**INTRODUCTION**

Climbing has become an extremely popular sport, especially in the adolescent community. As a consequence climbing gyms and training possibilities have started appearing everywhere. The need for competition has led to an increasing number of events on national, European and even world-class level including youth competition. National youth climbing teams are a standard for every nation with a climbing history and also for nations with no alpine history like Malaysia or..

**ABSTRACT**

A literature overview on growth plate fractures in different sports with a focus on climbers is given. A biomechanical analysis of the possible causes of this injury in the finger are offered. The injury has increased over the last years and can lead to permanent damage of the finger. We developed a biomechanical approach to explain the causes leading to this injury. For evaluating our theoretical approach we designed a questionnaire examining the circumstances leading to the injury as well as the training routines of eighteen injured adolescents. Of the 22 injured fingers, 95% concerned the middle finger; in 64.3% the crimp grip led to the injury and was the preferred handhold (71.4%). Half of the injuries occurred during bouldering competitions. 81% of the injuries were Salter Harris grade 3, only two were grade 1 and 5 respectively. With rest all adolescents regained full finger function, one athlete remains with permanent finger damage because he kept climbing. Most of the injured adolescents were male (75%). They were in average 14.1 years of age and all within the year of their peak velocity growth. Adolescent climbers thus are at a high risk for epiphyseal fractures especially during their growth spurt.

**Key Words:** Growth plate fractures, fingers, adolescents, climbing, prevention.
Thailand. This in turn has led to vigorous training regimes among adolescents using established training methods from the adults, like campus boarding or the finger board with exceptionally high strains on the fingers. As a consequence new pathologies started emerging that had so far never occurred: epiphyseal fractures of the finger middle joints.

Such fractures have previously been described in other sports on various locations, nevertheless not on the fingers. The first cases were observed in the proximal humeral physis in baseball, described as the Little Leaguer’s shoulder. The cause for this injury is believed to be a consequence of the whiplash action of the arm during a throwing movement. With repetitious throwing, this can result in a widening of the epiphyseal plate as in a Salter Harris I fracture. According to this hypothesis most of the epiphyseal fractures observed in Baseball are Salter Harris I fractures. Carson et al. who reported 23 cases of Little Leaguer’s shoulder, found evidence suggesting that this injury directly related to the amount and intensity of throwing. There have been several suggestions as to limit the amount of innings being played by adolescents in baseball. Recovery is achieved with rest over a period of 3 months.

After having been observed in the baseball community, stress fractures of the distal radius in gymnasts were being recognized on a regular basis and this pathology became the most commonly reported physeal stress injury with over 60 reported cases in the literature. The pathomechanism is believed to be complex rotational vaults in which the athlete always rotates in the same direction with a hyperextension and ulnar deviation of the fulcrum wrist plus resisted supination and active flexion, from the lumbricals and long flexors of the hand. As a consequence of this loading mechanism the injuries most often observed, are Salter Harris II stress fractures with an epiphyseal widening and irregularity and cystic changes of the metaphyseal aspect of the growth plate. The injury is mainly seen in highly competitive athletes training almost every day for several hours.

The climbing community only started reporting epiphyseal stress fractures in the fingers in 1997 and later by Chell in 1999. As a consequence of repetitive loading of the fingers the fractures observed were always in the proximal interphalangeal joint. Most often they were fractures of the Salter Harris III type with a fracture through the epiphysis of the middle phalanx. Within the short period of time (24 years) a total of 65 epiphyseal fractures of the fingers have been reported in climbers representing the highest rate of this injury so far in any sport. The only other case report about stress fractures in the finger as a consequence of repetitive loading is in piano playing.

Most injuries heal with rest and the athletes are able to return to their sport most often reaching their previous level easily. However with regard to every typical injury there are reports of either premature closure of the physis or deformities as a consequence of asymmetric epiphyseal injuries that did not heal.

The purpose of this study was to develop a theoretical model for the biomachanic cause of this pathology. Furthermore we wanted to determine the pathomechanism, and risk factors leading to this injury using a questionnaire in a group of injured adolescents and evaluate our theoretical model.

**MATERIAL AND METHODS**

We collected the data of 18 adolescent climbers with epiphyseal fractures over the period of five years between 2009 and 2013. We obtained plain radiographs on every injured finger as well as magnetic resonance imaging. Biometric data (age, gender) were obtained on visits of the patient. Informed consent to further analyze the injury was obtained by the parents and the adolescent. Further data were analyzed using a detailed questionnaire, which was completed by the injured
adolescent and the parents. The questionnaire focused on determining the moment of the growth spurt using growth charts as well as pubertal development according to the Tanner stages. Furthermore we determined how much time was spent on training and specifics about training methods, especially about campus boarding and bouldering with high intensity. We investigated the favorite hand position during training and competition climbing, differentiating between a crimp grip and a sloper position. And finally we asked about the injury itself, about when it had occurred (training, competition) and the specifics surrounding the injury.

RESULTS

Over the last five years 18 adolescents presented themselves with epiphyseal fractures. Together we were able to diagnose 22 fractures, as four patients had bilateral fractures (22.8% of all adolescents). The middle finger was concerned in 21 of the 22 fingers amounting to 95%. We were able to obtain a questionnaire from 14 of these patients. When the injury occurred nine patients (64.3%) were holding on to a crimp, two (7.1%) had a hanging finger position and five (35.7%) could not remember the circumstances resulting in the injury. When asked about their favorite hand position, ten (71.4%) preferred crimps and only four (28.6%) preferred slopers. The injury occurred during bouldering in 7 (50%), during a competition (not further specified) in 3 (21.4%) cases and during a normal training session (different training methods involved) in 3 (7.1%) cases. Most of the patients were participating in one kind of competition or other around the time of the injury. Most of them (9 adolescents, 64.3%) were doing bouldering and lead climbing competitions, three (21.4%) did only bouldering competitions, one (7.1%) only participated in lead climbing competitions and one had never participated in a competition so far. Taken together twelve out of fourteen (85.8%) were doing bouldering competitions and ten out of fourteen (71.5%) were doing lead competitions around the time of the injury. Most (71.4%) of the subjects said that they had warmed up properly before having the injury, only one (5.6%) could remember injuring himself while warming up, whereas the rest (21.4%) didn’t remember or didn’t remember the circumstances of the injury.

Eighteen fractures were Salter Harris grade 3 (81.8%), two were grade 1 (9.1%) and two were grade 5. However, the two fractures with grade five occurred in the same climber. Considering the outcome 69.2 % (9 out of 13) had a very good outcome with the complete return of the finger function as before. At the time of the finishing of the paper three subjects (23.1%) were still in rehabilitation and their results are pending. However one patient could not recover full finger function in the two affected middle fingers with swelling around the joints and movement impairment (Fig. 1, 2 and 3).

Of these 18 adolescents 14 were male (75%) and 4 female (25%). They were 14.1 years old on average (minimum 12.75 years, maximum 15.8 years). Their average height was 1.65 m (SD 0.087 m) and their average weight was 50.2 kg (SD 7.9 kg) leading to an average BMI of 18.04 kg/m² (SD 1.7 kg/m²). On average they had grown 7.2 cm (std 1.6 cm) in the past year and when investigating their growth curves they were all growing at the peak velocity of their respective growth curves. They were growing below the 50th percentile by 0.77 cm (SD 6.6

FIGURE 1. Hand in the crimp grip position
and were 6.6 kg lighter, their BMI was thus 1.6 kg/m² below the 50th percentile. Their first signs of puberty had appeared 14.4 (std. 12.26) months prior to the injury.

At the time of the injury the subjects had been training 2.4 (SD 0.4) hours per session for 3.4 (SD 1.1) times per week on average, amounting to 8.2 (SD 3.4) hours of training per week. This training consisted mostly of climbing with 3.6 (SD 3.2) hours per week and bouldering with 3.2 (SD 1.5) hours per week. A small element was due to strengthening exercises with 1 (SD 1.3 hours) hour per week and only a few had done campus board training at the time with 0.2 (SD 0.5) hours per week. They were climbing an average level of 8.9 (SD 0.6) on the UIAA metric scale.

After diagnosis of an epiphyseal fracture our team suggests 6 – 8 weeks of rest before doing a control of the finger using MRI. As a consequence, the subjects in this study started climbing again after a mean of 6.8 weeks and regained their previous level of climbing within 3 months. The only exception was the athlete who did not regain full finger function, as the fractures were already more than a year old when he came to see us. Rest and rehabilitation did not improve or change the outcome.

DISCUSSION

When analyzing the results of this study one of the most worrying findings was the sheer number of adolescents who had injured themselves over such a short amount of time. This was even more pronounced as 4 cases were presented to us from a neighboring country in a time frame of 2
months. No other sport has had such a high frequency of epiphyseal fractures so far\(^3,7,15\).

The fact that 4 patients had a fracture on both hands (22.8%), always on the same, namely the middle finger worried us, as that implies that there may be either preexisting condition or other determinants that haven’t been considered so far.

In only one case the middle finger was not the one injured, thus in 95% of the cases the middle finger was the injured finger. This distribution is logical when considering the biomechanics of the hand. As the middle finger is the longest finger of the hand, it received the most strain, especially in a crimp grip position (Figure 3), as explained in a biomechanical model by Vigouroux et al.\(^{17}\) When investigating the circumstances of the injury, most adolescents (64.3%) remembered a crimp grip position as the cause of the injury, proving this theory.

The crimp grip as the most detrimental hand hold was also reflected in the fact that most adolescents (9 out of 14 representing 71.4%) in our study preferred this hand hold, whereas only four (28.6%) preferred slopers.

Five adolescents couldn’t remember the circumstances of the injury as they could not remember one clear event leading to the injury but rather a worsening condition over time similar to the stress fractures in other sports such as baseball and gymnastics\(^5,6-8\). This in itself is another important finding. Whereas epiphyseal stress fractures in other sports have always been a consequence of too much training resulting in a gradual increase in pain and injury, this injury most often occurred as an acute injury, enabling the patient to remember the circumstances of the onset of pain. However, we still believe that it is a stress fracture resulting from overuse leading to one acute trauma, more pronounced and thus more acute in climbers as it concerns such a small anatomical structure as the finger, whereas in other sports bigger joints such as the shoulder or wrist are concerned leading to less acute onsets.

Because the patients were able to remember the circumstances of the injury, we were also able to determine during what kind of activity the injury occurred and bouldering was the most often remembered circumstance with 50%. Bouldering was also the competition form in which most of the subjects participated in, around the time of the injury with 12 out of 14 of the subjects amounting to 85.8%, whereas only 71.5% of the subjects were doing lead competitions at the time, stressing that most of them were participating in both forms of competitions. There have been tendencies to ban international boulder competitions in adolescents in the past\(^{18}\). However, these measures cannot be held up as there are more and more local competitions, which allow adolescents to participate, and which are not under the surveillance of any institution. Furthermore bouldering is a very trendy and much liked form of climbing which is especially popular in the younger generations. Thus banning bouldering competitions is not very promising. However, measures need to be taken in bouldering as well as in lead climbing competitions to limit the stresses on the fingers of adolescents. This can easily be achieved by using children friendly handholds which cannot easily be crimped in competitions in which adolescents are allowed to participate. Another aspect is the amount of climbing an athlete is asked to undertake in a competition. A lot of local competitions in the boulder gym next door plan a course of 20 to fifty boulder problems that can be tried over a time frame of several hours. Although an adult may get tired after two or three hours or may be so smart to limit him- or herself to a few boulder problems in order not to get injured, such a thing will not occur in adolescents. They will keep on going until the time is up, thus putting enormous strains on their finger over a prolonged time frame. Limiting the number of boulders in competitions in which adolescents are allowed to participate is thus a necessary step.

A surprising result was the fact, that most of the adolescents (71.4%) were sure they had warmed up properly before being injured. Climbing without a proper warm up has been associated with several climbing injuries, namely the pulley rupture\(^{19}\) and muscle strains of the shoulder and elbow. A lot of work has therefore been invested in instructing coaches and athletes to warm up
properly before putting high strains on their fingers. The epiphyseal stress fracture of the finger however seems not be a consequence of a missing warm up, and can thus not be prevented by doing it. However, this does not imply, that warming up is unnecessary, as the other injuries stated above are positively influenced when warming up. We were surprised to note that so many of the subjects warmed up properly before starting strenuous exercises.

Most of the fractures observed in our study were of grade Salter Harris 3 (81.2%). Only two subjects had minor fractures of grade 1 and one patient had a crush injury (Salter Harris 5) in both middle fingers. In baseball mainly Salter Harris 1 fractures are observed3-5, in gymnastics mainly Salter Harris 2 fractures6,7,9. Our findings concur with previous studies in climbers who also observed type 3 fractures most often12. This is a consequence of the biomechanics, as in climbing the epiphysis is pushed out on the dorsal aspect of the finger when the finger is subjected to high forces in the crimp grip position (Figure 4).

Although the outcome was good in most of our patients, in one patient a permanent damage to both of his middle fingers occurred (Figure 1). This patient had injured himself one year prior to presentation in our clinic and only sought advice after his new physiotherapist advised him to come and see us. Several physicians had not recognized the injury and had not recommended taking a break from training. The knowledge of this injury is essential as an untreated injury in an adolescent climber can lead to a misalignment of the finger as a consequence of cessation of growth of the broken growth plate15. This finger is then hindered in its full range of motion and even impairs the other fingers of that hand. This will not only carry consequences for the sport but also for the rest of the adolescents life as a career involving his or her hands may well be unfeasible.

Over the time period of this study we saw more boys injuring their growth plates (14 out of 18) than girls (only 4 out of 18). This may have several causes. For one climbing is still a sport which is dominated by males. In competition about twice as many boys participate than girls. However the endocrine aspect of the adolescent growth spurt needs to be taken into account as well. As stated above, the growth spurt is caused by a stimulation of growth hormone production by low doses of estradiol20. As the doses of estradiol increase, the growth is increasingly inhibited up to the fusion of the physes21. The differences in estradiol levels during puberty may well explain the higher number of injuries in boys than in girls. This needs to be monitored in the future in order to determine factors helping to prevent such injuries.

The subjects in this study were not exceptionally small with an average height of only 0.77 cm below the 50th percentile, which is surprising as small stature is said to be typical for climbers22. They were however exceptionally light with 6.6 kg below the 50th percentile and had thus a BMI of 1.56 kg/m² less than the average population at that age, which reflects previous findings in which climbers tend to be exceptionally light with a low BMI22. We were also able to evaluate growth curves of eight of the subjects and were able to see, that all the injuries occurred around the time of the pubertal growth

![FIGURE 4](image.png) Extension deficit of the PIP joint of the middle finger on one side. The other side was comparably impaired.
spurt. This confirms literature findings, which suggest that the epiphyseal plate is exceptionally vulnerable during times of rapid growth\textsuperscript{23,24}. This higher vulnerability is believed to be the consequence of the structural changes during rapid growth leading to a thicker and more fragile plate. In addition to that, the bone mineralization may lag behind the linear growth, rendering the bone more porous\textsuperscript{25}.

When investigating the training regimen of the subjects we were pleased to note that only little training was spent on the campus board. However, the fact that five subjects admitted to use this training method is already too much. This strenuous exercise at a time when the growth plate is most vulnerable is extremely dangerous and further measures need to be taken to increase the awareness of this danger. We had athletes tell us that trainers had encouraged them to start campus board training even though signs are posted in many climbing gyms that this training method should only be undertaken in adolescents under close supervision. A ban of this training method below a certain age may not yield positive results as the adolescents may then just continue with this training method in private. Special training regimes using the feet and thus taking weight off the fingers may be more promising, as adolescents want to train as hard as adults. With 8.2 hours of training per week the subjects were mostly training at a high level, which also reflects, in the high average grade achieved by the subjects as they were climbing a mean 8.9 on the UIAA score. This result reflects the findings from other sports where especially highly competitive athletes tend to have fatigue fractures of their growth plates\textsuperscript{6,7,9}.

Using this questionnaire study and clinical findings we were able to establish the pathomechanism behind this injury as well as the biomechanics, presented in the following sections.

**Pathomechanism**

The growth plate is made up of one cell type, the chondrocyte, at different stages of differentiation\textsuperscript{26}. The chondrocytes in the resting zone replicate at a slow rate and replenish the pool of proliferative chondrocytes\textsuperscript{27}. The chondrocytes in the proliferative zone replicate at a high rate resulting in cells lining up along the long axis of the bone\textsuperscript{26}. Once the cells stop dividing they differentiate into hypertrophic chondrocytes increasing their height 6–10-fold, making up the main part of longitudinal growth\textsuperscript{28}. The hypertrophic chondrocytes then calcify the surrounding extracellular matrix and produce factors that attract the invading bone cells and blood vessels, including vascular endothelial growth factor\textsuperscript{29}, before undergoing apoptosis. All these injuries have repetitive loading as a common denominator. As there is no true blood supply to the physis but only an advance from the blood vessels of the epiphysis and metaphysis as well as from the perichondrial ring and vessels of the peristeme\textsuperscript{30}, repetitive loading can alter the metaphyseal perfusion and thus interfere with the mineralization of the hypertrophied chondrocytes\textsuperscript{31}. The hypertrophic zone then continues to widen as a consequence of constant growth in the germinal and proliferative zones, shown experimentally by Jaramillo et al.\textsuperscript{32}. Similar MRI findings as in the study done by Jaramillo et al.\textsuperscript{32} in rabbits were also seen in Chinese acrobats and young competitive gymnasts\textsuperscript{33}. Usually this widening of the epiphyseal plate is only temporary, as the resting and dividing cellular layer of the growth plate, and the attendant epiphyseal and metaphyseal blood supplies, are essentially undisturbed. However, if an ischaemic condition sets in as a consequence of repetitive loading with too much weight, an osseous necrosis and deformity within the developing ossification centre can be caused, leading to growth irregularities in the physis. Are At these changes localized, asymmetric growth can be observed, or the entire physis may be involved leading to an overall slowdown of the rate of growth or even complete cessation of growth in that joint\textsuperscript{15}. 

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The growth plate seems to be exceptionally susceptible to injuries during periods of rapid growth\textsuperscript{23,24,33,34}. The physeal strength of the physeal cartilage has been shown to decrease during pubescence in animal studies\textsuperscript{35} as well as in humans\textsuperscript{36}. The causes for this decrease in strength are a consequence of the structural changes during rapid growth leading to a thicker and more fragile plate as well as the fact that bone mineralization may lag behind the linear growth, rendering the bone more porous\textsuperscript{25}. Furthermore, shear resistance is a function of the amount of matrix and collagen. Increased cell size in the hypertrophic zone reduces the amount of matrix available to resist shear and an increase in weakness is thus predictable\textsuperscript{37}.

The process of longitudinal bone growth is governed by a complex network of endocrine signals, including growth hormone, insulin-like growth factor I, glucocorticoid, thyroid hormone, estrogen, androgen, vitamin D, and leptin\textsuperscript{26}. However, the pubertal growth spurt including the fusion of the epiphyseal plate after this spurt is primarily caused by estrogen and to a lesser degree by androgen\textsuperscript{26,38-40}. The growth spurt is caused by a stimulation of growth hormone production by low doses of estradiol\textsuperscript{30}. As the doses of estradiol increase, the growth is increasingly inhibited up to the fusion of the physes\textsuperscript{21}. Estradiol is thus the reason why women have smaller bones relative to their size than men\textsuperscript{41}. The fracture rate around puberty is the highest during life\textsuperscript{24}. The risk of fracture relates to the level of bone mineral density (BMD) and to low BMD in mothers\textsuperscript{41}, which in turn might be explained by a thinner cortical shell due to a higher calcium demand for bone growth. Presumably the signal for increased cortical remodeling is parathyroid hormone (PTH), as the levels of hormone are higher in early than in late puberty\textsuperscript{42}. Studies investigating the effects of calcium intake on bone mass during puberty, when PTH levels are high, showed benefits\textsuperscript{42}. However, there was no effect of calcium or Vitamin D intake on the occurrence of stress fractures in preadolescent and adolescent girls\textsuperscript{43}.

Whether an increase in muscle-tendon tightness about the joints as a consequence to the growth spurt leads to an excessive muscular stress on the physis is controversial in the literature\textsuperscript{34,44,45}.

**Biomechanics**

The mechanism behind this injury is believed to be a high repetitive stress on the proximal interphalangeal joint using a crimp grip position of the hand (s. Figure 4)\textsuperscript{1,12}. In this finger position the physis is subjected to a compressing force coming from the fingertip on one hand and from the flexor muscles on the other hand. As the finger is flexed to a maximum this compressive force is uneven, applying more force to the dorsal aspect of the growth plate. This in turn leads to the fracture line going through the dorsal aspect of the growth plate as well as the epiphysis (Figure 5). This is exaggerated in campus board training in which the athlete performs climbing movements with the feet off the ground, thus subjecting the fingers to the full body weight. A study investigating radiographic changes in the fingers of top level climbers revealed that only those climbers who performed this kind of training had osteoarthrotic changes as a consequence of neglected epiphyseal fractures\textsuperscript{46}.

**CONCLUSION**

We were able to investigate epiphyseal fractures of the fingers in adolescent climbers and some of the circumstances leading to these fractures. As this is only a descriptive study risk factors cannot be determined. However the fact that all athletes were climbing at a high level with a rigorous training routine may well be a factor increasing the risk for such an injury. Furthermore we were able to show that all subjects were within a year of the first signs of puberty and within their pubertal growth spurt, a time when the growth plate is especially vulnerable for injuries.
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