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ijhighschoolresearch.org
REVIEW ARTICLE

Finger Injuries among Adolescent Climbers: Causes, Prevention, and Rehabilitation

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ABSTRACT: Rock climbing's increase in popularity brings more intense training methods, leading to more instances of finger injuries. Adolescents in particular are prone to finger injuries, as physiological changes during puberty cause the fingers to be less resistant to the biomechanics involved in climbing. To ensure a balanced risk-reward ratio, understanding and assessing the cause, prevention, and rehabilitation of any kind of injury is of the utmost importance. This review paper covers adolescent hand anatomy to determine what makes it more susceptible to certain injuries. Finger Flexor Pulley Injuries (FFPIs) and Epiphyseal Growth Plate Injuries (EPGIs) are common among adolescents, and a proper recovery plan is necessary to prevent an acute injury from developing into a chronic condition, such as osteoarthritis. It is proposed that adolescents are more prone to injuries because of the body's priority on growth rather than reinforcement. After an injury, the initial diagnosis is the most important part of the recovery process.

KEYWORDS: Biomedical and Health Sciences, Pathophysiology, Pulley, Injury, Growth Plate, Fracture, Osteoarthritis.

Introduction

Rock climbing as a sport is increasing in popularity, and along with it comes more intense training methods. As a result, injuries are appearing more often as the competitive setting sees more serious climbers. In a 2000 study, a total of 126 injuries were examined: 63% were located in the hand, and 37% were located elsewhere in the upper body.[1] These injuries are typically a result of the intense forces applied to the fingers, most notably in the "half crimp" and "full crimp" hand positions. This technique forces the proximal interphalangeal joint (PIP) to be flexed at 90 degrees and hyperextends the distal interphalangeal joint (DIP). These practices can cause gradual strain, breaks, or ruptures to parts of the hand, such as the epiphyseal growth plate or pulley system.[2]

The issue persists when considering the population of youth climbers as well. Many teenage climbers undergo the same intensive training as professionals, and the injuries they sustain as a result can cause lifelong issues.[3] A handful of climbers experience early chronic developments in their career with conditions such as osteoarthritis making themselves present, and others go a long time in their career without experiencing any physiological change.[4] This presents us with the question of what variables are in play that allow an otherwise acute injury to an adolescent to become chronic. It is hard to know for certain if a permanent pathological change is a result of the injury itself or failure to nurse the injury back to health efficiently.[5] In the case of the latter, it is vital that both athletes and doctors are aware of what the proper steps should be in recovery to maintain a long-lasting climbing career.

In this paper, I will examine the physiology of an adolescent rock climber's hand as it experiences growth to determine what factors a) make it more susceptible to injury, and b) contribute to an injury becoming chronic vs staying acute. I will analyze what rehabilitation processes have been proven to be most effective in ensuring full and stable recovery.

Review Methodology

The articles included in this review article were sourced from PubMed by searching keywords listed above. Articles with relevance to growth plate injuries, pulley injuries, and osteoarthritis were closely examined. If the author decided an article was especially useful, more articles from the same author or authors were prioritized. The date of publication was examined on all articles for the author to compare how research in adolescent hand injuries has evolved and what questions remain unanswered.

Hand Anatomy

Included in the human hand is a finger flexor pulley system (FFPS), which consists of synovial and retinacular tissue, known as pulleys. The combination of both these tissues allows for fluid movement and flexion of the fingers within the tendon sheath, as well as securing tendons in place. Within each finger (excluding the thumb), there are 5 annular pulleys labeled A1-A5 and 3 cruciate pulleys labeled C1-C3. Together, the pulley system forms a lubricated tunnel that contains the flexor digitorum profundus (FDP) and flexor digitorum superficialis (FDS), keeping them close to the bone. (See Figure 1) The A2 and A4 pulleys attach directly to bone, while the A1, A3, and A5 pulleys attach to the volar plate.[2] The volar plate, which is found on the palmar side of the hand, works to prevent hyperextension and connects the proximal phalanx to the middle phalanx.

In addition to the FFPS, epiphyseal growth plates are located at the bases of interphalangeal joints. These growth plates

DOI: 10.36838/IJHSR810.57

are made up of chondrocytes, cells that secrete proteins that collectively form the extracellular matrix. Specifically, chondrocytes in fingers' growth plates make up hyaline cartilage, a type of cartilage that ossifies when fully mature, producing new bone. These cells will undergo apoptosis, making room for new chondrocytes to continue bone growth.[3] Within both males and females, the hormone estradiol also contributes to slowing down bone growth and allowing the growth plates to fuse. During periods of rapid growth, estradiol levels are low, which allows for stimulation of bone growth. Once estradiol levels pick up, bone growth is inhibited, and the growth plates begin to close and eventually fuse.[6] Considering females have more estrogen, their growth plates finish growing and fuse earlier than those of males. This may lead to male climbers experiencing a higher rate of injury during adolescence in comparison to females.

A study done on the German Junior National Team and additional recreational climbers revealed that the hands of climbers undergo cortical hypertrophy over time.[5] To bear the intense forces experienced during climbing, many climbers' fingers experience thickening of the cortical bone, which makes up the outer layer of phalanges. This change is not rapid; hypertrophy occurs slowly over the course of a climber's career, as proven in a study of male elite climbers after a 10-year follow-up.[7] Although this study had a primary focus on adults, it was observed that adolescents experience the same cortical hypertrophy but at a slower rate. These changes to the fingers are adaptive rather than pathologic.

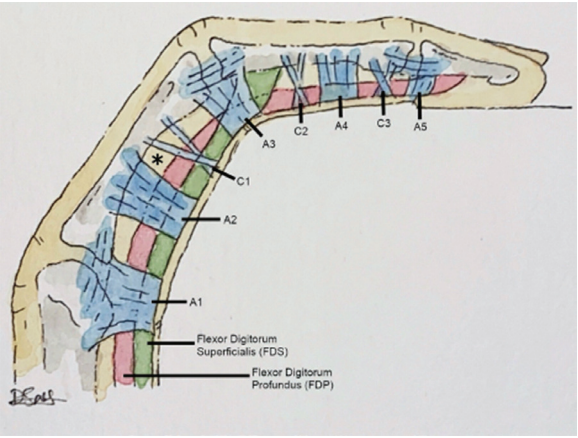

Figure 1: The Finger Flexor Pulley System is made up of five annular pulleys labeled as A1-A5 and three cruciate pulleys labeled as C1-C3. The FDS and FDP flexor tendons are contained within the lubricated tendon sheath.[2]

Pathological Changes

Injuries vary from being acquired from an acute onset event or over a period of time in which repetitive microtrauma has occurred. The most common site of acute injuries is the FFPS. They are the most common injuries in rock climbing, as proved by studies done in the periods 2017-2018, 2009-2012, and 1998-2001. In each study, the percentages of pulley injuries among the climbers studied were 31.1%, 29.5%, and 49.4%, respectively, among the full group.[8] As mentioned above, "crimping" is a hand position that climbers commonly use to pull themselves from small ledges. To assist the FDP and FDS tendons in generating the force possible to make this movement possible, the FFPS works to keep these tendons close to the bone to generate torque in a similar way as drawing a bowstring would work.[9] When too much force is applied for the pulleys to handle (e.g, the climber "pulls too hard"), this can cause a partial tear, full tear, or full rupture of the pulley.

These acute events can be identified by a pop or snapping sound in any of the fingers, along with a tearing sensation after attempting to bear a load with it. As a result, the FDP and FDS tendons are contained to the bone by one less anchor point, a condition known as "bowstringing". (See Figure 2) Although inconclusive, an accepted tendon-to-bone distance is around 2 mm, with anything greater showing the possibility of pulley injury.[2] Of the 5 annular pulleys, the A2 is the thickest and strongest, with an average length of 16.3mm. It attaches directly to the bone at the proximal phalanx and bears the most load, but this consequently means it also has the greatest possibility for injury when bearing load.[10]

A grading system proposed by Volker Schoffl et al. exists that classifies the injury with a grade from 1-4: a Grade 1 injury is a simple strain with a tendon-bone length of <2 mm without any real bowstringing; a Grade 2 injury is either a full rupture of the A4 or a partial rupture of the A2 or A3; a Grade 3 is a full rupture of the A2 or A3; and a Grade 4 consists of many ruptures throughout the entire FFPS. Both MRI and Ultrasound are viable radiographs in accurately detecting the injury.[2]

Comparing adolescent climbers to adult climbers, FFPS injuries don't present many differences. In both age ranges, they occur as a result of intense, acute events, and the degree to which the injury presents itself is more correlated with the intensity of the activity in which the pulley was injured rather than the physiological anatomy of the aging hand.

Although acute FFPS injuries are the most common type of injury in the rock-climbing community as a whole, epiphyseal growth plate injuries (EPGIs) are incredibly common among adolescent athletes.[6]

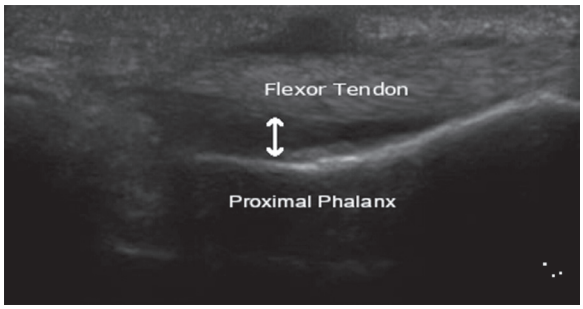

Figure 2: Bowstringing is depicted by the flexor tendon being unnaturally far from the bone. A greater distance between the flexor tendon and the proximal phalanx results in a loss of mechanical torque.[2]

Unlike FFPS injuries, EGPIs are typically a result of repetitive use rather than an acute event. As noted above, epiphyseal growth plates are made up of chondrocytes that secrete cartilage matrix. This phase of bone formation is highly important to hand development in adolescents. The problem arises when adolescents experience repetitive mechanical stress as a result of intense training. Repetitive mechanical stress is thought to

disrupt blood supply to the physis of the hand, and therefore hypertrophied chondrocytes struggle to mineralize cartilage.[3] Based on these findings, it is proposed that growth plates become more fragile and prone to fracture, explaining why adolescents are more prone to these kinds of injuries.

Growth plate fractures can be classified using the Salter-Harris classification system. A Salter-Harris fracture refers to a fracture in the growth plate that can be classified as one of 5 types, with types 1 and 3 being the most common among rock climbers.[6-11] A type 1 is when the break occurs straight through the growth plate at the proximal phalanx, and a type 3 is when the break extends through the growth plate to the end of the bone. (See Figure 3) Both these injuries can cause a great amount of stiffness, swelling, restricted range of motion, and pain in the target area.[11]

Furthermore, a diagnostic study done with 57 male climbers and 38 female climbers presented 137 injuries across the body. Of the entire catalog, 45.3% of the injuries were growth plate injuries, with males making up the majority. Although the diagnosis was done with more male than female climbers, evidence supports that males are even more prone to EPGIs than females, especially when considering that they have open growth plates for a longer period of time than females, as mentioned above.[12]

Chronic Developments

As mentioned above, it has been observed that over the course of a person's climbing career, their cortical bones tend to broaden at the joint base of their fingers to adapt to the intense rigor of the sport.[5] Evidence of cortical hypertrophy supports the notion that climbers' hands undergo adaptive changes, but it is unclear whether changes can be pathologic beyond injury. The most common example is the development of the condition osteoarthritis, a disease process that causes a breakdown of cartilage that can result in pain, swelling, decreased range of motion, difficulty gripping, or a decrease in pinch strength.[13] Across a vast amount of research, there appears to be an uncertainty in the risk of adolescent climbers developing osteoarthritis.

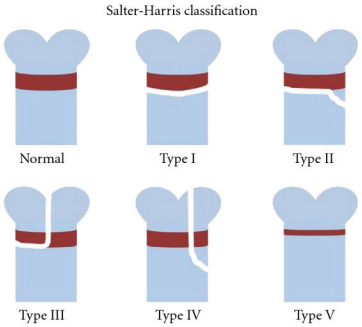

Figure 3: Salter-Harris breaks the visualized diagram. The red band indicates the growth plate. Type 1 is a fracture that goes through the growth plate, separating the end of the bone from the growth plate. Type 2 is a fracture that goes through the growth plate and extends into the metaphysis (below the red band). Type 3 is a fracture that goes through the growth plate and extends into the epiphysis (above the red band). Type 4 is a fracture that extends through the growth plate, metaphysis, and epiphysis. Type 5 is a fracture that compresses or crushes the growth plate.[19]

In one case, climbers as young as 20 years old have been radiographed and shown signs of osteoarthritis, while a group of tested Swiss climbers in the age range of 10-17 years showed no signs of the condition despite a climbing career of up to 7 years.[4] A reasonable hypothesis is that the adolescent climbers have not had a long enough climbing career for these pathological changes to occur. Of course, as mentioned above, cortical hypertrophy is still present, but these changes are adaptive rather than pathologic.

In another study, this hypothesis that adolescent climbers have not climbed long enough for pathological changes to occur is supported regarding investigating the development of osteophytes, bony outgrowths at the base of bone, most commonly found at the DIP.[7] It was suggested that base osteophytes start forming in the first 15 years of a rock climber's career. After reexamining the patients 10 years later, it was observed that the already present osteophytes progressed to such a point that they can be considered symptoms of osteoarthritis.[7] This data suggests that, along with adaptive cortical hypertrophy, base osteophytes develop over the course of a climber's career. However, whereas cortical hypertrophy occurs as an adaptive measure, base osteophytes slowly progress during the first 15 years of a climber's career in an insignificant way. After this time period, osteophytes manifest themselves as radiographic signs of osteoarthritis.

To summarize, an adolescent climber may go a long way in their career without experiencing any of the injuries mentioned above, such as an EPGI or FFPI, but along with adaptive changes their hands and fingers undergo, pathological changes may develop along with them. This does not mean that adolescents develop osteoarthritis during this age, but rather it should not be surprising for the condition to manifest itself more prolifically later in a climber's career. Time is always a factor, but there is still the question of the minority group that contracts osteoarthritis at such a young age.

In addition to slow-rate osteoarthritis developing with base osteophytes over a long period of time, EGPIs contracted under intense training measures, such as campus boarding, are another way for osteoarthritis to occur. As mentioned above, radiographic evidence is the most common and most efficient way to diagnose a case of osteoarthritis. Doctors use the Kellgren-Lawrence Classification system to assign the subject bone a grade from 0-4, with a grade 0 signifying no evidence of osteoarthritis and a grade 4 signifying severe osteoarthritis. Doctors make this conclusion by searching for the presence of osteophytes, joint space narrowing, and any bone deformity.[15]

In the study done on the German Junior National Team mentioned above, there was only one case of osteoarthritis, and it so happens that the climber experienced an epiphyseal growth plate fracture. In addition, the climber was also reported to have engaged in intense campus board training. This presents the hypothesis that EGPIs may be a cause for early-onset osteoarthritis, and the EPGI itself may be a result of intense training. Moreover, if osteoarthritis does not present itself immediately after the injury, it has been observed in some cases that it still presents itself up to 10 years later.[5-10]

DOI: 10.36838/IJHSR810.57

Another study over the course of a 4-year period examining EGPIs of adolescent climbers reported that almost half of the athletes trained on campus boards. The question of whether or not campus boarding in particular is the root cause of EPGIs and, therefore, some cases of osteoarthritis is now present. Above, I mentioned that EPGIs are typically the result of repetitive overuse injuries, and this remains the case with campus boarding. However, campus boarding is a special type of training most commonly used to build raw finger strength and, therefore, adds to the already intense load being placed on the fingers during normal climbing sessions. In summary, intense training that puts the growth plates at risk of injury, such as campus boarding or heavy reliance on crimping, can lead to EPGIs. These, in turn, have a high likelihood of manifesting into osteoarthritis via the Kellgren-Lawrence scale.[6]

Diagnosis and Rehabilitation

Like any other sport, athletes who have experienced any sort of finger injury should prioritize proper rehabilitation and healing before returning to climbing. To indicate a fully healed finger, an athlete must be pain-free, have a full/close-to-full range of motion, have minimal swelling, and have qualitative radiographic data that proves complete internal healing.[6] Before designing a proper recovery program for climbers, it is vital for doctors to properly identify the kind of injury as well as the severity.

For the FFPS, grade 1-3 injuries can be approached non-surgically with taping methods and specified weeks of rest. Taping with methods such as H-tape helps reduce bowstringing in the A2 by up to 50%.[8] Grade 1-2 injuries can heal in 6 weeks, and taping for an additional 3 months is recommended after the athlete begins climbing again. For a Grade 3, immobilization of the finger with a splint or ring is recommended for up to 2 weeks before carrying out the same process as a Grade 1-2. As for Grade 4 injuries, surgery is the best course of action. Grafting tissue is an efficient way of repairing a ruptured pulley or tendon, and the return-to-climb protocol remains the same in ensuring complete healing.[16]

For EPGIs, X-ray should be the priority, but it is important to note that fractures may take a few months to show up on an X-ray.[17] In this study, with 28 climbers, many came into the clinic with finger pain but did not actually have a visible fracture present. The pain without a visible break can be concluded as early-stage EPGI, in which the bone starts to atrophy and becomes brittle as a result of intense training. In this case, it is recommended for doctors to follow up with their patients for 2-3 months until the patient has no pain. In this way, we prevent the development of an actual stress fracture.[18]

In the case of a visible fracture, CT scans are the most effective radiographs in assessing damage. Although both MRIs and CT scans are promising diagnostic techniques, MRIs are not well-suited to depict the full severity of the injury. CT scans present a much more accurate image of the injury, but both scans are costly in the medical industry. To compensate, it is suggested that CT scans are only ordered if doctors are unable to determine if the bone is healing with only X-rays.[17]

Salter-Harris fractures can be treated conservatively in a non-surgical manner as long as a correct diagnosis is made at an early enough point. Splinting the finger into one position to allow the bone to heal is the most common method of rehabilitation for around 3 months. In one case, a patient went many months without consulting a doctor about finger pain, and the result was severe osteoarthritis.[17] This leads me to conclude that, in addition to the climber following through with immobilizing the finger to ensure proper healing, a correct diagnosis from a doctor early on is vital in preventing any long-term effects, such as osteoarthritis.

Outlook

Rock climbing is a high-risk sport that constantly puts athletes at risk of injury, especially with its growing population of both adult climbers and youth climbers.[1-3] The purpose of this paper was to dive into the specifics of finger injuries, with a focus on their presence in adolescent climbers.

Injuries to the finger flexor pulley system are common in climbers of all ages, and injuries to epiphyseal growth plates are exclusive to adolescents.[2,3] Both injuries are caused by excessive load placed on the fingers as a result of the intense biomechanics needed to generate force.[2] FFPS injuries happen in a single acute event in which the intense load causes a pulley to sprain, tear, or rupture. This decreases the amount of support holding the flexor tendon to the bone, causing the finger to lack stability and strength while climbing.[2]

After a critical review of literature regarding the body's development phase during the adolescent stage of life, I concluded that the body prioritizes growth rather than reinforcement, causing the fingers to be more brittle as the bone develops. EPGIs happen as a result of repetitive stress to the fingers that eventually fractures the growth plate while it is fragile.[3] It is normalized for adolescent climbers to engage in rigorous training methods such as hangboarding, but such training methods put a great deal of stress on the fingers.[5]

This paper also explored the conditions under which climbers end up developing more serious pathological chronic issues, such as osteoarthritis. Climbers' fingers undergo a great deal of cortical hypertrophy as an adaptive measure to bear with the intense load they experience, but bony outgrowths along the base of the bone, called osteophytes, also start developing along the first 15 years of a climber's career.[5] These osteophytes can grow to the point of causing symptoms of osteoarthritis without the climber ever experiencing any injury.[13] In the case of an EPGI, osteoarthritis may manifest itself sooner in a climber's career.[5]

To effectively treat these injuries, a proper diagnosis and recovery plan are essential. For FFPS injuries, anything under a grade 4 injury can be approached conservatively with time and taping to help heal.[8] Grade 4 injuries with multiple pulley ruptures need to be approached surgically.[16] For EPGIs, it is important to diagnose first with x-ray imaging and then treat the injury with adequate rest time till the climber is pain-free. If there is no visible fracture on an X-ray but the climber still feels pain, a CT scan can give a clearer picture to visualize the break.[17] The climbers should avoid putting any stress on the

finger until they are completely pain-free, and treatment is typically conservative, involving splinting the finger into one position.

In both adolescent and mature rock-climbing athletes, thickening of the cortical bone occurs as an adaptive measure to the intense load placed on the fingers. However, because of the adolescent body's priority on growing and developing, they are more prone to growth plate injuries. In addition, younger athletes should be cautious of rigorous training methods such as campus boarding, for it can increase the chances of getting injured. To ensure an injury has the highest likelihood of successful healing without developing into a pathologic chronic condition such as osteoarthritis, a correct diagnosis of the injury and a proper recovery plan are essential. The top priority is ensuring the climber has no pain, and climbing should be fully put on hold or severely limited in time and intensity till pain subsides. Many finger injuries can be treated conservatively with either taping or splinting, and surgical repair should be considered in cases of severe ruptures or breaks. Altogether, youth climbers should be consistent in warming up properly to minimize the risk of injury, and any injuries should be approached carefully to ensure a long-lasting climbing career.

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DOI: 10.36838/IJHSR810.57

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