-length discrepancy. J Bone Joint Surg (Am) 1987; 69: 1100-6.

Soukka A, Alaranta H, Tallroth K, Heliövaara M. Leg-length inequality in people ofworking age. The association between mild inequality and low-back pain is questionable. Spine 1991; 16: 429-31.

Soukka A, Alaranta H, Tallroth K, Heliövaara M. Authors' reply. Spine 1992; 17: 459-60.

Steindler A. Kinesiology of the human body under normal and pathological conditions. 2th ed. Springfield: Charles C Thomas, 1964: 666-9.

Sutherland DH. Gait disorders in childhood and adolescence. Baltimore: Wililliams & Wilkins, 1984: 1-13.

Taillard W. Die röntgenologischen Methoden zur Messung der langen Röhrenknochen. Z Orthop 1956; 88: 151-8.

Terjesen T, Benum P, Rossvoll1, Svenningsen S, Fløystad Isern AA, Nordbø T. Leg-length discrepancy measured by ultrasonography. Acta Orthop Scand 1991; 62: 121-4.

Thompson TC, Straub LR, Campbell RD. An evaluation of femoral shortening with intramedullary nailing. J Bone Joint Surg (Am) 1954; 36: 43-56.

Thornton L. A method of subtrochanteric limb shortening. J Bone Joint Surg (Am). 1949; 31: 81-6.

Thurston AJ, Harris JD. Normal kinematics of the lumbar spine and pelvis. Spine 1983; 8: 199-205.

Timperlake RW, Bowen JR, Guille JT, Choi IH. Prospective evaluation of fifty-three consecutive percutaneous epiphysiodeses of the distal femur and proximal tibia and fibula. J Pediatr Orthop 1991; 11: 350-7.

Tjernström B, Olerud S, Rehnberg L. Limb lengthening by callus distraction: Complications in 53 cases operated 1980-1991. Acta Orthop Scand 1994; 65: 447-55.

Torode IP. The behaviour of limb inequality in specific disorders. In: The management of limb inequality (Ed. Menelaus MB). Churchill Livingstone. Edinburgh 1991; 3: 37-48.

Trias A, Mueller K, Ray RD. Epiphyseal stapling. Surg Gynecol Obstet 1961; 113: 315- 23.

Vink P, Huson A. Lumbar back muscle activity during walking with a leg length inequality. Acta Morphol Neerl Scand 1987; 25: 261-71.

Wagner H. Operative Beinverlängerung. Chirurg 1971; 42: 260-6.

Wagner H. Technik und Indikation der operativen Verkürzung und Verlängerung von Ober- und Unterschenkel. Orthopäde 1972; 1: 59-74.

Westh RN, Menelaus MB. A simple calculation for the timing of epiphyseal arrest. J Bone Joint Surg (Br) 1981; 63: 117-9.

Wieringen JC van. Secular growth changes. In: Human growth (Eds. Falkner F, Tanner JM), Plenum Press, New York, 1987, Vol.2; 445-73.

White JW. Femoral shortening for equalization of leg length. J Bone Joint Surg 1935; 17: 597-604.

White JW, Stubbins SG. Growth arrest for equalizing leg lengths. JAMA 1944; 126: 1146-9.

White JW, Warner WP. Experiences with metaphyseal growth arrests. South Med J 1938; 31: 411-4.
Whittle MW. Calibration and performance of a 3-dimensional television system for kinematic analysis. J Biomech 1982; 15: 185-96.
Wilde GP, Baker GCW. Circumferential periostal release in the treatment of children with leg-length inequality. J Bone Joint Surg (Br) 1987; 69: 817-21.
Wilson AJ, Ramsby GR. Skeletal measurements using a flying spot digital imaging device. AJR 1987; 149: 339-43.
Winquist RA, Hansen ST, Pearson RE. Closed intramedullary shortening of the femur. Clin Orthop 1978; 136: 54-61.

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Jorianne, voor je bijna eindeloze geduld en steun waardoor ik dit proefschrift kon schrijven.

Curriculum vitae

Harald Ignatius Hubertus Lampe werd op 27 juni 1964 geboren in Rotterdam. In 1983 werd eindexamen Atheneum-B gedaan aan het Aloysiuscollege in Den Haag. De studie geneeskunde werd gevolgd aan de Erasmus Universiteit Rotterdam, waar het artsexamen werd behaald in 1990. Aan diezelfde universiteit volgde daarna een aanstelling op het instituut orthopaedie. In samenwerking met de afdeling Biomedische Natuurkunde en Technologie, werd onder supervisie van prof. dr B. van Linge, prof. dr ir C.J. Snijders en dr. B.A. Swierstra begonnen met het onderzoek zoals beschreven in dit proefschrift. In 1992 en 1993 werd de vooropleiding algemene heelkunde gevolgd in het St. Clara Ziekenhuis (opleider dr. T.I. Yo). In januari 1994 werd begonnen met de opleiding orthopaedie in het Academisch Ziekenhuis Rotterdam, Dijkzigt (opleiders dr. A.F.M. Diepstraten en prof. dr. J.A.N. Verhaar). Stages zijn gevolgd in de Dr. Daniël den Hoed Kliniek (reuma chirurgie, o.l.v. J.R.W. ten Kate), in het Leyenburg Ziekenhuis (algemene orthopaedie, opleider dr. A.J.M. Sauter) en in het Sophia Kinderziekenhuis (kinderorthopaedie, o.l.v. dr. A.F.M. Diepstraten).