Diagnosis and Management of Primary Periphyseal Stress Injuries of the Fingers in Adolescent Climbers: A Critical Review

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Abstract

The worldwide rise in popularity of climbing and development of climbing as a competitive sport is reflected by its debut at the 2021 Summer Olympic Games in Tokyo. Digital Primary Periphyseal Stress Injuries (PPSI) in adolescent climbers may pose a significant risk to long term skeletal health. The aim of this article is to critically review research on the diagnosis and management of PPSI of the fingers in adolescent climbers. We adopted a systematic approach to searching for relevant literature. Articles were identified after searches of the following electronic databases: Discover, Academic Search Complete (EBSCO), PubMed, Embase, SPORTDiscus, and ScienceDirect. Conclusive evidence suggests digital PPSI are a consequence of repetitive microtrauma. Pain reported by adolescent climbers on the dorsal aspect of the proximal interphalangeal joint should be investigated promptly to avoid serious negative consequences. Clinicians should be aware of the efficacy of imaging techniques to inform a clinical diagnosis. A conservative management approach is preferred but in rare cases surgical intervention may be necessary. A diagnostic and therapeutic algorithm for digital PPSI is presented.

Introduction

The worldwide rise in popularity of climbing and development of climbing as a competitive sport is reflected by its debut at the 2021 Summer Olympic Games in Tokyo, and inclusion in the Paris Games in 2024 and Los Angeles Games in 2028. In recent years there has been a marked increase in the standard of competition climbing performance including lead climbing, speed climbing and bouldering. Elite adolescent climbers participate in intensive coach led structured training programmes and competitions, including the Youth Olympic Games. Adolescent climbers have competed at the very highest standard in open age categories on the World Cup Circuit.

The risks to skeletal health from stress injuries of the finger epiphyseal-physeal-metaphyseal (EPM) complexes in adolescent climbers is not widely known. A critical review of the incidence, diagnosis, and management of injuries in sport climbing and bouldering emphasised the importance of early diagnosis of epiphyseal growth plate injuries in adolescent climbers to prevent serious negative consequences (1); these include premature closure, growth arrest, and deformity. There are differences in the nomenclature used to describe injuries of the epiphyseal growth plate although nowadays the term Primary Periphyseal Stress Injuries (PPSI) is preferred (2). PPSI may involve damage to one or more of the integral structures within the EPM complex. Halsey, Johnson and Jones (3) raised concern about confirmatory bias and incorrect pattern recognition causing misdiagnosis of PPSI by health care professionals unfamiliar with climbing related injuries. Differential diagnosis of PPSI is challenging due to the complex anatomical structures involved, knowledge of the EPM complex and the appropriate selection and interpretation of imaging techniques to support the clinical decision making and management process (4).

The aim of this article is to critically review research on the diagnosis and management of PPSI of the fingers in adolescent climbers. We will discuss the pathophysiology of injury and the challenges of establishing a differential diagnosis, and we will present a diagnostic and therapeutic algorithm for PPSI.

We adopted a systematic approach to searching for relevant literature. Articles were identified after searches of the following electronic databases: Discover, Academic Search Complete (EBSCO), PubMed, Embase, SPORTDiscus, and ScienceDirect. MESH search terms included ''epiphyses," ''growth plate,'' "salter-harris fractures," adolescent,'' ''pathology,'' and text search terms included growth plate; epiphyseal; climb* (Boolean Phrase); injury* (Boolean Phrase); fracture* (Boolean Phrase). Text search terms were used in combination. Titles and abstracts were reviewed for relevance according to the following eligibility criteria: a primary study, case report, cases series, review article on any type of climbing that reported an estimate of the prevalence of injury and/or investigation or discussion of potential risk factors, published in English and/or German. We conducted a narrative synthesises of relevant studies by gleaning information from articles to summarise and explain our findings.

Pathophysiology

Histologically, epiphyseal growth plates are characterized by chondrocytes at different stages of differentiation, which replicate in the resting zone at a slow rate and replenish the pool of proliferative chondrocytes (5-7). Chondrocytes in the proliferative zone thereby replicate at a high rate, resulting in cells lining up along the long axis of the bone (6, 7). After the cells stop dividing, they differentiate into hypertrophic chondrocytes inducing longitudinal growth (7, 8). During further maturation, the cells calcify and produce factors that attract the invading bone cells and blood vessels, including vascular endothelial growth factor (9), before undergoing apoptosis (7).

Repetitive mechanical stress is the commonly reported aetiology of injury PPSI (10). Repetitive mechanical stress is theorised to disrupt normal metaphyseal blood supply in the metaphysis, thereby altering metaphyseal perfusion which affects the mineralization of hypertrophied chondrocytes (11) . These events may initially be observed as epiphyseal plate widening on imaging; if mechanical stress continues unabated, fractures may occur in the EPM complex (10). If PPSI are misdiagnosed and/or treated insufficiently, chronic ischaemic conditions may result in osseous necrosis and deformity (12).

Epiphyseal growth plates seem particularly susceptible to injuries during periods of rapid growth (7, 13-16). It has been shown in animal and human studies that the strength of the physeal cartilage decreases during pubescence (14, 16). This decrease in strength is a consequence of the structural changes during rapid growth, leading to a thicker and more fragile plate (7, 13). Most clinical cases of digital PPSI in climbers are reported during the pubertal growth spurt when the physis in the middle phalanx closes from palmar to dorsal (4). The occurrence of transitional fractures has been found during the phase of partial closure (4). The pubertal growth spurt, including the fusion of the epiphyseal plate, is primarily caused by estrogen and to a lesser degree by androgen (6, 7, 17-22). It has been proposed that the greater proportion of digital PPSI reported in male adolescent climbers is due to differences in estradiol levels during puberty (7).

In adolescent climbers, the middle and ring fingers are commonly affected digits. The underlying cause of injury is considered to be repetitive stress and microtrauma of the proximal interphalangeal (PIP) joint rather than a single acute event (4, 7, 10, 23, 24). In a case series of 18 adolescent climbers, Schöffl and Schöffl (7) found 95% (21/22) of PPSI affected the middle finger; this was confirmed by follow up work using prospective multicentred analysis that found 91.9% (34/37) PPSI affected the middle finger and only 8.1% (3/37) affected the ring finger in 27 adolescent climbers (4). In contrast, Bärtschi et al. (23) in a case series of 28 adolescent climbers found 58.2% of PPSI affected the middle finger and 29.9% affected the ring finger. Bilateral cases of PPSI, simultaneously or consecutively have been reported (4, 7).

Most injured climbers report using the crimp grip prior to the onset of injury (4, 7, 10, 24-26). As the middle finger is the longest, it receives the highest stress in a crimping position (7). The crimp grip position involves a hyperextended distal interphalangeal joint and a highly flexed proximal interphalangeal joint, and this causes high pressure at the dorsal aspect of the growth plate of the middle phalanx base (4, 7, 23). In addition, the central slip of the extensor tendon attaches at the dorsal aspect of the growth plate, and repeated traction at the point of insertion has the potential to pull the epiphysis out of place (12, 25, 27). In deep flexion there is a translatory shift of the base of the middle phalanx on the head of the proximal phalanx and Bartschi et al suggest this to be a contributary cause of damage to the physis (23). During the crimp grip position a number of different forces influence movement of the physis dorsally (See Figure 1). There is a longitudinal compressive force along the axis of the digit from the contact of the distal portion of the finger with the climbing surface. The flexor digitorum superficialis insertion, more distal to the physis, pulls the metaphysis of the middle phalanx in a volar direction while forces exerted through the central slip pull dorsally on the physeal plate. This is exaggerated during campus board training in which the athlete performs dynamic climbing movements with the feet off the ground, thus subjecting the fingers to the full body weight (7). Schöffl et al. investigated radiographic changes in the fingers of elite level climbers and found that only those climbers who performed campus board training had early osteoarthrotic changes as a consequence of neglected epiphyseal fractures or repetitive epiphyseal strain (28).

[Insert Figure 1 here] *Forces Acting on the Physis of the Finger During Crimp Grip.*

Conclusive evidence suggests digital PPSI in adolescent climbers are a consequence of repetitive microtrauma (4, 7, 10, 12, 23-25). However, there are cases where climbers attribute injury to an acute traumatic event rather than repetitive stress (4). PPSI have also been associated with a specific type of climbing behaviour (7). Recently, Meyers et al. (29) reported an increased occurrence of PPSI in adolescent speed climbers and speculated that the underlying cause was an overall increase in training load per se and not necessarily the specific biomechanical demands of speed climbing itself.

Challenges in Interpretating Epidemiology

Epidemiological studies in sport provide key information on rates, patterns, and associated risks of injury. In particular, the establishment of injury burden, as a measure of overall impact of a health condition, facilitates meaningful comparisons of conditions within a specific population of athletes (30). A major limitation in estimating the incidence and prevalence of PPSI in adolescent climbers is the paucity of robust longitudinal studies that have controlled for exposure, climbing behaviour and load in a sufficiently large sample. Comparison of case series information has suggested an increase in the proportion of reported injuries (4, 31, 32), but such increases are likely confounded by differences in the denominator (number of climbers) at different time points. Most published articles are based on single case reports and case series with basic information on exposure absent. Therefore, it is not possible to accurately determine a temporal link. Based on current epidemiological evidence we cannot be certain that PPSI are the most common injury in adolescent climbers. However, the consequences of failure to detect and/or mismanage a PPSI of the fingers in an adolescent climber can be severe. Therefore, it is necessary for health care professionals to be aware of the condition, diagnostic challenges, and appropriate treatment options. Furthermore, it is important that appropriate preventative guidance is widely known.

Clinical Presentation & Diagnosis

The clinical presentation is of an adolescent climber with gradual onset of single or multiple PIP joint injury without a clearly defined aetiology. Pain usually presents dorsal, around the insertion of the central slip of the extensor mechanism and may be associated with swelling. Pain may be exacerbated by activity and persist despite rest and associated with a recent increase and/or changes in climbing activity, for example weighted pull-ups and feet off campus boarding. An increased use of the full crimp grip position while climbing, possibly relating to a recent progression onto harder routes with smaller holds, may be noted. The middle finger PIP joint is most commonly affected, but the ring finger may also be involved either alone or with the middle finger (1, 4, 25, 33). Hand dominance and side of presentation are not known to be correlated. The most common age of presentation is between 13-15 years and gender distribution favours males (1, 4).

Significant differential diagnoses exist but are usually associated with a sudden traumatic event rather than a gradual onset. These include damage to the peri-articular structures including the collateral ligaments, accessory collaterals, and volar plate. The most common differential diagnosis is an A2 pulley rupture at the distal end of the A2 pulley; this is also the most common injury in adult climbers (33). Pain associated with an A2 pulley injury is usually felt on the palmar aspect of the hand, slightly proximal to the PIP joint and may be associated with bowstringing of the FDS tendon on confrontational testing. Tendinopathy, extensor hood dysfunction and traumatic joint effusions are all possible alternative diagnoses which may also have a gradual onset. Both clinical examination and imaging help with establishing a clear diagnosis.

Clinical examination identifies a swollen PIP joint which may be held in slight flexion. Both active and passive flexion may be restricted compared with other digits. Pain at the limits of flexion is often felt dorsally. Careful palpation of the joint is relatively unremarkable laterally. Palmar palpation is less tender. Dorsal palpation of the base of the middle phalanx around the insertion of the central slip of the extensor mechanism is most tender. A modified Elson's test to assess the central slip can be attempted (34). This puts strain onto the central slip as it inserts into the physeal plate on the dorsum of the PIP joint and this may exacerbate the pain.

In the adolescent climber, finger pain of gradual onset and persisting beyond two weeks of rest, should be investigated (3, 4). The subjective, dynamic, and paradoxical nature of pain means that one should not glean too much specific pathological information solely from pain report. The link between pain and tissue damage may be tenuous, e.g., in situations where climbers continue to climb pain free despite the presence of injury. Situational context activates endogenous neuromodulatory systems that can amplify or diminish pain in the presence of pathology (35). Bioplastic mechanisms can uncouple pain from pathology when pain persists beyond the normal time for healing, i.e., nociplastic pain (36). Nevertheless, one purpose of pain is to alert people to bodily threat, and therefore finger pain presenting to clinic needs further investigation for likely pathology.

Diagnostic Imaging

Radiological imaging is a key tool in the diagnosis and follow up of PPSI injuries. A radiograph is excellent for identifying physeal injuries, fractures, and avulsed fragments, the later which can be easily missed on Ultrasound (US) or Magnetic Resonance Imaging (MRI). A radiograph can also demonstrate post-traumatic abnormalities of the physis including widening, remodelling, premature fusion or abnormal alignment. Furthermore, radiographs can demonstrate ancillary findings in both acute and chronic injuries such as soft tissue swelling (37). Stress radiographs can be used in select cases to assess for stability, though in practice the diagnostic benefit can be limited by pain (38). A minimum of two views perpendicular to each other is recommended, typically an Antero-Posterior view and a Lateral view (See Figure 2). Oblique views are optional and offer an alternative view of the physis that may reveal fractures if the plane of the fracture was not co-linear with the initial views. In cases where plain radiographs do not reveal a fracture but a high suspicion of PPSI exists, a Magnetic Resonance Imaging (MRI) should be performed and used to confirm diagnosis (3).

[Insert Figure 2] *Plain radiograph: Salter Harris type III fracture at the base of the middle phalanx*.

An ultrasound (US) should be performed to assess for a soft tissue injury, with the benefit of dynamic assessment of the soft tissues with gentle stress on the affected digit (39, 40). US also elegantly demonstrates soft tissue oedema, joint effusions and synovitis. Physeal injuries can be seen with high resolution ultrasound scanning (41), however US is not a reliable tool to exclude these in the fingers and should be interpreted in the context of an accompanying radiograph and/or MRI (42). US is a user dependent modality, preferably performed by an experienced operator and we would recommend the use of high-resolution linear array transducer probe, typically 18MHz.

Computed Tomography (CT) and MRI (See Figure 3) are useful adjuncts when more detailed information is needed, particularly in complex cases (4). They can further characterise a known injury or confirm a suspected injury in the context of a normal radiograph and/or ultrasound. Radiographs are usually sufficient in assessing these injuries, however in select adolescent's further information can be gleaned from cross-sectional imaging.

[Insert Figure 3] *MRI confirming the Salter-Harris type III fracture at the base of the middle phalanx.*

MRI should be optimised with correct patient positioning, use of a dedicated surface coil, and small field of view images with specific protocols (43). A 1.5 Tesla MRI can provide adequate information; however, a 3 Tesla MRI will provide higher resolution images and thus potentially yield better diagnostic information (27). MRI provides excellent assessment of signal abnormalities of the physis, and the adjacent osseous and chondral structures (27). It can also demonstrate associated tendon, pulley and ligamentous injuries (39). MRI has the added benefit of depicting marrow oedema, which in simplistic terms is bright on fluid sensitive images such as T2-fat saturated images or short tau inversion recovery images.

CT is of benefit in assessing the bony architecture and depicting localised areas of sclerosis and osteopenia that are not appreciable on a radiograph (38). CT can demonstrate post-traumatic fusion of the growth plate, small avulsed fragments and is particularly of use to aid surgical planning where clinically appropriate. A non-contrast CT of the hand is performed, with multiplanar reconstructions in axial, coronal and sagittal planes. 3D volumetric reconstructions can also be obtained. Due to the high levels of radiation, CT should only be performed in instances where it would potentially influence clinical management.

A Salter-Harris type III physeal fracture of the middle phalanx is the most common presentation reported in adolescent climbers to date. As our understanding of PPSI develops then we may need to develop an alternative classification system which takes into account those injuries that may not always present as fractures (4).

Diagnostic Algorithm for PPSI

We have developed a new clinical diagnostic and therapeutic algorithm for PPSI by consensus and based on evidence and expertise of the authors (see Figure 4). The algorithm is an evolution of previous work published by Jones and Johnson (33), Jones, Schöffl and Johnson (1) and Schöffl et al., (4). The rationale for the development of an algorithm for PPSI is the increase in our understanding of the condition in terms of pathology; application and staging of imaging techniques and efficacy of conservative and surgical management options. We accept global differences and variation in surgical specialities, hospital referral, imaging and management; therefore, local consistency with the algorithm may vary.

[Insert Figure 4] *Diagnostic & Therapeutic Algorithm for Digital PPSI*

Management

In general, the treatment is based on a conservative management approach, and excellent results have been reported (3, 4, 23). Bartischi et al., (23) evaluated the clinical outcomes of epiphyseal stress fractures in 28 adolescent climbers. All patients were treated conservatively for between 3-12 months, mean time for radiological union of a fracture was 35 weeks and recovery for a symptomatic sprain was on average 24 weeks. Case reports have tended to state guidance rather than specific detail; recently Meyers et al., (44) presented a return-to-sport protocol for youth climbers who had sustained an epiphyseal fracture of the finger. Whilst broadly supporting the authors rehabilitation recommendations; using a percentage reduction model of normal climbing time to calculate load for each stage of rehabilitation is imprecise. Total load is better considered using variables such as performance standard (i.e., grade of climb), number of ascents (completed and attempts) and type of climbing behaviour for example lead, redpoint, bouldering (33, 45). It is vital that clinicians engage with coaches to set realistic load boundaries based on individual data. As repetitive load is the principal stimulus for digital PPSI, abstaining from climbing, gradual phased return to activity, patient education and the setting of realistic time goals are key principles for a successful rehabilitation and unimpaired recovery.

The initial management for digital PPSI requires the immediate cessation of all climbing related activities for approximately 6-8 weeks (3, 4, 7). During this period cardiorespiratory fitness should be maintained and selective progressive resistance exercises for major muscle groups undertaken. Dependent on injury severity a resting splint may be utilised for the initial 2-3 week period, with removal to complete active and passive range of motion exercises (4, 25). Prior to commencement of climbing specific rehabilitation, radiological evidence of healing, full pain free range of motion and clearance from the respective health care professional is advised (44).

The climbing specific rehabilitation phase aims to return a climber to pre-injury levels of performance. Using an individual management approach allows the differentiation of workload based on severity of injury to be set. This may be achieved by a combination of the following: reducing the number of weekly sessions, limiting performance standard, modifying climbing behaviours, use of holds that promote open handed techniques. Rehabilitation can include the use of climbing specific training equipment for example a 'grip block' (See Figure -5) and 'hangboards' to progressively increase strength in a controlled manner. Dynamic finger training, for example 'campus boarding,' should be avoided during all stages of rehabilitation (46).

The central tenet of management is the progressive incremental increases of workload volume. The climber should be informed that rehabilitation times vary, and load modification should be maintained until symptoms resolve (23). Any aggravation of symptoms should result in the immediate suspension of rehabilitation activity and Health Care advice sought before return.

[Insert Figure 5] *Grip Block (Reproduced with permission of Lattice Training Ltd)*

There is a small cohort of patients who fail to respond to non-surgical management of PPSI and have been reported as benefitting from spot drilling of the epiphyseal plate to induce fusion of the physis and resolution of their painful symptoms. El-Sheikh et al., (12) report success with their technique performed percutaneously in two patients who had symptoms for over 9 months prior to surgery. A

0.7mm k-wire was drilled through the dorsal fragment under image guidance at 4 different angles: into the intact epiphysis transversely, the intact physis, the middle phalanx proximal metaphysis and the middle phalanx distal metaphysis. Post-operatively they were immobilised for 2 weeks, followed by graduated range of motion exercises before a return to training at 3 months. Decisions regarding the need for this intervention and the timing of the operation need to be taken carefully on a case by case basis with an appropriately qualified surgeon.

In terms of preventative measures, we recommend the routine monitoring of load in adolescent climbers particularly during their peak velocity growth phase (45). Consideration should also be given to use of the Oslo Sports Trauma Research Centre questionnaire on health problems (47). The questionnaire has utility in the early detection of symptoms of injury in athletes. The questionnaire is administered weekly, simple to complete and alerts medical staff to any potential problems that may require further investigation.

Summary

PPSI of the fingers in adolescent climbers may pose a significant risk to long term skeletal health in those individuals who are misdiagnosed and/or continue to climb unrestricted following diagnosis. Risks include partial or complete separation of the epiphysis from its attachment, premature closure, and in some cases deformity. Pain reported by adolescent climbers on the dorsal aspect of the proximal interphalangeal joint should be investigated. Clinicians should be aware of the efficacy and limitations of imaging techniques to inform a clinical diagnosis of PPSI and its use subsequently to monitor return to sport decisions. A conservative management approach is preferred but in rare cases surgical intervention may be necessary.

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