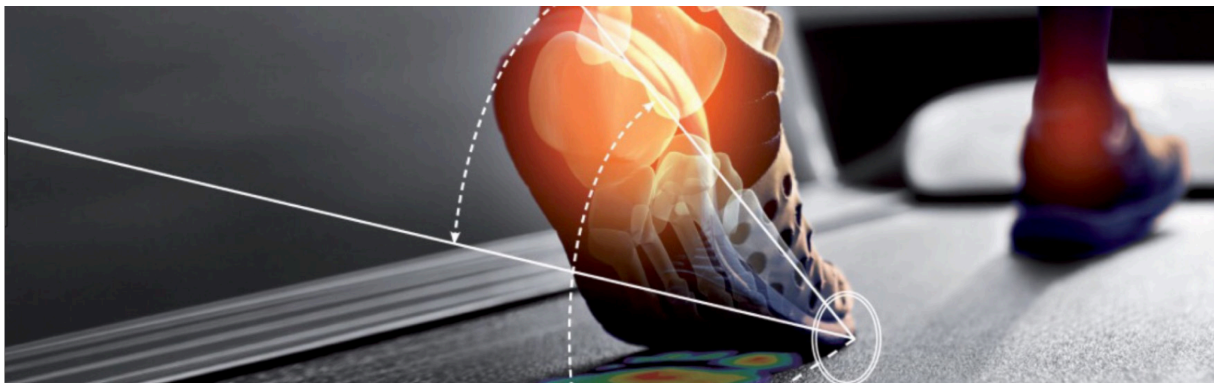


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Spatiotemporal gait analysis and functional outcome after surgical treatment of calcaneal fractures in children



Laurène Niederhauser¹, Dr.Nicolas Lutz², Dre.Aline Bregou³

¹Medical student, University of Lausanne, Switzerland

² Tutor/ Senior surgeon at the children hospital of Lausanne, Switzerland

³Co-tutor/ Senior surgeon of the pediatric unit for orthopedic surgery and traumatology (UPCOT), at the children hospital of Lausanne, Switzerland

Expert: Dr. Jean-Marc Joseph, associate surgeon from the pediatric surgery sector-CHUV

Picture 1: <https://www.mysportspodiatrist.com.au/digital-gait-analysis>

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List of abbreviations and symbols:

AMO	Ablation of osteosynthesis material
AOFAS	American orthopaedic foot & ankle society
CHUV	Centre hospitalier universitaire vaudois
CT	Scanner
DIACF	Displaced intraarticular calcaneal fractures
EQ-5D-Y	EuroQol, 5 dimensions, adapted version for children (quality of live questionnaire)
HEL	Hôpital de l'enfance de Lausanne
LCP (plate)	Locking compression plate
LOWESS	Locally Weighted Scatterplot Smoothing
ORIF	Open reduction internal fixation
P-value	Probability value
QoL	Quality of life
RX	Plain radiography (X-rays)
SD	Standard deviation
UPCOT	Unité pédiatrique de chirurgie orthopédique et traumatologique
VAS	Visual analogue score

0. Abstract:

0.1) Background: The purpose of this study was to evaluate the functional and clinical outcome in children having undergone an open reduction with internal fixation (ORIF), for a displaced intraarticular calcaneal fracture, as well as to analyze their gait characteristics with a spatiotemporal gait analysis and compare the results obtained with a control group.

0.2) Methods: All children, aged between 0-18 years old, operated from an intraarticular displaced calcaneal fracture between 2007-2017 in Lausanne and with informed consent were reviewed. We analyzed their medical files and radiographies, they filled in questionnaires about their quality of life (EQ-5D-Y) and about the functional outcome of the surgery (AOFAS ankle-hindfoot), they underwent a clinical exam of both, ankles and feet, and a spatiotemporal gait analysis using the Gait up system, Physilog®. Every score of the questionnaires and parameter of the gait analysis, like the stride length, the stance, the swing, the loading,... were then compared to the control's data.

0.3) Results: We reviewed six patients operated for an intraarticular displaced calcaneal fracture and fifteen control cases. None of our six patients was suffering obvious walking impairments nor was strictly restrained in his daily life activities. However, some statistically significant discrepancies were pointed out in walking parameters compare with the control group. Our patients were globally older ($p<0.0592$) and taller ($p<0.0436$) than the controls. This has been playing a distinction in stride length ($p<0.001$) since taller people take physiologically longer steps. Patients having undergone a surgery for a calcaneal fracture were recorded with a faster maximal swing speed ($p<0.029$) and a smaller minimal toe clearance ($p<0.037$). The difference in 3D path length ($p<0.0001$) in between the controls and our patients was also statistically significant.

0.4) Discussion: The maximal swing speed and the minimal toe clearance, both having an impact on the probability of tripping, were modified in operated patients, increasing their risk of falling; this, though, was not observed during our study. The 3D path length expresses the length of a step in terms of swing width and stride length; it represents the circumduction. Its value was also significantly different in between the controls and our patients, meaning that operated patients do have a distinct manner of taking steps since the foot movement after the surgery is modified due to stiffness in the hindfoot and the decrease of eversion. Compared to the controls, our patients statistically had a longer stride length, a smaller clearance and seemed to have a restricted swing width.

0.5) Conclusion: Even if there is no subjective activity limitation, we could highlight differences in term of subtalar mobility and correlate them with modifications in some gait parameters within the fracture group. These limitations are potential indicators for developing overload of adjacent articulation and subsequent early arthritis. Therefore, we think that the restoration of the calcaneum anatomy with an anatomic reduction and realignment of the posterior facet of the subtalar joint is a relevant point for an efficacious recovery and in order to minimize later gait disbalance or disabilities, thus offering the injured child the best future in terms of gait motion and quality of life. Finally, the spatiotemporal gait analysis is useful to assess walking parameters and is a great means of evaluation as well as a good follow-up tool.

0.6) Publication: Peer reviewed journal

0.7) Key Words: Calcaneal fracture, children, ORIF, gait analysis

1. Introduction:

First of all, it is probably necessary to define which patients we took into account when using the word children. In this study, the term children included every young people aged between 0-18 years-old. It is true, that in most cases the calcaneum is mature already before, but we decided to consider patient until 18 years old as a convention.

1.1 Anatomy of the calcaneum:^{1,2,36} + Appendix 1

The calcaneum is a specially shaped bone which has a role of lever arm powered by the gastrocnemius and plays a role in weight bearing (until seven times the body mass²) and allows smooth movements of the foot and its adaptation to every surface.

It is made of three cartilaginous facets and six surfaces. The calcaneum is the largest talar bone and is in contact with: the astragal (talus), the cuboid and the fibula, offering a complex articular surfaces' network. It can develop itself around two ossification's centers appearing one after the other and reaches its mature shape at the age of 13-16 years old¹⁷.

The Achilles' tendon is attached to the calcaneum, more precisely on the dorsal posterior surface of the tuberosity.

1.2 Physiological walk: Appendix 2

The walk is the natural means of locomotion of every human and requests the action of many muscles, a good joint's congruency, resistance of ligaments, thus offering a global flexibility and ensuring the stability and propulsion of the foot. A gait cycle is measured from heel-strike to heel-strike so from the first contact of the foot on the ground to the next contact with the floor of the same foot. A gait cycle is composed of two phases:

- a) A stance phase which represents the time when the foot touches the ground and constitutes about 60% of the total gait cycle. During the stance phase, the leg has a role of support and stability.
- b) The swing phase corresponds to the period of time during which the foot is in the air. It lasts about 40% of a normal gait cycle. This phase enables the limb to move forward.

Each phase can be subdivided into smaller units like the loading response, mid-stance, terminal stance, pre-swing, initial swing (toe off), mid-swing, terminal swing.

The subtalar joint, consisting in two contact points between the calcaneum and the talus (respectively named the anterior talocalcaneal articulation and the posterior talocalcaneal articulation) and separated with the sinus tarsi, is often put under great pressure during a gait cycle. The subtalar joint is very complex and needs to be intact in order to offer the best congruency and to fulfill his roles by allowing small smooth sliding movements, de-multiplying the constraints applied to the foot and ensuring the flexibility of the ankle.

Gait analysis are becoming more frequent nowadays and mostly in orthopedy and neurology because we realized all the useful information it brings us and its considerable capacities to enable us to understand some pathologies or putting more precise and defined diagnoses on walking disorders. Thus, helping the surgeon in the decision making concerning the treatment. A gait analysis is also a good tool for therapeutic follow-ups.

The relevant parameters assessed during a spatiotemporal gait analysis are^{3,4}:

-in general, the speed (s), the variability (%), the asymmetry (%), the cadence (step/min), the gait cycle time (s), the stride length (m)

-temporally, the stance (% of cycle duration), loading (% of stance), foot-flat (% of stance), push-off (% of stance), the swing (% of gait cycle), the double support (% of cycle duration),

-spatially, the peak swing speed (°/s), the strike angle (°), the lift-off angle (°), swing width(m).

1.3 Biomechanics of the foot:

Every mobilization of the subtalar joint results in movements in the three planes of motion and cannot be individualized. The eversion of the foot for example, is an association of pronation, dorsal flexion and abduction. The inversion, on the opposite, is created by a combination of supination, plantar flexion and adduction.

The subtalar joint works in coordination with the ankle and the medio tarsal articulation and fore foot. But the inversion and eversion are mostly realized thanks to the subtalar joint, which is protected and reinforced by ligaments and muscles.

During gait, the subtalar joint has to switch from a flexible structure allowing the adaptation of the foot to every ground surface to a stiff structure necessary to provide a lever arm when the heel is lifting up.

The stability is at its best when the subtalar joint is in neutral position, so when the person is standing in an upright position.

Movement of the subtalar joint during a normal gait starts with a slight inversion of the calcaneum when the heel touches the ground. After that, as soon as the subtalar joint is put under weight, a sudden eversion occurs. The eversion offers, due to an unlocking effect, smoothness to the fore foot and capacity to adapt to the ground surface. Gradually, as the heel is rising off the floor, an inversion of the calcaneum occurs and will reach its maximum when toes start to leave the ground.

All these fluid movements of the foot and capacity of switching from smoothness to rigidity, depending on the phase of the gait, are regulated mostly by the subtalar joint.

1.4 Calcaneal fractures in children and treatment:

Intraarticular calcaneal fractures are rare in children^{1,12}. Therefore, little has been published on these fractures during the pediatric ages⁸. The smaller number of cases in the young population, compare to the adult one, might come from the bone properties in children, its elasticity, density and strength and the lower body weight of the individuals¹³.

Clinical manifestations of a calcaneal fracture can be complex to detect especially in children, in whom symptoms are often unspecific and can delay the diagnostic⁸.

A fracture is to be suspected when the child is having trouble in walking or is having an ongoing limp⁴³. An extended swelling is also to notice most of the time and must be carefully observed and monitored in order to avoid a compartment syndrome³⁶.

Actually, it looks like these fractures are a little bit more frequent¹⁶ because of the new recommendations in terms of radiographies when looking for a fracture of the calcaneus^{9,14} and because nowadays there exists more extreme sports providing more risks for such fractures, knowing that most of them are due to high velocity injuries or high height falls^{2,31,36}.

The Böhler's angle, is an important angle measurable on lateral radiographies and helps with the decision making regarding the fracture management and the reconstruction of the anatomy as well as the realignment of the calcaneal fracture^{18,20,54}.

In these days, there is controversy regarding the best treatment method^{10,12,13,15,21,26,29,31}. For adults with intraarticular fractures, studies state that the best treatment is the surgical one, which consists in an open reduction followed by an internal fixation (ORIF). Even if, studies about children's calcaneal fractures are much rarer, they recommend a conservative treatment for extra-articular and non-displaced intraarticular fractures and a surgical intervention for the displaced intraarticular calcaneal fractures³⁶. Indeed, the surgical treatment of a displaced intraarticular fractures can reduce the sequelae that could have been caused by a conservative treatment in such case²⁹. Some authors, though, are still reluctant to the use of a surgery even in the child displaced intraarticular fracture and no reliable study can prove the real benefit of the surgery^{8,34,41}. Nonetheless, the articles speaking about the reluctance of the surgical treatment for intraarticular displaced calcaneal fractures are not really scientifically robust and they do not describe the conservative treatment used nor the long-term outcome. Thus, we found more reliable to apply the same guidelines to the children than those from adults in order to

avoid early arthrosis for example. Therefore, the gold standard for such complex fractures is the surgical treatment even in children.

Nowadays, some studies also focus themselves on the possibility of using different surgical techniques⁶⁹, like a minimal invasive approach (minimal invasive sinus tarsi approach for open reduction and internal fixation) instead of the common ORIF done by an extended lateral approach, in order to reduce complications like infection^{38,39} and wound healing problems^{24,27,28,30,33,68}.

1.5 Goals of the study:

Studies about calcaneal fractures in children are limited in terms of number as well as in terms of quality; the follow-up period is often too short and the number of cases too small. Until today, no report concerning spatiotemporal gait parameters following ORIF for intraarticular fractures in children has been reported. Thus, in this research, every operated patient underwent a spatiotemporal gait analysis by wearing the Physilog®'s foot inertial sensors (Gait Up Ltd., Lausanne, CH) and the results were then compared with a control group.

Since we are aware that these children should be given the best treatment in order to avoid later consequences on the walk, on functional movements of the affected articulation and on their quality of life², this thesis is focusing on evaluating the outcome of the ORIF in children with displaced intraarticular fractures³⁴ and the consequences of the intraarticular fractures on the biomechanical parameters and function of the foot.

2 Methodology:

My co-tutor (Dre. Bregou) and I decided to write a study about calcaneal fractures in children knowing that the literature on this topic is poor. Moreover, we wanted to realize a spatiotemporal gait analysis in order to concretely demonstrate facts about the walk in operated kids compared to control cases and to analyze more deeply the outcome of the surgery (ORIF). This would be, to our knowledge, the first article covering both aspects: calcaneal fractures in children and gait analysis. Our researches on different databases like Pubmed, Google scholar, Cochrane using the keywords: children calcaneal fractures, gait analysis, ORIF,... confirmed that evidence based literature on intraarticular displaced calcaneal fractures in children is very limited since these complex fractures are rare in this age group and almost none of them are thorough analysis. Other sources were used to enrich the bibliographic part of the study, especially websites like Orthobullets, Gait Up, aofoundation, HUG (livret des internes) or even books, mainly the Rockwood and Wilkins' Fractures in Children.

The literature was mainly used to appreciate what was already known about calcaneal fractures in children and to discriminate all aspects that have not been studied before. Articles were also then used as references to compare and discuss our results.

2.1 Subjects and design of the study:

See appendix 3 to appreciate the methodological process.

The CHUV was requisitioned for providing a list of patients who underwent a surgery for a calcaneal fracture at least 12 months ahead and who were aged between 0-18 years old at the time of the surgery. This study is therefore retrospective.

In order to fill the selection criteria, the children also had to have been operated in Lausanne and have no walking impairment neither due to neurological nor due to metabolic or constitutional bone diseases. No concomitant foot's fractures must be present. And they must have given their consent stating that they were volunteering to take part in the study.

When selecting the listed patients filling all these criteria, we had a total of 10 participants. It was impossible to contact one of the patients because this person had changed his living address and mobile phone number.

Another patient is residing in a foster and was living at the moment an emotionally hard time of his life, so its caretakers advised us to come back to him later in the year.

One theoretically eligible participant is living in Luxembourg and had no time to come over for a consultation in Lausanne. However, we contacted him and he allowed us to use the information we had about him and to analyze his radiographies and file.

In the 7 remaining attendees, one underwent the ORIF surgery in October 2017, but we decided to include him in the study, even if at the case selection time, he was not filling the criterion stating that the surgery must have taken place at least 12 months ahead, knowing that the master thesis had to be written for the end of the year 2018. A participant had had more than just an ORIF as surgical treatment since he experienced an open calcaneal fracture, for this reason we decided to exclude him from the study in order to evaluate more precisely the outcome of the ORIF as being the gold standard treatment method for intraarticular closed displaced calcaneal fractures.

2.2 Hypothesis:

The null hypothesis was, that there is no difference in spatiotemporal gait parameters between the children who have undergone an ORIF of calcaneal fracture and the control group.

2.3 Collected Data

2.3.1 Anthropometrics' data:

Body weight was measured using a digital scale, to the nearest 0.1kg and height was measured bare feet with a stadiometer to the nearest 0,1cm.

BMI was then calculated with the common formula: $\text{weight (kg)} / \text{height (in m)}^2$

The foot size was measured from the sketch of the foot on a white paper. And the shoe size was directly measured from the sole of the shoe.



Picture 2: www.gaitup.com

2.3.2 Spatiotemporal gait analysis' data:

The material used for the gait analysis was the Physilog® inertial sensor system, created by Gait up in Lausanne, which can break down every step procuring us information such as angles, speed, position, symmetry, variability, ... The wearables captors are easily fixed on each shoe thanks to a Velcro strap, after what all the recorded values are transferred to the computer on a dedicated application.

The data collected were, globally: the speed (m/s), the variability (%), the asymmetry (%), the cadence (step/min), the gait cycle time (s) and the stride length (m). For the temporal aspect of the gait analysis, we were interested in measuring: the stance (% of cycle duration), loading (% of stance), foot-flat (% of stance), push-off (% of stance), the swing (% of gait cycle), the double support (% of cycle duration). The spatial dimension will be attested using: peak angular velocity during swing (also called peak swing speed) (°/s), strike angle (°) and lift-off angle (°), swing width(m)^{3,4}. The minimal toe clearance is the most relevant clearance value since it expresses the minimum height of toes during the swing phase and could be responsible for increasing the risk of tripping.

2.4 Consultation process:

Each patient's medical record was analyzed in details and the inclusion/ exclusion criteria were reviewed enabling us to screen the susceptible partakers in the study.

The thus selected patients were sent a letter stating the purpose of the research and asking for their participation. The potential participants received a phone call a few days later to see if they agree to be volunteering and in order to answer any possible remaining question about the study.

A medical consultation at the HEL (Hôpital de l'enfance) was scheduled with every positive responder.

During the consultation, every patient had to fill in questionnaires (the EQ-5D-Y to evaluate their quality of life) and (the AOFAS hind foot to score the functional outcome). The American Orthopaedic Foot and Ankle society (AOFAS) Ankle-Hindfoot scoring system has the advantage, even it is not specific to the calcaneum, to evaluate equally objective and subjective criteria and is a reference in many studies about ankle and foot surgeries^{16,21}. The AOFAS score obtained were graded,

very good >90 points, good 80-89 points, acceptable 70-79 points and bad <69 points, according to the Kitaoka classification, which is said to be the most appropriate one⁵⁷.

Volunteers had to answer questions concerning possible restriction in movement or pain, discomfort during daily activities and pastime activities. The scar sensibility was also an inquiry. Date of removal of osteosynthesis' material, trauma history and the recovery process were retrieved from their medical file.

The clinical examination consisted of passive and active movement of the ankle, in order to evaluate the range of motion. Mobility, stability and alignment of the foot were assessed.

In order to picture any enlargement or deformity of the foot (hind-foot more particularly), feet prints were drawn on white papers, the patient standing bare feet on the sheet.

After that, they underwent the gait analysis as described above. The gait analysis was divided into two parts, the first consisted in walking back and forth three times on a straight distance, a total distance of approximately 200m was covered by each participant at a self-selected pace. Walking a total distance of approximately 130m on a turning trajectory, represented the second part of the task, so that we could measure different parameters of both feet while walking straight but also while turning. The Physilog® data were then saved on a computer for later analysis.

The same procedure was repeated with healthy patients. These control cases selected had about the same age than our cases and had no family's relationship with doctors working at the HEL or CHUV. They were rewarded with a FNAC voucher for their participation.

2.5 Radiographies' analysis:

The radiographies of each patient were tracked down and analyzed in detail. Böhler's angles were measured when possible before and after the surgery. The consolidation of the bone was described, and the quality and general result of the reduction were noticed. Fractures were radiologically classified by the Sanders classification for the CTs (scanners) and X-rays (standard radiographies) were distinguished using the Essex-Lopresti classification which is useful to separate the joint depression and tongue-type fracture.

The subtalar joint congruency was also observed.

All the results were then analyzed and compared between the two groups (operated children and control cases) as well as within the same group.

2.6 Data processing and storage:

Once all the values were obtained, they were entered in a table previously created on purpose.

This table restating all the measures taken and all the information found in the patients' file, was a good way to see the contrasts and similarities between different criteria and allowed the understanding and the establishment of links between two or more values.

All data will be encoded with a specific neutral number in order to respect the confidentiality of every person and meet the protection recommendations.

At the end of the study, all data anonymized will be conserved under Dre. Bregou's responsibility in a locked place in her office for 10 years.

This project was approved and validate by the swissethics instutionnal review board and fulfills the lawful requirements of the LRH (Loi fédérale relative à la recherche sur l'être humain) and the ORH (Ordonnance relative à la recherche sur l'être humain).

2.7 Statistical Analysis

All our results are presented the same way: calculating the mean value, the standard deviation (SD) and the probability-value (p-value).

The tables were prepared in advance and completed once every gait analysis was done. Articles 4 and 5 were used as references in selecting the most relevant criteria to be then analyzed and discussed.

A statistician helped us analyzing in detail our results and confronting data between them. Results are represented into box plots. He used non-parametric two-sample Wilcoxon rank sum (Mann Withney)

test. Due to the low number of cases, he carried out, in a second time, a regression analysis using a LOWESS approach (locally weighted scatterplot smoothing) to optimize the statistical power for the gait analysis results. Both analysis' techniques gave us p-values.

3 Results:

Results are partly showed in appendices 4,5 and 6 and are interpreted in the discussion's paragraph. Spatiotemporal gait analysis data obtained are not strong in terms of number of participants and are not sufficient to draw conclusions but in terms of gait cycles' data, we collected way enough of them in order to be significant enough and deduce tendencies.

4 Discussion :

4.1 Epidemiology:

We found in literature and in our study as well, that calcaneal fractures affect more boys than girls, probably because boys are more active at this age and try all kind of extreme sports. The adolescence, being a period during which teenagers want to discover the world and show everyone their capacities, appears to be the ideal time in youth for such high-velocity injuries.

Indeed, most fractures in our case series happened at a mean age of 13,14 years old (range: 11-15) which coincide with the entrance in the adolescence phase.

Previous studies have shown that the principal causes responsible for calcaneal fractures are high height falls, ski accidents, vehicle-associated accidents. When analyzing the causes of trauma of our patients, we confirm the literature by identifying four ski accidents, three falls/jumps from height. An interesting demographical aspect to notice, on behalf of the mechanism of injury, is that these uncommon fractures affect two kinds of people, the sportive people who are doing extreme sports, moreover ski. And the less educated ones who, for example, jump from a wall trying to escape from the police after a theft and desperate kids trying to suicide by jumping outside the window.

4.2 Treatment:

As stated in the introduction, there is still a lot of controversy concerning the best treatment method for calcaneal fractures^{10,12,13,15,21,26,29,31}. This ambivalent debate is particularly questionable in children, since many factors like radiographies, growth, bone proprieties, and their absence of convention make it even more difficult. It is surely challenging to offer every child the best treatment ensuring no pain, total recovery, full range of motion, no gait disabilities, no growth restriction and thus until adulthood. Furthermore, literature about calcaneal fractures in pediatric is poor.

Most of the time, these fractures produce a major ankle's edema due to the surroundings damaged caused by the injury. During the first days following the trauma, the surgery is often not possible due to the poor local state of the wound, soft tissues, ... Thus, a functional treatment, including bed rest, elevation of the leg with application of cold to diminish the local swelling and pain relievers, is firstly recommended.

Once suitable conditions are recovered, a long-term treatment can be applied. It seems like today's most recommended technique is the ORIF. Anyway, at the CHUV, the surgery suggested for a displaced intraarticular calcaneal fracture is the ORIF, meaning Open Reduction Internal Fixation^{32,44}. The ORIF is a safe operative procedure, even if like every surgery, it has some risks. The main risk being the infection that can develop along the scar, either directly after the surgery or years after it. Bleeding might also be a possible complication.

During this specific surgery, the operator avoids as much as possible the precious parts forming the joints in order not to cause stiffness or weakness of these structures in the future. He must also be careful not to damage the nerves, blood vessels, ligaments, muscles and bones placed in the surroundings of the fracture. The solution to this is the common approach of the ORIF, named the L-incision approach³⁶ which consists in an L-shaped incision along the external malleolus providing thus to the surgeon, a wide unobstructed view on the lateral face of the calcaneum, without cutaneous

tension and avoiding the precious anatomical parts. However, this extended dissection has the inconvenient to have a high potentiality for later infection^{38,39}. Therefore, some surgeons are trying to use new⁶⁹, less invasive surgical approach in order to diminish later complications^{24,27,28,30,33,68}.

Once the skin is opened, the following part of the surgery consists in reducing the fracture using a

bone elevator with the goal of reestablishing a normal heel height and width. This step consisting in the restoration of the articular surface of the subtalar joint is the most crucial for a successful outcome^{20,36,40}.

The multiple fragments are then temporarily held in place with Kirschner's wires (at least two). After that, a specific calcaneal plate, most often a locking compression plate (LCP plate), is fixed with screws in order to put together every part of the fractured bone and help it heal and consolidate. The Kirschner's wires, once the plate has been fixed, can be removed and finally, the wound, in order to avoid any dehiscence, is closed using a double-layered closure technique^{65,66}.

The major benefit of an efficacious ORIF is the possibility to return to daily activities after the rehab period and to practice again sports. In general, the surgery enables a good congruency of the subtalar joint allowing an adapted footprint on every surface and reducing articular pain. The ORIF is the most valuable treatment and provides the best possible outcome for displaced intraarticular fractures. In our study, every patient underwent an ORIF and none of them have nowadays shoe-fitting problems.

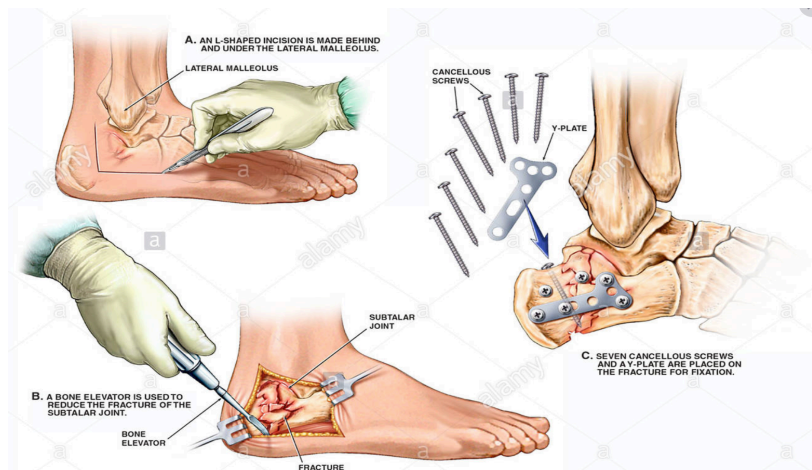
Osteosynthesis material had already been removed in all our patients. The average time after which the AMO took place was 402.86 days (range: 301-514 days) corresponding to 13.26 months, so a little bit more than a year.

The question about the necessity of an AMO is still relevant in these days and not only concerning the calcaneum. There is no algorithm concerning the time or any requirement to remove the osteosynthesis material. Criteria like infections, mechanical impairments, pseudoarthrosis are good reasons for the removal of the implanted material but otherwise, the AMO should not be a routine procedure. However, in pediatric cases the AMO could be strongly advised in order not to impair with the harmonious growth of the child, since depending on where the material is implanted, the epiphyseal growth plate can be damaged, disturbing thus the expansion of the child^{58,17}.

4.3 Post-operative follow-up:

Strict discharge for six to eight weeks with the necessary thromboprophylaxis, no sport during three months are general follow-up's recommendations applied to each patient operated from the calcaneum, as well as the wearing of a plastered splint after the surgery, sometimes followed by a plastered boot.

Not all of our patients benefited from physiotherapy after the surgery. This could be an important aspect of the rehabilitation to analyze in further studies in order to demonstrate if physiotherapy could help reduce the stiffness of the subtalar articulation and increase its mobility for example by elongation of the triceps surae muscles; and to see the real benefit of including physiotherapeutic care in the follow-up procedures, knowing that rapid loss of bone mineral mass⁵⁵ and muscles in addition to stiffness of the ankle have also a negative impact on the gait.



Picture 3: <https://www.alamy.com/stock-photo-calcaneus-calcaneal-fracture-with-fixation-surgery-7712045.html>

4.4 Complications:

In this study every calcaneal fracture had been approached using an “L”insicion”. We recorded one case who suffered from a post-operative infection, more precisely from an osteomyelitis and who needed two wound debridements.

This patient had fifteen years old when he fell from a roof from a height of about 5-6 meters. His multi-fragmentary displaced intraarticular calcaneal fracture was treated operatively with an ORIF using an L-approach. The surgery took place nine days after the accident in order to decrease the hematoma holding the leg elevated in a splint while lying in the bed. However, even with these precautions, the patient, a year later, developed an infection of the bone and muscles which led to a fistula at the level of the skin. This was an urgent reason for an ablation of the osteosynthesis material (AMO) followed by two repeated debridements during one of which a biopsy was made. On the images, we found an osteolytic zone mainly situated in the posterior part of the calcaneum. This case had an almost flattened Böhler’s angle that was rectified to 26°. We are still taking care of this young adult freshly aged of eighteen years old and trying to understand the reason of his complications after the surgery. Obviously, the infection risk is also increased when the patient does not take care of his scar and does not respect the hygiene rules given by the doctor.

It is a learning case, and it was exciting to assess his clinical status compare to the other children and to compare his walking parameters to the others to denote how complications like infections can impair the gait. Our observation was that even if the scar had well evolved and was completely closed, the hindfoot mobility, especially in eversion and inversion, was very reduced, he had a completely rigid articulation. It was not easy to talk with this patient and he was not really cooperative making the analysis and the questionnaires not 100% reliable. For example, the AOFAS score is probably not as good as he pretended regarding to the poor clinical exam outcome and regarding to his way of walking.

4.5 Radiographies :

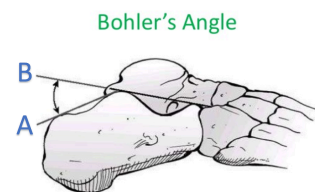
H.McKim Thomas, in his article about calcaneal fractures in childhood⁶, confesses how hard it was in 1969 (date of the article) to interpret calcaneal angles and the congruency of the subtalar joint,... These difficulties remain nowadays even if there has been a lot of progress in quality and new possibilities in the radiologic field. Indeed, when analyzing the radiographies, I realized how tricky it was to clearly perceive the complex anatomy of the calcaneum and to verify its good position and congruency with the surroundings articulations.

On top of that, it is even more tough to identify calcaneal fractures in children growing since the epiphyses are not closed and the bone shapes and conformation are not definitively established. An advantage in young patients is their unique bone potential. It enables a rapid and solid consolidation of the articulation, which we noticed on the radiographies.

The Böhler’s angle is the angle defined by a line A connecting the highest point of the posterior talar articular surface and the superior margin of the calcaneal tuberosity, and a line B linking the anterior process with the highest point of the posterior talar articular surface. One advantage of it, is its good inter-observer reliability.

This angle is measured on lateral radiographies and is the one used to quantify the deformity of the calcaneum²⁰ and to help the surgeon make a decision concerning the fracture management¹. Normally, the Böhler’s angle measures between 20 to 40 degrees. Thus, an angle under 20° suggests a calcaneal fracture. But we must be careful because in some calcaneal fractures the Böhler’s angle can be respected. It is also important to keep in mind that these values are for adults⁵⁴ and that no standards have been established for the pediatric age.

Matthew J. Boyle et al.¹⁸, tried to establish a referential for Böhler’s and Gissane’s angles in children. What they came up with, is that there are big differences in Böhler’s angles depending on the age group. For example, kids between 0-2 years-old seem to have an eloquent variability in degrees which is, to their point of view, either due to the fact that the calcaneum has an asymmetrical dual ossification process or that the younger the child is, the harder it is to precisely measure the Böhler’s



Picture 4:
<https://www.slideshare.net/saumyaorthodoc/ortho-journal-club-7-by-dr-saumya-agarwal>

angle on radiographs. Another influential reason for them to perform this case series report was that the value of this most commonly used calcaneal angle seems to be a useful prognostic tool for evaluating outcomes⁶⁶. Indeed, previous studies have shown that a relatively big decrease of Böhler's angle could lead to poorer results regardless of the treatment's technique used⁶⁰. In our study, we do not retrieve this tendency, but it is to be kept in mind that we only dealt with a small sample of subjects.

According to Clint SA and his associates⁶¹, the Böhler's angle, despite its large fluctuating range of degrees during the growth of the child due to continuously morphological changes in the calcaneum occurring at this time of one's life, remains a reliable measurement and validate its use in studies dealing with calcaneal fractures in children, like ours. However, they precise that surgeons must be aware of this Böhler's angle's age variation in children when planning the treatment according to this value.

Regarding the reduction of the fracture in our patients, we detected a global satisfying restoration of the Böhler's angle, since in four patients out of six, the angle, after the ORIF, measured between 20°-40° so does meet the standards (at least the adults' one). Our patients' average value of the Böhler's angle after the reduction, reached 31.5° (range 12°-49°) which is situated in the middle of the normal degrees' range.

An inconvenient in calcaneal fractures in children is that there exists no definite classification. Nevertheless, the general trend is to apply the adult's classifications, so either the Essex-Lopresti when facing a plain radiography (X-rays) or the Sanders' one when dealing with CTs⁶², since both classifications seem to be valid in children as well⁴².

The usual way of processing with children with a calcaneal fracture's suspicion, is to start with three view-series of plain radiographies (lateral, dorsoplantar and axial), since x-rays emit lesser radiations compare to scanners. It is imperative to know that the fractured line might not directly be seen^{9,14}, moreover in young patients, due to the surroundings soft-tissue injury and the global inflammation. When plain radiographies show at first no abnormality but that a broken heel is highly suspected, X-rays must be repeated ten to fourteen days after the accident¹.

Thanks to the technological improvements in scanners; angles, anatomy, joint infringement and the global damage of the calcaneum are more precisely seen^{1,12}. For this reason of precision, the CT is needed pre-operatively for the treatment of displaced intraarticular fractures. The Sanders classification will help the surgeon estimate the injury he is facing with. The radiological classification had been constantly updated in the last years since the quality and performance of the scanners has been evolving. However, to reach even better outcomes in the future, an explicit classification picturing the damage caused by the accident and a deeper knowledge about Böhler's angle's signification and proprieties, both leading to a detailed treatment protocol would be advantageous, for the surgeon in terms of treatment decision-making as well as for the patient in terms of recovery. It would also help in detecting the patient at risk for post-operative complications and allow us to react sooner and in a more aggressive way⁶⁶.

We noticed that our case series had different types of fracture but all of them were closed displaced intraarticular fractures which confirmed the indication for a surgery as stated in the introduction.

No association between the classification's type of fracture and the mechanism of the traumatism, or with the age at which the trauma occurred was revealed by our results.

According to Raffaele Rubino et al.⁵¹, the Essex-Lopresti does not correlate with clinical assessments, like the AOFAS, contrary to the Sanders' classification which does have a statistical relationship with the AOFAS. If we analyze the correlation between the Sanders' classification and the AOFAS scores obtained by our cases (appendix 4, table 2), we can underline that Sanders 3ac fractures seem to have a better outcome since they scored a higher AOFAS. Sanders 4 fractures seem to be predictive of an only acceptable or bad outcome. Due to the restricted number of patients included in our study, this result is not robust enough to draw from it a firm conclusion.

4.6 Clinical assessment:

4.6.1 AOFAS Score

The AOFAS (Appendix 7) is a scoring system assessing the global everyday residual pain, the walking perimeter, the ability to walk on different type of surfaces, abnormalities of the walk, restrictions in mobility in the sagittal plan (flexion- extension) and in the mobility of the hindfoot (inversion-eversion). Stability and static of the ankle. The limitation in free time activities.²

As said in the methodology, the AOFAS hind-foot score is not specific to the calcaneum but is the reference for every foot and ankle injuries needing a surgery.

Figure 3 in appendix 5, indicates, with maximum points ranked, tendencies like the fact that every participant seems to have a stable ankle and to have a perimeter of at least one kilometer and that the great majority can walk on every type of surfaces which are positive facts to keep in mind. On the other side, the majority of them had a decreased flexion and extension capacity and their hind-foot mobility (inversion-eversion) was restricted, creating a certain rigidity. These observations illustrate well the clinical deficits found in our patients.

A very good score was found in only one patient out of six. Good results were obtained in 3/6 patients. One patient scored an acceptable result and 1/6 patient expressed a bad outcome³⁴ (Figure 4 in appendix 5).

4.6.2 EQ-5D-Y Score

The EQ-5D (Appendix 8) is a standardized questionnaire evaluating the quality of life of a patient. The EQ-5D-Y is the version adapted to the youth. The EQ-5D is not specific for the calcaneum but can really be applied to every health conditions and will still have a good reliability and can be easily reproducible.

“EQ-5D is a standardized measure of health status developed by the EuroQol Group in order to provide a simple, generic measure of health for clinical and economic appraisal⁶⁷.”

The EQ-5D-Y consists of one page of questions about today's patient's health and containing, on the other side, a visual analogue scale (VAS) estimating the quality of life at the moment. The questions' formulation and the words used are adapted to children. The questionnaire evaluates 5 dimensions: mobility, looking after myself, doing usual activities, having pain or discomfort, feeling worried, sad or unhappy. Every question is followed by three possible level of answer, no difficulty, some difficulties, lots of difficulties.

The analysis of the questionnaire is then done thanks to the attribution of a 5 digits code, each digit representing one state of health and the higher the number, the worst the quality of life. These 5 digits codes can then be transformed with a formula in an index which is more representative of the global quality of life of the person and which is easier to use in statistics.

The comparison of EQ-5D-Y in between controls and patients, demonstrated that in both groups, the VAS diverged a lot. It was surprising to see that half of our controls were evaluating their quality of life (QoL) as being worse than those having undergone the surgery. This was a rather positive sign that our patients are doing well nowadays and do have a satisfying quality of life, even if this parameter is very subjective and differs from one another.

However, when analyzing in detail the EQ-5D-Y's score of our case series (appendix 4, table 2, last column), we noticed that a majority of the operated children (4 out of 6) were still suffering, every now and then, from pain and/or discomfort.

Patient 16 was the only one facing some difficulties doing everyday activities, he precised that he was feeling some soreness when walking long distances. Patient 15 expressed some worry and sadness, which was reflected in his low VAS of 70, but he did not say more about it.

4.7 Gait comparisons: Appendix 6

For our gait analogy to be as significant as possible, we took more than the double case of controls and tried to cover the same range of age than our patients.

We thus enrolled, six patients aged from 13 to 18 years old and fifteen controls between 10 to 16 years of age, who took part in the gait analysis. Gait parameters were then compared in between controls and patients and we also confronted the unaffected foot's values to the affected foot's ones. In our results' tables, as a convention, we designated the right foot (R) as being the injured one for the statistical analyses to be easier, then, to interpret.

4.7.1 Straight and turning trajectories:

Every participant, during the analysis, accomplished two tasks:

- 1) Straight walk of about 200m
- 2) Two loops, one in each direction, thereby effecting a total of approximately 130m

The recorded parameters allowed us, then, to underline the differences in walk on straight and turning trajectories. Studies like the one from Strike et al.⁵⁹, have already shown disparities in speed, stride length, stance phase, ... when turning compared to straight gait. These variations were retrieved in our study. For example, when paying attention to the general tendency (controls and patients confounded) our observations confirmed that speed, stride length, swing, loading and push-off phases of stance, strike angle and lift-off angle were reduced compared to straight walk. In opposition, cycle duration, stance, foot-flat and double-support seemed to be increased, most of the time, when walking on a turning trajectory.

Gait analysis' data were evaluated with two different analytical methods.

The Wilcoxon rank-sum (Mann Withney), which is a non-parametric test allowing to test the null hypothesis that selected values in sample A can occur as likely as in sample B, it relies on mean values.

The regression analysis, LOWESS is a non-parametric method consisting in fitting a smooth curve between values of a sample A and of a sample B. It helps better see trends when there is only few or sparse data. In our case, the LOWESS was done, in a second time, due to the small number of operated patients we were working with and in order to draw more precise conclusions.

Both analytical methods provided us with p-values. If only the Wilcoxon rank-sum test was positive, then the test was not considered as significant. If just the LOWESS was positive, then the result could be significantly interpreted. Of course, it is always better when both tests are positive.

4.7.2 Controls versus patients operated for a calcaneal fracture:

Appendix 6) figure 2

4.7.2.1 Height:

The difference of height in our two groups seemed to be slightly significant. The patients composing the control group were in general younger and thus also smaller in size than our patients. The height might have had an impact on the stride length, which, in fact, seemed to be longer in our control group which was bigger in size. However, the cadence seemed not to be eloquently different within the two groups. The body mass index was not so much divergent comparing the two groups proving that the difference in height within the same group must have not been that strong and moreover it is important to keep in mind that the control group was composed of two times more patients and globally older ones.

4.7.2.2 Gender:

Five patients out of six were boys and only one of our case was a girl which is reflecting the fact that boys are more at risk for such fractures since they are more attracted by dangerous sports.

4.7.2.3 Stride length:

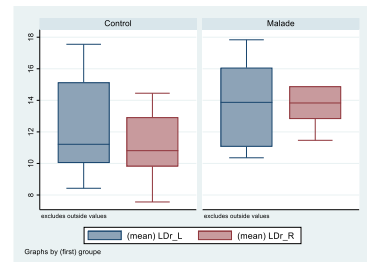


As said in the analysis of the height, the stride length was longer in our patients than in the control group, but the patients operated were also older and bigger in size. Additionally, patients may have been more willing to show how good they were walking, since they knew we were testing their walking abilities to compare them with other children who had never been operated from a calcaneal fracture.

4.7.2.4 Loading:



It seemed to us, at first, as if the loading, which represents the percentage of the stance spends for touching the ground with the heel, lasted longer in our patients. Meaning that our patients were probably spending more time in the loading of the heel. Explanations to this could have been the rigidity of hindfoot in patients operated, which might have prolonged the loading and created a problem in the locking-unlocking mechanism of the joint when putting the foot down or due to a loss of balance in these patients. However, when using, in a second time, the LOWESS analytical method, we noticed that the difference in loading was no more significant, even if on the box plot, loading values were globally bigger in operated patients. With the local regression method, we were thus, able to confirm that loading values were divergent within the two groups, but not significantly enough.



4.7.2.5 Push-off:

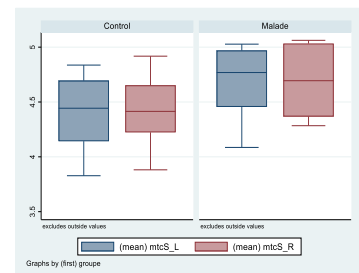


The push-off was not statistically different in our patients.

4.7.2.6 Maximal swing speed:



The maximal swing speed corresponds to the maximal speed of the foot during the swing at minimal toe clearance. According to the Gait Up brochure designed to help understand and interpret the walking parameters measured by the sensors, it seems that the faster the swing speed, the greater the probability to hit an obstacle during the gait, so to fall due to obstacle avoidance. The maximal swing speed is thus, to a certain point, linked to the minimal toe clearance and both parameters can be responsible for increasing the risk of falling. In the statistical analysis, the maximal swing speed was significantly faster in the operated group. This was also observed on the box plot. The operated patients, having a quicker maximal swing speed, a reduced minimal toe clearance and subtalar stiffness, have a higher risk of tripping, but we did not observe it during this study.



4.7.2.7 3D path length:



The 3D path length represents the trajectory of the foot expressed in terms of stride length and swing width. It tells us about the circumduction. The 3D path length was powerfully different within the two groups.

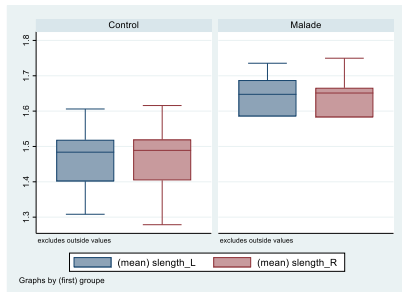
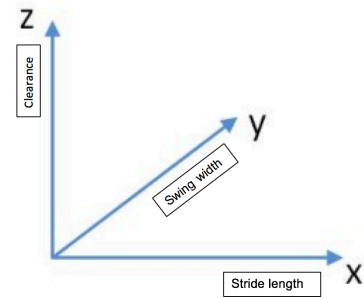
Stride length was bigger in operated patients

Swing width was not significantly different. Almost the same values for both groups were retrieved.

To evaluate the tridimensional movement of the foot, we can use the 3D path length and add to it the clearance. Like this we can dissect the foot's motion in space, in length (stride length), width (swing width), and height (clearance).

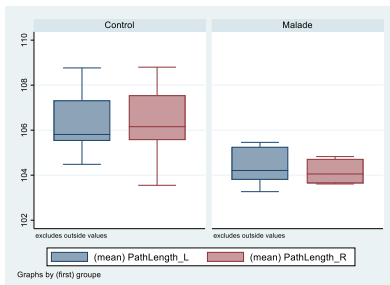
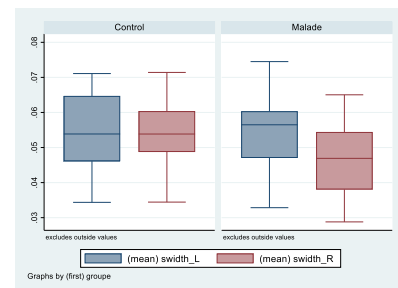
Clearance: Operated patients had a smaller clearance, so their foot was closer to the ground during the swing.

→ According to these three parameters, it seems that operated patients had longer strides but with less movement of the foot in the air. So that they did have a longer stride, a smaller clearance and probably a narrower width. It would be very interesting to analyze in detail the movement of the foot in the air and its position's changes during the swing phase. The following axis system pictures the three components of a foot motion and helps realizing the complexity of the movements performed during an everyday gait.



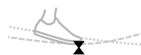
Stride length box plots depict the bigger steps taken by our patients

Swing width box plots show us that the operated foot had a smaller swing width compare to the unaffected foot. But this was not statistically significant.



By looking at the box plots, we noticed that 3D path lengths were very different in between controls and our patients, and an interesting aspect was to see that the healthy foot adapted itself to the operated foot.

4.7.2.8 Minimal toe clearance:



To evaluate the foot clearance, which represents the height of the foot above the ground during the swing phase, it has been chosen to analyze the minimal toe clearance, so the minimum height of toes during the swing, which seems to be the most representative of the global foot clearance and which can potentially increase the risk of tripping.

Minimal toe clearance seemed to be significantly different within the two groups. Our patients seemed to have the foot closer to the ground during the swing and this could increase the risk of falling.

4.7.2.9 Double support:



The double support parameter, which represents the phase of the gait cycle during which both feet are touching the ground and is expressed as a percentage of gait cycle duration, reflects the stability of the walker. As A.Bregou et al.³ showed in their study, patients suffering from cerebral palsy have a slightly increased double support time reflecting the instability these patients are facing with. The same has been observed in the old population, since they are confronted with the problem of fear and instability⁵⁶. Knowing this, we wanted to investigate if the period during which both feet are touching the ground (double support) was also increased in children who had undergone an ORIF. Our results showed that our patients had a longer double support than the controls, but this difference seemed to be not statistically

significant and since to our knowledge, no such a study has been done before, it was not possible for us to compare our findings. But it might be possible that operated children lack a bit of balance and prefer spending a little bit more time with both feet on the ground.

4.7.3 Patients operated for a calcaneal fracture: Affected versus unaffected foot: Appendix 6) figure 3

4.7.3.1 Swing and stance :

Differences in stance and swing within the same person seemed to be almost significant. So, discrepancies were seen in the walk of one's person. The affected foot spent in general less time in swing and stance phase compare to the unaffected foot, however, the difference in cadence between both feet was not symbolic.

4.7.3.2 Loading:



The comparison of the loading of the operated versus the healthy foot was not statistically relevant, a motive for that, might be an adaptation of the healthy foot to the operated one.

4.7.3.3 Lift-off angle:



The lift-off angle was almost significantly different, but it seemed to be strangely bigger with the operated foot than with the unaffected foot whereas we would have expected the hindfoot of the affected foot to be less mobile. However, it could be explained by the increase of the equinus position encountered after the surgery.

4.7.3.4 Strike angle:



Values for strike angles were not seriously distinct from one to the other foot within the operated patients.

4.7.3.5 Swing width:



The difference of swing width was almost analytically significant within both feet. The unaffected foot had a wider trajectory on the side during the swing. But when comparing the two groups (controls and patients), the swing width values were almost equivalent to each other.

The pictograms come from www.gaitup.com

5 Conclusion:

To conclude, when looking at an operated child walking, no obvious abnormalities is to be observed. Moreover, these young patients have no complaints during their daily activities and are not restricted in their lives. However, by the clinical examination, a considerable stiffness of the hindfoot, reflected in a loss of mobility mostly in the eversion-inversion, is to be noticed.

Spatiotemporal gait analyses also provide us with some insight in regard to modified gait parameters and thus, made us acknowledge that our null hypothesis was wrong. The minimal toe clearance, the maximal swing speed and the tridimensional path length differ significantly in the children operated for a calcaneal fracture.

An essential aspect not to forget, is that foot motion is very complex and composed of more than one movement and that every component of the foot journey is achievable thanks to anatomical congruency, muscles, ligaments, ... After an ORIF, the movement of the foot in the air, as well as on the ground, seems to be slightly divergent to the one of someone who never suffered a calcaneal fracture needing a surgery and that the unaffected foot, in operated patients, tends to adapt itself to the affected foot in order to offer a smooth and comfortable gait to the patient.

Intraarticular fractures are themselves a cause of future joint stiffness, in addition to this, the limitation of toe clearance and the diminution of swing are potential indicators for developing overload of adjacent articulation and subsequent early arthritis, due to the alteration of adaptive mechanisms in subtalar movement they represent.

Surgeons are aware of the fact that the surgery is also another factor for early arthritis, meaning that if a surgeon decides to operate, he knows it is the best solution for his patient and that his patient will suffer less from the surgery and its possible consequences than if no intervention is done. A conservative treatment could, indeed, increase the risk of subtalar arthritis so, at the same time, of joint stiffness, the risk of pain and of secondary arthritis of the midfoot and of the ankle.

Therefore, we think that the restoration of the calcaneal anatomy with an anatomic reduction and realignment of the posterior facet of the subtalar joint is a relevant point for an efficacious recovery and in order to minimize later gait disbalance or disabilities, thus offering the injured child the best future in terms of gait motion and quality of life. For these reasons, surgery will still be performed for the intraarticular displaced calcaneal fractures in children since there exists no evidence-based contraindications to this medical management and because we saw that children do have a good tolerance to it. Our study highlights meaningful points and discrepancies that would have probably been even worse if people suffering from a displaced intraarticular calcaneal fracture had not been operated at all, but there is unfortunately no other study to prove it, however, we can deduce it when looking at the radiographies.

In the postoperative care, specific exercises and work of the subtalar joint are missing.

Physiotherapy (for e.g. Muscles reinforcement, proprioception...) and other rehabilitation therapies could be useful additional care to give every patient the best chances to heal and avoid later disabilities. A prospective study should be done to assess this statement.

This study confirms us that lots of progress have been made in the last few years concerning the diagnosis and treatment of such fractures in children but that there are still lots of uncertainties and unknowns. The spatiotemporal gait analysis is a very useful tool to assess walking parameters^{3,4,5,35,37,56,59} and helps doctors better understand the movement of one's body and of his articulations, thus reinforcing the diagnosis or implying a specific treatment.

6 Limitations / improvements:

This study has some limitations, in particular, its retrospective design, the reduced sample size, the poor literature on the topic and the impossibility of comparing our gait analysis values to previous results since no such a dynamical study had been realized on children before.

Long-term studies would be required for significant findings. A follow-up period of at least one year was one of our selection criteria, which is, to our mind, the minimal time needed to ensure a good recovery and to retrieve one's personal walk characteristics. However, the longer the follow-up period, the better it is to have an idea on long-term consequences. On average, our patients came for the follow-up 2.43 years after the surgery took place and the longest control period of our case series lasted 5 years.

In terms of radiographies, we were missing some images of the fractures pre-operatively, mostly when the cause of the traumatism was a ski accident and that the clichés had been taken at the local hospital of the ski resort and were then not transferred or recorded on the server used by the CHUV once the patient was redirected to the university hospital for further medical care.

To increase our level of comparison, we could have done X-rays of every control's ankle in order to analyze how the foot anatomy and Böhler's angle were looking like in non-operated and active children. Even if this would have been of a great help, since there are no standard values for the Böhler's angle in children, it is never safe to irradiate children, so we decided to avert taking any eventual risks.

For meaningful analyses of the gait it would have been necessary to let them walk longer distances because often the walk changes once muscles are starting to get tired and the patient once bored, think less about his walk and loses his concentration which makes his natural gait comes back.

An interesting point could have been to check how many different surgeons did these surgeries since they were all performed at the CHUV. If most of the ORIF were operated by various surgeons, it can lead to variabilities due to diverse surgical experiences and have an impact on the successfulness of the treatment and recovery.

The exclusion, from our study, of every people suffering from another injury at the same foot may have play a little bias, since in reality, it is possible to have more than only one injury at the same foot, especially with high velocity trauma. So, the cases selected thanks to this exclusion criteria might have better gait analysis's results than the polytraumatized one.

To increase the level of validity of this study, we could have look for the take-off foot before doing the gait analysis in order then to interpret the results more precisely. The take-off foot might play a role in the loading.

A curious aspect, to go further in this study, would be to re-analyze our patients in the adulthood in order to observe the functionality and mobility of their feet, to see if they developed any gait disabilities and to detect any early subtalar osteoarthritis in these patients operated for a calcaneal fracture in the childhood.

Moreover, the results could also then be compared not only to children who never had problems to their feet, but also to children born with clubfoot.

Since we noticed that operated patients have a higher chance of falling due to the fact that they have a quicker maximal swing speed, a diminished maximal toe clearance, a modified tridimensional path length and a limited subtalar mobility, studying the tendency of tripping in this group of patients would be meaningful.

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