The underused hip in ipsilaterally orthotics-dependent children

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Abstract

Background The aim of this investigation is the development of primarily healthy hips in children who have required orthoses/prostheses over the long term due to ipsilateral distally located deformities of the leg. These children show ipsilateral in-toeing gait and Duchenne’s limping followed by a coxa valga antetorta and facultative hip decentration. A practical question is whether these hips are in danger of decompensation. An additional theoretical question is how the external shape and internal architecture changes if a primarily healthy hip is underused.

Methods Ten children with healthy hips who are unilaterally long-term orthotics/prosthetics-dependent agreed to undergo an instrumental gait analysis. The results were analyzed and correlated with clinical findings, a common activity score and planimetric radiographic data.

Results The intra-individual comparison revealed a number of significant changes in the hip of the deformed leg ($p < 0.05$). Clinically, the internal rotation was increased ($15^\circ \pm 4.2^\circ$), while the external rotation was diminished ($13^\circ \pm 1.3^\circ$). Radiologically, the projected caput–collum–diaphyseal angle, the lesser trochanter to articular surface distance and the head–shaft angle were increased by $11.1^\circ \pm 15.4^\circ$, $5.8 \pm 4.2$ mm and $11.9^\circ \pm 0.6^\circ$, respectively. Both the Sharp and acetabular angles were increased, the former by $3.6^\circ \pm 0.6^\circ$ and the latter by $3.2^\circ \pm 0.6^\circ$. Kinetic gait analysis showed increased stride length ($6.8 \pm 3.7$ cm), shortened stance phase ($6.6 \pm 1.6$ %) and reduced forces transmitted to the ground ($92.2 \pm 34.3$ N). The kinematic analysis showed increased hip abduction ($14.0^\circ \pm 8.2^\circ$), while the pelvic obliquity was not significantly changed ($0.01^\circ \pm 0.01^\circ$).

Conclusions Duchenne’s limp and lack of weight-bearing stress are the decisive pathogenic factors of the underused coxa valga and acetabular dysplasia. These changes follow the mechanobiological concept of “function modifies design”, which means function influences external shape and internal architecture of bones and joints. As a practical consequence we recommend that one pelvic radiograph be performed as a precaution at the end of puberty of children with these conditions.

Level of evidence Level II retrospective study.

Keywords Orthotics/prosthetics-dependent children • Diseased hips • Healthy hips • Unloading coxa valga • Instrumental gait analysis • Mechanobiology of the hip

Introduction

A healthy child burdens the lower limb joints daily about 10,000–15,000 times during walking and running [1–4]. Based on clinical experience we have noted that children with primarily healthy hips but who have been orthotics/prosthetics-dependent for many years due to underlying limb length discrepancy (LLD), below-knee amputation and deformities at the knee, leg or foot, develop coxa valga (Fig. 1).
Studies using several biomechanical models of the adult [5–8] and infantile hip [9, 10] have revealed that the forces acting on the hip joint are determined firstly by the external moment due to the body weight and by the counteracting moment of the hip abductors and secondly by the forces acting on the greater trochanter, which are the hip abductors, parts of the knee extensors and the dynamic input of the iliotibial band. These forces may be reduced either by reduction of the external forces, such as while using orthotics or prosthetics, or by shortening the body weight lever arm by Duchenne’s limp [11].

Accordingly, in children who have been orthotics/prosthetics-dependent over the long term, the weight-bearing stress is reduced, which results in the growth plate of the femoral head acquiring a horizontal alignment due to changes in both the direction and amount of muscle forces acting on the hip joint. This in turn results in an increased femoral neck–shaft angle and, consequently, the development of coxa valga.

A theoretical purpose of this study was to clarify, by means of instrumental gait analysis, the gait criteria of children with primarily healthy hips but who suffer from acquired or congenital leg deformities and have become permanently orthotics/prosthetics-dependent, in order to elucidate the possible pathogenic factors that might lead to development of an unloading coxa valga and secondary hip dysplasia. An additional practical purpose was to analyze whether the hips of these children are in danger of decompensation.

Materials and methods

Clinical and demographic data

This study is a retrospective review of all orthotics/prosthetics-dependent children of both genders who suffered unilateral congenital or acquired deformities distal to the knee but with primarily ipsilateral healthy hips between 1996 and 2013. Children younger than 6 years or those with neuromuscular or metabolic diseases were excluded from the study. The contralateral healthy leg was used for comparison. Prior to initiation of the study, approval was granted by the Institutional Review Board and the Research Ethics Committee of University Hospital of Munich.

A total of 12 children (9 males, 3 females) were eligible for study inclusion based on the initial data trawl of the electronic patient database and underwent clinical and radiological hip examination. Among these, two children refused to undergo the instrumental gait analysis. Thus, the final study cohort comprised ten children [8 (80 %) males, 2 females (20 %)].

The deformities were etiologically based on five entities: local neurofibromatosis or tibial pseudoarthrosis (n = 5), severe congenital club foot (n = 1), congenital tibial longitudinal defects (n = 2), congenital fibular longitudinal defects (n = 3) and tibial deformation following Ewing’s sarcoma (n = 1). The mean age of the patients was 12.56 (range 6–18.5) years, and the average unloading period was 10.6 (range 3.25–16.33) years. Seven children had a diseased left leg and three had an affected right side.

The clinical parameters assessed were LLD, which was determined by measuring the distance (in centimeters) of the anterior superior iliac spine to the medial malleolus, goniometric measurement of hip range of motion (ROM), which was determined according to the Neutral-0-Method [12], Duchenne’s limp when the upper part of the body could not be stabilized during gait, resulting in a rocking motion towards the diseased side and UCLA score [13, 14].

Radiological measurements

We analyzed a total of 17 pelvic radiographs. Only technically accepted images were included. The parameters
assessed were: the projected angle between the femoral neck and diaphysis (pCCD) as described by Müller [15] and Hefti [16], the lesser trochanter to articular surface distance (LTA) as described by McCarthy and Weiner [17], the angle between the femoral epiphyseal line and diaphysis (CF) as described by Birkenmaier [18], the Sharp–Ullmann angle [19] and Hilgenreiner’s acetabular (AC) angle [20]. The pCCD and CF angles as well as the LTA distance reflect the growing femoral head morphology, biomechanics and the reactions of the epiphyseal plates to the biomechanical changes. Similarly, both the Sharp–Ullmann and AC angles function as indicators of acetabular morphology and biomechanics.

Instrumental gait analysis

Kinematic and kinetic data as well as the time–distance parameter were acquired and analyzed to describe fundamental gait characteristics of our children. Gait analysis was performed in the three dimensions using the Zebris Treadmill System (FDM-T System with the CMS-HS System; Zebris Medical GmbH, Isny in Allgäu, Germany). The following anatomical landmarks were tracked by applying a marker to the left midfoot, left distal thigh, right midfoot, right distal thigh and the sacrum. The ground plane was then calibrated using a pointer marker, followed by determination of the following anatomical points: sacrum, anterior superior iliac spine (right/left), knee external joint line (right/left), knee internal joint line (right/left), ankle lateral malleolus (right/left), ankle medial malleolus (right/left), lower heel (right/left) and tip of big toe (right/left).

The children were asked to walk on the treadmill at a self-selected speed and the following parameters were collected: time–distance parameter (speed, step length and cadence), phases of the gait cycle, kinetic data (forces transmitted to and pressure on the ground) and kinematic data (pelvic tilt, rotation and obliquity as well as hip flexion/extension, abduction/adduction and internal/external rotation).

Results

Clinical results

The clinical results are presented in Table 1. The mean UCLA score was 5.83 (range 2–10) and the LLD was 8.8...
(range 1–32) cm on the diseased side. On the diseased side the hip internal rotation was significantly increased (15° ± 4.2°) and the external rotation significantly diminished (13° ± 1.3°) (p < 0.05).

Radiological results

The intra-individual comparison between both sides revealed a number of changes in the hip of the deformed leg:

Regarding the changes in the proximal femoral end, the pCCD angle (Fig. 2) was age dependent, with a significantly higher mean value on the diseased side (p < 0.001).

When compared to the normal age- and gender-specific reference values [12], the observed values indicate a tendency to develop coxa valga (148.05° ± 11.04°) on the diseased side. The mean LTA was also significantly increased (p < 0.01) compared with the healthy side (8.07 ± 2.14 and 7.49 ± 1.72 cm, respectively). Additionally, the CF angle (Fig. 2), which indicates the horizontal orientation of the epiphyseal plate, was significantly higher (p < 0.001) on the diseased side (74.86° ± 8.79°) than on the healthy one (62.93° ± 8.19°).

Both the Sharp-Ullmann and AC angles (Fig. 2) were significantly higher (p < 0.01) on the diseased side (45.85° ± 4.97° and 17.29° ± 3.8°, respectively) than on the healthy one (42.29° ± 5.6° and 14.04° ± 4.43°, respectively), indicating shallower acetabulum with increased inclination. Four patients showed slight acetabular dysplasias according to the grading of Tönnis [21].

### Table 2 Comparison of parameters of instrumental gait analysis on both the diseased and healthy sides of the patients

| Parameters of the instrumental gait analysis | Diseased side | Healthy side | t test | p value |
|---------------------------------------------|---------------|--------------|--------|---------|
| Step length (cm)                            | 34.2.99 ± 13.59 | 27.5 ± 9.89 | <0.05 |
| Step time (s)                               | 1.25 ± 0.82   | 0.8 ± 0.3    | <0.05 |
| Gait cycle                                  |               |              |        |         |
| Stance phase (%)                            | 66.77 ± 5.92  | 73.35 ± 7.5  | <0.01 |
| Initial double support (%)                  | 23.02 ± 9.06  | 20.16 ± 7.62 | >0.05 |
| Midstance (%)                               | 25.32 ± 8.51  | 31.96 ± 7.73 | <0.01 |
| Terminal stance (%)                         | 18.6 ± 6.4    | 21.21 ± 6.79 | >0.05 |
| Swing phase (%)                             | 33.22 ± 5.94  | 26.65 ± 7.5  | <0.01 |
| Kinetic gait analysis                       |               |              |        |         |
| Forces transmitted to the ground (N)        | 295.55 ± 124.54 | 387.77 ± 158.78 | <0.05 |
| Pressure on the ground (N/cm²)              | 12.63 ± 2.42  | 22.52 ± 15.59 | <0.05 |
| Kinematic gait analysis                     |               |              |        |         |
| Pelvic obliquity (°)                        | 1.25 ± 10.27  | 1.26 ± 10.28 | −0.7   | >0.05 |
| Hip adduction (°)                           | –             | 11.78 ± 7.47 | –      |         |
| Hip abduction (°)                           | 13.99 ± 8.23  | –            | –      |         |
| Hip internal rotation (°)                   | 13.39 ± 12.59 | 16.21 ± 26.18 | >0.05 |
| Hip external rotation (°)                   | 7.66 ± 13.7   | 6.47 ± 8.5   | >0.05 |

*p < 0.05 indicates significant difference

Values are presented as the mean ± SD

The lower limb length discrepancies were corrected by the orthoses to ≤1 cm.
The results of the gait analysis are shown in Table 2. Analysis of the time–distance parameter of our patient series revealed a mean cadence of 82 ± 25.02 steps/min and a mean speed of 1.39 ± 0.64 km/h. Surprisingly, we observed a significantly longer step length and time \((p < 0.05)\) on the diseased side (34.29 ± 13.59 cm and 1.25 ± 0.82 s, respectively) than on the healthy one (27.5 ± 9.89 cm and 0.8 ± 0.3 s, respectively). We also found a significantly shorter stance phase (66.77 ± 5.92 %) on the diseased side \((p < 0.05)\) than on the healthy one (73.35 ± 7.5 %).

Kinematic gait analysis revealed that compared to the healthy limb, significantly lower forces were transmitted from the diseased limb to the ground (295.55 ± 124.54 N) with significantly lower pressure (12.63 ± 2.42 N/cm²) on the treadmill \((p < 0.05)\) (Fig 3).

FIG. 4 Kinematic gait analysis. Pelvic tilt and position of the leg in the coronal plane of the diseased versus healthy side

Discussion

Discussion of materials and methods

There were a number of limitations to our study. First, the number of cases was very small due to the rarity of these deformities in children. Second, a comparative control group of normal healthy children was not available. However, we used clinical and radiological assessments as well as gait analysis in the review of patients’ data in order to make a precise evaluation of the diseased side versus the other healthy side. In addition, inter-observer bias of pelvic x-ray measurements per examiner was limited by determining the mean of three measurements of each radiological angle or distance. Additionally, to improve the intra- and inter-individual
reliability, two examiners measured the hip ROM. Finally, a calibration of the gait analysis system was performed before each measurement in order to avoid the systemic error. Another limitation was the retrospective character of our radiological measurements. As a consequence of this study design, the geometrical analysis of the hips was based on planimetric radiography and is therefore inferior data obtained from three-dimensional clinical and anthropological studies [22–25]. We present the projected and not the anatomical neck–shaft angle. The reduced external and enlarged internal rotation of all diseased hips, however, suggests that all patients suffered from a coxa valga antetorta.

**Discussion of results**

Our results confirm the development of an underused or “unloading” coxa valga [26] and secondary acetabular dysplasia in unilaterally orthotics/prosthetics-dependent children. The increased radiological measures of the proximal femoral end (pCCD, CF angles and LTA) obtained in this study support the findings of previous (English language) [27, 28] and very early (German) studies [29, 30] where the authors observed a secondary coxa valga in children with reduced weight-bearing due to deformities, leg length differences or amputations. In terms of acetabular morphology, a slight secondary dysplasia (as evidenced by increased Sharp–Ullmann and AC angles) developed, in accordance with findings reported by Mau [31].

Familiarity with the mechanisms and forces that influence a normal infantile hip is needed to understand the natural history of the underused coxa valga. These mechanisms and forces can be explained by the so-called “clustered-pillar-concept” (Fig. 5), which was first published in 1993 [9] and again in 2009 [8] and applied to the normal growth of the infantile hip in 1997 [32]. According to similar concepts in biomechanical engineering [6] and mechanobiological studies [5, 7, 10, 33], and in contrast to the historical models of Koch [34] and Pauwels [11], this concept involves modification of the shape of the coxal femoral end by two resulting forces. The first of these is $R_h$, the hip joint contact force, and the second one is the resulting force $R_t$ which provides compressive stress to the greater trochanter growth plate from a cranio-lateral direction by a vasto-gluteal muscle sling and by the iliotibial tract.

A summary of the kinetic results of our gait analysis includes a longer step length and duration, a shortened stance phase and a lower ground reaction force on the diseased side. The lack of proprioception from the diseased limb and the weight of the prosthesis itself might compel the children to lengthen their step and take a longer time to move their limbs during a prolonged swing phase. Our results are in agreement with those of Pereira [35], who reported that patients with symptomatic leg-length discrepancies showed not only small force peaks during walking but also needed a longer time to reach these peaks.

For our comparison, we assumed that in normal walking the center of body mass is placed over the weight-bearing leg by a lateral displacement in the stance phase [36]. This is achieved by a slight adduction of the leg and a lateral shift of the trunk (“physiologic Duchenne”); simultaneously, there is a pelvic tilt that reduces the vertical displacement of the center of mass (“physiologic Trendelenburg”) and acts as a shock absorber [37]. In contrast, we found that all of our patients abducted the leg and widened the step towards the diseased side. Walking with an abducted leg without any further compensation is not possible, as the center of mass would not be positioned vertically to the weight-bearing foot. Consequently, the
abducted leg compels the patients to use the second possible mechanism of shifting the center of gravity laterally: according to the schematic drawing in Fig. 6b they have to shift the trunk to the affected side.

Another surprising result is that the pelvic tilt of the diseased side does not decrease as normally expected in the stance phase. One possible explanation is that patients use their affected leg more cautiously with longer strides and at less maximum pressure, as seen in our results. This adaptation may reduce the dynamic forces which are one cause of the decreased physiologic pelvic tilt.

According to the computations of Pauwels [11], Duchenne limping shortens the body lever arm and secondarily weakens the abductor muscles. This mechanism unfortunately reduces the growth rate of the greater trochanter growth plate and leads to a coxa valga. Duchenne limping therefore would appear to be the most important pathogenic factor in the development of an underused coxa valga. These bony changes follow the common biomechanical law “Function modifies Design” and confirm the theory of causal histogenesis in that the external shape and internal architecture of the hip joint reflect the loading history of the hip [38].

Based on our radiological data, four patients had only slight acetabular dysplasias according to the grading of Tönnis [21] without any need of operative correction. We conclude that long-term orthotic-dependent patients with an underused coxa valga are likely not in danger of developing severe acetabular dysplasias. As a practical consequence of our study, we recommend discontinuation of periodical X-ray controls of the hips, to be replaced by one pelvic radiograph at the end of puberty as a precautionary measure. If distally orthotic-dependent patients suffer from additional diseases that promote coxa valga and hip decentration, the possibility of orthosis as an additional risk factor for hip migration should be considered.

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Conflict of interest All authors declare that they have no conflict of interest.

Compliance with ethical standards This study was approved by the University Hospital Human Research Ethics Committee (REC487-13). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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References

1. Tudor-Locke C, Craig CL, Beets MW et al (2011) How many steps/day are enough? For children and adolescents. Int J Behav Nutr Phys Act 8:78
2. Duncan JS, Schofield G, Duncan EK (2007) Step count recommendations for children based on body fat. Prev Med 44:42–44
3. Laurson KR, Eisenmann JC, Welk GJ et al (2008) Evaluation of youth pedometer-determined physical activity guidelines using receiver operator characteristic curves. Prev Med 46:419–424
4. Dollman J, Olds TS, Esterman A et al (2010) Pedometer step guidelines in relation to weight status among 5- to 16-year-old Australians. Pediatr Exerc Sci 22:288–300
5. Taylor ME, Tanner KE, Freeman MA et al (1996) Stress and strain distribution within the intact femur: compression or bending? Med Eng Phys 18:122–131
6. Fetto J, Leali A, Moroz A (2002) Evolution of the Koch model of the biomechanics of the hip: clinical perspective. J Orthop Sci 7:724–730
7. Rudman KE, Aspden RM, Meakin JR (2006) Compression or tension? The stress distribution in femur. Biomed Eng Online 5:12
8. Skuban TP, Vogel T, Baur-Melnik A et al (2009) Function-oriented structural analysis of the proximal human femur. Cells Tissues Organs 190:247–255
9. Heimkes B, Posel P, Plitz W et al (1993) Forces acting on the juvenile hip joint in the one-legged stance. J Pediatr Orthop 13:431–436
10. Shenefelt SJ, Carter DR (2004) Mechanobiological predictions of femoral anteversion in cerebral palsy. Ann Biomed Eng 32:297–305
11. Pauwels F (1976) Biomechanics of the normal and diseased hip: Theoretical foundation, technique and results of treatment; an atlas. Springer, Berlin
12. Ryf C, Weymann A (1999) Range of motion: AO Neutral-0 Method: measurement and documentation. Thieme, Stuttgart
13. Naal FD, Impellizzeri FM, Leunig M (2009) Which is the best activity rating scale for patients undergoing total joint arthroplasty? Clin Orthop Relat Res 467:958–965
14. Sechrest VF, Kyle RF, Marek DJ et al (2007) Activity level in young patients with primary total hip arthroplasty: a 5-year minimum follow-up. J Arthroplasty 22:39–47
15. Müller ME (1957) Roentgen diagnosis of mechanical hip joint relationships. Radiol Clin 26:344–354
16. Hefti F (2000) Deviations in the axes of the lower extremities. Orthopäde 29:814–820
17. McCarthy JJ, Weiner DS (2008) Greater trochanteric epiphysiodesis. Int Orthop 32:531–534
18. Birkenmaier C, Jorysz G, Jansson V et al (2010) Normal development of the hip: a geometrical analysis based on planimetric radiography. J Pediatr Orthop B 19:1–8
19. Ullmann K (1939) Zur Frage der röntgenologischen Beurteilung des knöchernen Pfannendaches mit weiteren Ergebnissen der Röntgenstammbaumforschung. Verh Dtsch Orthop Ges, 33. Kongr 1938. Z Orthop 69:268–271
20. Hilgenreiner H (1925) Early diagnosis and early treatment of congenital dislocation of the hip. Med Klin 21:1385–1388
21. Tönnis D, Legal H, Graf R (1987) Congenital dysplasia and dislocation of the hip in children and adults, vol 101. Springer, Berlin
22. Robin J, Graham HK, Selber P et al (2008) Proximal femoral geometry in cerebral palsy: a population-based cross-sectional study. J Bone Joint Surg Br 90:1372–1379
23. Tardieu C (2010) Development of the human hind limb and its importance for the evolution of bipedalism. Evol Anthropol 19:174–186
24. Bonneau N, Baylac M, Gagey O et al (2014) Functional integrative analysis of the human joint: the three-dimensional orientation of the acetabulum and its relation of the femoral neck. J Hum Evol 69:55–69
25. Carriero A, Zavatsky A, Stebbins J et al (2014) Influence of altered gait patterns on the hip joint contact forces. Comput Methods Biomech Biomed Eng 17:352–359
26. Schröter J, Güth V, Overbeck M et al (1999) The Entlastungs- Gang. A hip unloading gait as a new conservative therapy for hip pain in the adult. Gait Posture 9:151–157
27. Brookes M, Wardle EN (1962) Muscle action and the shape of the femur. J Bone Joint Surg Br 44:398–411
28. Siffert RS (1981) Patterns of deformity of the developing hip. Clin Orthop Relat Res 160:14–29
29. Lindemann K (1930) Das Wachstum des Schenkelhalses bei der sogenannten Entlastungs-Coxa valga. Langenbeck’s Arch Surg 228:249–260
30. Simons B (1933) Untersuchungen zur Entstehung der Coxa valga, insbesondere der Entlastungs- und Adduktoren-Coxa-valga. Arch Chir 32:32
31. Mau H (1988) Secondary flattening of the acetabular roof in children. Z Orthop Ihre Grenzgeb 126:377–386
32. Heimkes B, Posel P, Plitz W et al (1997) Age-related force distribution at the proximal end of the femur in normally growing children. Z Orthop Ihre Grenzgeb 135:17–23
33. Birdbaum K, Prescher A, Niethard FU (2010) Hip centralizing forces of the iliotibial tract within various femoral neck angles. J Pediatr Orthop B 19:140–149
34. Koch JC (1917) The laws of bone architecture. Am J Anat 21:177–298
35. Pereira CS, de Andrade MS, Sacco IN, et al. (2014) Vertical ground reaction force differences in runners with Leg Length Discrepancy. In: ISB XXth Congress—ASB 29th Annual Meeting. Cleveland, Ohio; 2005: 786. [The American Society of Biomechanics Website]. Available at: http://www.asbweb.org/conferences/2005/pdf/0786.pdf. Accessed 29 July 2014
36. Inman VT, Ralston HJ, Selber P et al (2008) Proximal femoral geometry in cerebral palsy: a population-based cross-sectional study. J Bone Joint Surg Br 90:1372–1379
37. Perry J (1992) Gait analysis. Slack, New York
38. Carter DR, Beaupre BS (2007) Skeletal function and form: mechanobiology of skeletal development, aging, and regeneration. Cambridge University Press, Cambridge