Mechanisms of Acute Knee Injuries in Bouldering and Rock Climbing Athletes

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Background: There is limited insight into the mechanisms of knee injuries in rock climbing and bouldering in noncompetitive and competitive athletes.

Purpose: To examine the traumatic mechanisms of injury, demographics, distribution, and severity of knee injuries in affected athletes.

Study Design: Case series; Level of evidence, 4.

Methods: During a 4-year period, we performed a retrospective multicenter analysis of acute knee injuries in competitive and noncompetitive climbing athletes. Traumatic mechanisms were inquired and severity levels, therapies, and outcomes recorded with visual analog scale, Tegner, Lysholm, and climbing-specific outcome scores.

Results: Within the observation period, 71 patients (35% competitive athletes, 65% noncompetitive athletes) with 77 independent acute knee injuries were recorded. Four trauma mechanisms were identified: high step (20.8%), drop knee (16.9%), heel hook (40.3%), and (ground) fall (22.1%). The leading structural damage was a medial meniscal tear (28.6%), found significantly more often in the noncompetitive group. A specific climbing injury is iliotibial band strain during the heel hook position. Most injuries resulted from indoor bouldering (46.8%). Surgical procedures were predominantly necessary in noncompetitive climbers. One year after the injury, the Tegner score was 5.9 ± 0.8 (mean ± SD; range, 3-7); the Lysholm score was 97 ± 4.8 (range, 74-100); and the climbing-specific outcome score was 4.8 ± 0.6 (range, 2-5).

Conclusion: Increased attention should be placed on the climber's knee, especially given the worldwide rise of indoor bouldering. Sport-specific awareness and training programs for noncompetitive and competitive climbing athletes to reduce knee injuries should be developed, and sports medical supervision is mandatory.

Keywords: meniscal tear; anterior cruciate ligament (ACL) injury; injury mechanism; valgus; heel hook; sports injury

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With the worldwide growing interest and enthusiasm for rope climbing and bouldering, the sport has recently been selected as a new discipline for the upcoming 2020 Summer Olympics in Tokyo, Japan. Previous sports medicine research in rock climbing was dominated by studies focusing on sport-specific injury patterns of the upper extremity, such as finger pulley injuries or lumbrical muscle injuries,[12,16] and injury incidences have been described.[7,30] Overstrain injuries in climbing have been indicated to mainly affect the upper extremity, whereas acute traumatic injuries, such as ankle joint distortions, are predominantly seen on the lower extremities.[5,16,24] Nevertheless, available literature emphasizes the fact that, overall, most injuries are of a minor grade.[23] With 0.2 injuries per 1000 hours in recreational athletes[25] and 3.1 in competitive climbing,[26] incidence rates are documented to be low.

Rock climbing consists of 2 major subdisciplines that differ slightly in terms of physical demands and protection: "rope climbing" (ie, sport climbing) and "bouldering." While rope climbing requires a range of physical and psychological capacities, bouldering features a few very difficult movements at lower heights, thus demanding

physical strength and technical skills. Both disciplines are performed on real rock and artificial walls. The main devices used in the protection of a fall are a rope and harness in sport climbing and bouldering pads for bouldering. Given the worldwide indoor bouldering boom and the changes in the athletes' preferences toward this subtype of rock climbing, we are currently finding an increase of absolute injury numbers, which are of a greater variety than those previously explored.[2,5,11,19] Among these, knee injuries were recently reported to increase in numbers and relevance, and Josephsen et al[8] reported a higher percentage of knee injuries in indoor bouldering as compared with outdoor bouldering.[2,5,8,19,20] This change is explained by modern climbing and training methods causing a wider spectrum of climbing-related injuries.[5,11,19,21] While knee injuries are among the most frequently diagnosed sports injuries in general, rock climbing and bouldering have not been identified as highly hazardous activities for these types of injuries.[1,11,24] In a recent report from one of the world's biggest societies of sports medicine (German-Austrian-Swiss Society for Orthopaedic Traumatologic Sports Medicine), the incidence of knee injuries from our database has doubled as compared with findings from 1998 to 2001.[16,20] While 6.7% of all climbing injuries treated in our climbing-focused outpatient clinic in the recent past were knee injuries, other current studies report that up to 10% of total injuries are knee injuries among climbers.[2] This finding strengthens the theory that there is an increase of knee injuries caused by rock climbing and bouldering. To date, traumatic mechanisms and demographics of knee injuries in bouldering and rope climbing are undefined. In contrast, detailed descriptions of traumatic mechanisms have been described in other sports,[3,4,9] which have formed the basis for exercise-based injury prevention.[13,14]

The objective of this study was to analyze and describe various traumatic mechanisms, demographics, distribution, and severity of knee injuries in noncompetitive and competitive athletes. We hypothesized that there are various sport-specific mechanisms of knee injuries in rope climbing and bouldering.

METHODS

Patients

Between 2015 and 2018, we investigated all athletes (noncompetitive and competitive) with acute knee injuries related to rope climbing or bouldering (indoor and outdoor) treated in 2 specialized outpatient sports medicine clinics that are referral centers for climbing-related injuries (eg, German Alpine Club). Knee injuries caused by rope climbing or bouldering activities were defined as medical conditions forcing the athlete to rest from the sport because of pain or dysfunction and the necessity to seek help from a specialist. The study was approved by the institutional review board, and all patients provided informed consent.

Diagnostic Algorithm

Diagnoses were based on clinical investigation and radiological findings. All final diagnoses were reviewed and confirmed by the senior author (V.S.), who is a board-certified orthopaedic surgeon and certified knee surgeon with >25 years of experience. Patients who were initially seen and treated in emergency departments were later reexamined in the outpatient sports medicine clinics. While one clinic is a trauma center located in one of Germany's biggest and most popular outdoor climbing areas, the second clinic is located between world-renowned climbing destinations in Utah. A standard questionnaire and examination protocol was conducted. Only patients experiencing pain during or after rope climbing or bouldering were included in the study. Tegner, Lysholm, and climbing-specific scores were used for evaluation of preinjury status of the affected knee (Tables 1 and 2).

Classification

The Union Internationale des Associations d'Alpinisme (UIAA) metric scale was used for evaluation of climbing levels, and the V scale was used for evaluation of bouldering levels as previously published.[22,24] For classification of injury severities, the UIAA injury score was used following the UIAA MedCom recommendation.[22]

Traumatic Mechanisms of Injury

Athletes were asked to describe the exact mechanism of injury (MOI) that caused the pain, based on the body position and activity in the given climbing route and observations of their climbing partners. Subgroup analyses were then made per the different traumatic mechanisms (Figure 1).

Therapeutic Algorithm

Treatment consisted of an individualized posttraumatic injury therapy protocol for each athlete with gradual return to sports. In case of surgical treatment (eg, anterior cruciate ligament [ACL] reconstruction or meniscal repair), individual postoperative physical therapy protocols for each patient were used according to diagnostic and intraoperative findings. Physical therapy goals included range of motion, muscle strengthening, and dynamic stability exercises progressing to functional performance.

Outcome

All patients were seen for follow-up evaluations 6 and 12 weeks after the initial consultation and contacted after 1 year. The visual analog scale scores were collected at the initial visit and after 1 year. Tegner, Lysholm, and climbing-specific scores were recorded at 1 year.[18] All patients self-reported preinjury conditions (Table 2).

Statistical Analysis

Microsoft Excel was used for data collection; statistical analyses were performed with SigmaStat software (Systat Software Inc, Version 11.0). Values were checked for

TABLE 1
Patient Demographics, Treatment, and Outcome Grouped by Traumatic Mechanisms of Injury[a]

	All Patients	High Step	Drop Knee	Heel Hook	Fall	*P* Value
Patients	71	16	13	26	16	
Injuries	77	16 (20.8)	13 (16.9)	31 (40.3)	17 (22.1)	
Age, y	32.3 ± 10 (15-61)	35.7 ± 11.1 (21-53)	32.9 ± 12.1 (16-61)	32.2 ± 8.6 (16-49)	29.4 ± 8.4 (15-46)	NS
Sex, men:women	48:29	11:5	9:4	21:10	7:10	
Height, cm	174.8 ± 8.7 (154-194)	176.2 ± 6.3 (164-184)	175.1 ± 6.4 (167-185)	175.1 ± 10.9 (154-190)	172.4 ± 8.4 (160-194)	NS
Weight, kg	66.7 ± 11.9 (39-91)	68.4 ± 11.3 (51-86)	70 ± 13.6 (52-91)	68.1 ± 11.4 (49-90)	59.6 ± 11.1 (39-82)	NS
Level						
Rope climbing[b]	8.7 ± 1.9 (5-12)	8.6 ± 2 (5-11.7)	8.6 ± 1.6 (6-11)	9 ± 1.9 (5-12)	8.2 ± 2.1 (5-11.7)	NS
Bouldering[c]	7.6 ± 4.3 (0-15)	7 ± 4.6 (0-15)	6.8 ± 3.6 (2-12)	8.6 ± 4.5 (0-15)	6.9 ± 4.6 (1-14)	.03
Years						
Rope climbing	11 ± 7.6 (0-31)	11.4 ± 8.8 (0-30)	10.9 ± 8.6 (1-31)	12.2 ± 6.7 (2-24)	8.5 ± 7.1 (1-20)	NS
Bouldering	9.2 ± 7.3 (0-30)	11.2 ± 8.9 (0-30)	5.3 ± 4.8 (0-15)	10.7 ± 7 (0-20)	7.6 ± 6.9 (0-20)	.03
Bouldering[d]	58.2 ± 31.1 (0-100)	51.2 ± 29.0 (0-100)	41.9 ± 28.7 (0-90)	62.6 ± 31.7 (0-100)	69.1 ± 29.6 (0-100)	.045
Competitive level, yes:no						
Competing	28:49 (36.4)	5:11 (6.5)	3:10 (3.8)	14:17 (18.2)	6:11 (7.8)	
World Cup	17:60 (22)	3:13 (3.9)	1:12 (1.3)	9:22 (11.7)	4:13 (5.2)	
Training, h/wk	12.9 ± 10.7 (0-40)	11.3 ± 10.7 (0-30)	11.2 ± 8.9 (3-35)	15.1 ± 12.4 (2-40)	11.8 ± 8.7 (2-30)	<.001
Warm-up routine, yes:no	61:16	11:5	11:2	26:5	13:4	NS
Alternative sports yes:no	54:23	12:4	10:3	21:10	11:6	
Rope climbing injury						
Indoor	4	1	2	1	0	
Outdoor	20	10	5	3	2	
Bouldering injury						
Indoor	36	5	3	17	11	
Outdoor	17	0	3	10	4	
UIAA injury score	2.1 ± 0.4 (1-3)	1.9 ± 0.3 (1-2)	1.9 ± 0.3 (1-2)	2 ± 0 (2-2)	2.4 ± 0.5 (2-3)	<.001
Affected side, right:left	33:44	7:9	6:7	12:19	8:9	
Surgical treatment, yes:no	26:51	6:10	4:9	5:26	11:6	
Score[e]						
VAS	1 ± 0.7 (0-3)	0.7 ± 0.7 (0-2)	0.2 ± 0.4 (0-1)	0.4 ± 0.7 (0-3)	0.8 ± 0.8 (0-2)	NS
Tegner	5.9 ± 0.8 (3-7)	6 ± 0.8 (5-7)	5.9 ± 0.5 (5-7)	6 ± 0.9 (3-7)	5.8 ± 0.9 (4-7)	NS
Lysholm	97 ± 4.8 (74-100)	97.9 ± 3 (91-100)	97.9 ± 3.6 (90-100)	97.3 ± 4.9 (79-100)	95.3 ± 6.4 (74-100)	NS
Climbing	4.8 ± 0.6 (2-5)	4.8 ± 0.4 (4-5)	4.9 ± 0.3 (4-5)	4.9 ± 0.6 (2-5)	4.5 ± 0.8 (2-5)	NS

[a]Data are provided as n (%) or mean ± SD (range). NS, not significant; UIAA, Union Internationale des Associations d'Alpinisme; VAS, visual analog scale for pain.
[b]Rope climbing levels graded according to UIAA metric scale.
[c]Bouldering levels graded according to V scale.
[d]Percentage of bouldering in climbing/training routine.
[e]One year after injury.

normality with the Shapiro-Wilk test. To determine the difference among groups, a *t* test or rank sum test was used depending on normal distribution. A nonparametric Kruskal-Wallis 1-way analysis of variance on ranks was used for nonnormally distributed data among several groups. Unless stated otherwise, data are expressed as mean and standard deviation with range, as appropriate. Subgroup analyses were made for 4 trauma mechanisms as described before. *P* values <.05 were considered as statistically significant.

RESULTS

During the 4-year period, we treated 71 patients (45 [63.4%] male, 26 [36.6%] female) with 77 independent knee injuries caused by rope climbing or bouldering (Table 1). Twenty-five (35.2%) of the athletes performed the sport on a competitive level; among those, 15 (21.1%) were World Cup–level athletes. Only 5 injuries occurred during a competition (1 during national competition, 4 during World Cup competition), while 66 injuries occurred during training. Rope climbing and bouldering skill levels as well as demographic information are shown in Table 1. The mean UIAA injury score was 2.1 ± 0.4 (range, 1-3), and among the 7 injured athletes with an UIAA score of 3, two were male. Patients with a UIAA score of 3 experienced ACL ruptures with meniscal and collateral ligament tears or joint fractures as a result of a fall. None of the athletes had a UIAA grade 4 or 5 injury, and none of them died (UIAA 6). Rope climbing level (UIAA level) and climbing experience (climbing years) did not vary significantly between men and women, but men had a significantly higher bouldering level (V scale, $P = .03$) and experience (bouldering years, $P = .03$) than women.

Traumatic MOIs

Four types of traumatic MOIs were identified: the *high step* position (Figure 1A), the *drop knee* position (Figure 1B), the *heel hook* position (Figure 1C), and a *fall* to the ground (Figure 1D). No other MOIs were reported. Apart

Figure 1. (A) *High step* position of the right leg/knee during bouldering. While the left leg is fully unloaded, the majority of the athlete's weight is on the right leg with a fully flexed knee. (B) *Drop knee* position of the left lower extremity leading to a high mechanical load on the menisci. (C) *Heel hook* position during bouldering (right knee). The heel is used to apply pressure onto the hold while pulling on the foot by flexing the hamstrings. In addition, the knee is rotated outwardly, applying a high load onto the knee. (D) A *fall* during bouldering can cause severe knee injuries, even from lower heights in cases of uncontrolled falling, insufficient ground protection, or insufficient body tension attributed to fatigue.

from the fall, all body positions are commonly known techniques in climbing, although the only MOI previously described in the literature is the heel hook position.[21]

The high step position features a squat position of the affected leg and knee during rope climbing or bouldering. One leg is fully unloaded and mostly extended, and the majority of the athlete's weight is on the other leg, with a fully flexed knee and an externally rotated, flexed, and abducted hip (Figure 1A). An internally rotated hip with a flexed knee characterizes the drop knee position during rope climbing and bouldering. For improved body positioning, the athlete loads the extremity, which leads to a high mechanical load on the medial meniscus, especially during combined extension and rotation under load (Figure 1B). During the heel hook position, the heel is used to apply pressure onto the hold while pulling on the foot by flexing the knee via a strong hamstring contraction. In addition, the knee is rotated laterally, applying a high load to the knee[21] (Figure 1C). A fall as a traumatic MOI for severe knee injuries results from uncontrolled falling (eg, load in combination with rotational movements), insufficient ground protection, or insufficient body control owing to fatigue (eg, reduced core stability or limited neuromuscular control causing valgus loading of the knee), even from lower heights (Figure 1D).

With 46.8% of all injuries, indoor bouldering was the main cause of injury, followed by outdoor rope climbing (26%), outdoor bouldering (22.1%), and indoor rope climbing (5.2%) (Table 1).

Injury Distribution

Injury distribution is presented in Table 3. The leading structural damage in the knee was a medial meniscal tear, which was the leading diagnosis in 28.6% (n = 22) of all injuries. These injuries were predominantly caused by the high step, drop knee, and heel hook positions. Iliotibial band sprains were present in 19.5% (n = 15) of all injuries. This type of injury resulted exclusively from heel hook positions. ACL tears combined with medial collateral ligament and medial meniscal injuries were

TABLE 2
Sport-Specific Outcome Score After Climbing Injuries[a]

Grade	Outcome	Posttraumatic Climbing Capacity
V	Excellent	Full load capacity of the former injured joint/limb after 12 mo, no subjective strength deficit, regain of full climbing ability/preinjury climbing level, no pain
IV	Good	Full load capacity of the former injured joint/limb after 12 mo, subjectively minor strength deficit, regain of full climbing ability/preinjury climbing level, minor pain
III	Satisfactory	Minor restricted load capacity of the former injured joint/limb, subjectively major strength deficit of the former injured joint, regain of full climbing ability/preinjury UIAA climbing level minus 1 UIAA grade, minor pain
II	Fair	Major restricted load capacity of the former joint/limb, strength deficit and restricted ability to use the former injured joint while climbing, major decrease in climbing ability and grade, frequent pain
I	Poor	Climbing not possible anymore

[a]Modified from Schöffl et al.[23] UIAA, Union Internationale des Associations d'Alpinisme.

TABLE 3
Injury Distribution Listed by Main Diagnosis[a]

	Mechanism of Injury, n (%)				
Injury Type	All Injuries (n = 77)	High Step (n = 16)	Drop Knee (n = 13)	Heel Hook (n = 31)	Fall (n = 17)
Medial meniscal tear	22 (28.6)	8 (50)	5 (38.5)	7 (22.6)	2 (11.8)
Iliotibial band sprain[b]	15 (19.5)			15 (48.4)	
ACL tear[c]	7 (9.1)				7 (41.2)
LCL tear	6 (7.8)		1 (7.7)	5 (16.1)	
Lateral meniscal tear	4 (5.2)	1 (6.3)	2 (15.4)	1 (3.2)	
Patellar dislocation	3 (3.9)	1 (6.3)	1 (7.7)		1 (5.9)
Minor joint effusion	3 (3.9)	1 (6.3)	1 (7.7)		1 (5.9)
Cartilage injury	3 (3.9)	2 (12.5)		1 (3.2)	
Others	3 (3.9)	1 (6.3)			2 (11.8)
ACL					
Rupture	2 (2.6)				2 (11.8)
Partial tear	2 (2.6)			1 (3.2)	1 (5.9)
Medial meniscal tear + MCL tear	2 (2.6)	1 (6.3)	1 (7.7)		
MCL tear	2 (2.6)		2 (15.4)		
Popliteal muscle tear	2 (2.6)	1 (6.3)		1 (3.2)	
Joint fracture	1 (1.3)				1 (5.9)

[a]ACL, anterior cruciate ligament; MCL, medial collateral ligament.
[b]Heel hook injury as described before.[15]
[c]ACL tear with medial meniscal tear ± MCL tear.

detected in 9.1% (n = 7) and isolated ACL tears (n = 2) or partial ACL tears (n = 2) in 2.6%. Ninety-one percent of injuries that caused at least a partial tear of the ACL resulted from a fall to the ground. Lateral collateral ligament (7.8%; n = 6) or isolated lateral meniscal (5.2%; n = 4) tears occurred less frequently. Distribution of all other injuries is shown in Table 3.

Outcomes

All athletes had returned to sports within 12 months. One year after the injury, the mean visual analog scale for pain score was 1 ± 0.7 (range, 0-3); the Tegner Score, 5.9 ± 0.8 (range, 3-7); the Lysholm score, 97 ± 4.8 (range, 74-100); and the climbing-specific outcome score, 4.8 ± 0.6 (range, 2-5). The mean decrease in the Tegner score was 0.2, while the mean Lysholm score decreased by 2.8. The injury-related mean drop in the climbing-specific outcome score was 0.2. Two female athletes experienced a prolonged healing period with a major decrease in climbing ability and grade as well as ongoing pain 1 year after meniscal repair (n = 1) and open reduction and internal fixation (n = 1). Outcome scores separated by trauma mechanism are shown in Table 1.

Between-Group Comparison of Traumatic MOIs

High step and drop knee injuries were more common during rope climbing, whereas heel hook and fall injuries were more often caused by bouldering. Bouldering ability levels varied significantly among groups (P = .03). Patients who were injured during a heel hook had the highest ability level, and patients injured during a fall had the lowest bouldering ability level. Experience in bouldering (years) varied significantly, being highest in the high step group and lowest in the drop knee group (P = .03). Patients who were injured during a heel hook had the highest training volume per week (15.1 hours), while athletes from the drop knee group had the lowest (11.2 hours). While no significant difference was found in rope climbing experience (years) among the groups, the athletes' experience in bouldering varied significantly. The longest experience in bouldering was in the high step group and the lowest in the drop knee group. The percentage of bouldering among the athletes' entire climbing practice was also significantly different among the groups (P = .45): while athletes injured during heel hook or fall were predominantly bouldering athletes, patients injured in high step or drop knee reported spending less time with bouldering. Athletes who got injured in a fall or heel hook thereby reported spending almost 70% and 63% of their climbing time in bouldering, respectively. Athletes with a knee injury from a drop knee or high step reported spending only 42% and 51% of their climbing time in bouldering, respectively. The UIAA injury score was significantly higher in the fall group (UIAA score, 2.4) as compared with the other groups.

Noncompetitive and Competitive Athletes

Competitive athletes (35%) were significantly younger and lighter than the noncompetitive athletes. Rope climbing and bouldering levels, experience, training hours, and warm-up routines were all significantly higher in the

TABLE 4
Comparison of Knee Injuries in Noncompetitive and Competitive Athletes[a]

	Noncompetitive	Competitive	*P* Value
Patients	46	25	
Injuries	49	28	
Age, y	35.8 ± 9.9 (16-61)	26.5 ± 6.3 (15-39)	<.001
Sex, men:women	29:17	16:9	
Height, cm	176 ± 9.2 (154-194)	173 ± 7.6 (160-186)	NS
Weight, kg	70.2 ± 11.5 (49-91)	61.1 ± 10.4 (39-79)	.006
Level			
Rope climbing[b]	7.7 ± 1.6 (5-10.3)	10.5 ± 0.7 (9-12)	<.001
Bouldering[c]	5.1 ± 3.2 (0-11)	11.9 ± 2.3 (6-15)	<.001
Years			
Rope climbing	9.2 ± 8.1 (0-31)	14.2 ± 5.3 (4-24)	.001
Bouldering	6.5 ± 7.1 (0-30)	14 ± 5 (4-20)	<.001
Bouldering[d]	54 ± 36 (0-100)	65.4 ± 18.4 (30-100)	NS
Training, h/wk	7.2 ± 5.2 (0-20)	22.9 ± 10.6 (6-40)	<.001
Warm-up routine, yes:no	32:14	24:1	.009
Alternative sports, yes:no	29:17	21:4	NS
Rope climbing injury			
Indoor	2	2	NS
Outdoor	17	3	NS
Bouldering injury			
Indoor	21	15	NS
Outdoor	9	8	NS
Trauma mechanism			
High step	11	5	NS
Drop knee	10	3	NS
Heel hook	17	14	NS
Fall	11	6	NS
Injury type			
Medial meniscal tear	22	2	.001
Iliotibial band sprain	7	8	NS
ACL tear	5	6	NS
LCL tear	2	4	NS
Other	13	8	
UIAA injury score	2.1 ± 0.3 (1-3)	2 ± 0.4 (1-3)	NS
Affected side, right:left	20:29	13:15	NS
Surgical treatment, yes:no	21:28	5:23	.047
Score[e]			
VAS	0.6 ± 0.8 (0-3)	0.3 ± 0.5 (0-1)	NS
Tegner	5.6 ± 0.6 (3-6)	6.6 ± 0.6 (5-7)	<.001
Lysholm	95.9 ± 5.4 (74-100)	99.4 ± 1.5 (95-100)	<.001
Climbing	4.7 ± 0.7 (2-5)	4.9 ± 0.3 (4-5)	NS

[a]Data are provided as No. or mean ± SD (range). ACL, anterior cruciate ligament; LCL, lateral collateral ligament; NS, not significant; UIAA, Union Internationale des Associations d'Alpinisme; VAS, visual analog scale for pain.
[b]Rope climbing levels graded according to UIAA metric scale.
[c]Bouldering levels graded according to V scale.
[d]Percentage of bouldering in climbing/training routine.
[e]One year after injury.

competitive group of athletes as compared with the noncompetitive athletes. No significant difference in traumatic MOI was found between groups, although medial meniscal tears were significantly more frequent in noncompetitive athletes. Surgical procedures were required significantly more often in the noncompetitive group as compared with the competitive group. Tegner and Lysholm scores were significantly better in competitive climbers after 1 year (Table 4).

DISCUSSION

This is the first study to describe traumatic MOIs, injury patterns, and outcome measurements of acute knee injuries in noncompetitive and competitive rock climbers.

Four types of MOI were detected: the high step position, the drop knee position, the heel hook technique, and uncontrolled landing during a fall. In accordance with the Josephsen et al[8] study, the majority of knee injuries

in our study (47%) happened while indoor bouldering, even though both study centers are located in regions known for their famous outdoor rope climbing[8] (see Table 1). In total, injuries caused by bouldering activities represented 69% of all knee injuries within our study, which strengthens the theory that bouldering seems to be more prone to causing knee injuries than climbing with a rope. The reason for this might be that bouldering routes normally consist of few but very hard moves, which require strong body tension, difficult body positioning, and strength, especially placing the meniscus under enormous stress. Furthermore, falls to the ground are common in bouldering. Climbing routes, however, are generally much longer and require other skills, such as endurance, while a rope protects the athlete from a fall to the ground.[11]

Studies from other sports, including handball and basketball, have shown that insufficient landing with immediate valgus loading is a contributing factor in the ACL injury mechanism and that various intrinsic factors predispose female athletes for this type of injury.[9,10,29] In our study, knee injuries caused by a fall had a significantly higher UIAA score than injuries from other trauma mechanisms and were predominantly found in female athletes. Furthermore, those injuries were mainly found in athletes with less experience and potentially less body control and stability strength while landing[9,19] (see Table 1). Indoor bouldering gyms are widely available, and unexperienced athletes tend to choose indoor bouldering because of the ease of access.[19]

As in other sports in which various injury patterns correlate with the underlying traumatic MOI (eg, downhill skiing),[28] we found several climbing techniques to predominantly cause typical injuries. Iliotibial band sprains at the lateral condyle were caused exclusively by heel hook positions (Table 3, Figure 1C), which seems reasonable as the heel hook position is the only body position among the described mechanisms in which the iliotibial band is fully tightened and eventually glides over the lateral condyle of the femur under tension.[21] All ACL tears within our study group happened in cases of uncontrolled falls onto the ground. The mean bouldering level in athletes of the fall group was lower than that in the other groups (Table 3; Figure 1, C and D). This is an interesting fact and goes with the current increase of more severe injuries in beginners.[19] Nevertheless, we saw ACL tears also happen during World Cup events.[2,5,19] The mean climbing and bouldering level (UIAA metric scale, 8.7; V scale, 7.6) within the overall patient population of this study was consistent with other studies from our group but might not fully represent the climbing community as a whole.[16] Given the current wave of beginners in bouldering, even more injuries based on falls under insufficient body control might be expected.[19]

Medial meniscal tears were predominantly caused by the high step, the drop knee, and the heel hook positions (Table 3). While none of the athletes reported preexisting symptoms in the affected knee, asymptomatic preexisting meniscal degeneration with an acute aggravation caused by the specific motion needs to be considered. The athlete stresses the leg in a fully flexed knee in the drop knee and high step positions (see Figure 1, A and B), causing a high load on the meniscus. The heel hook technique rather causes a shear stress to the menisci by a slightly flexed but fully loaded knee under tension[21] (see Figure 1C). That athletes experiencing knee injuries while performing a heel hook had a high climbing or bouldering level as well as a high weekly training workload might strengthen the theory that stronger climbers use this technique more aggressively than others and thereby injure the knee.[21] For all 3 MOIs, a peak load is suspected to cause the injury. It can be speculated that it is the moment of maximum contraction of the knee flexor muscles that causes the injury in cases of heel hook–related injuries. We suspect injury-causing events for the drop knee and high step positions to be different. In both body positions, we can assume that the injury happens within the moment when the athlete releases one hand to reach the next hold, leading to an extra load on the lower extremities. A slipping foot from the contralateral foothold causing eccentric stress onto the other side could cause peak loads to the knee. Eccentric peak loads have also been found to cause finger injuries in rock climbers.[15] Furthermore, insufficient technical skills and fatigue might cause harmful rotational motion of the knee in experienced athletes.

In a recent systematic review, Eberbach et al[6] reported that 89% of patients achieved a return to sports at the preinjury level after meniscal repair and that the mean return occurred within 4.3 to 6.5 months (postoperative Tegner score, 6.2 ± 0.8).[6] While not all of our athletes with meniscal tears received a meniscal repair, the high sport-specific outcome score of 4.8 and the Tegner score of 5.9 go with the findings from Eberbach et al. Seijas et al[27] recently analyzed return to preinjury Tegner levels after ACL reconstructions and reported a mean Tegner level of 5.9 at 12 months after surgery. All of our patients with ACL injuries had returned to sport after 1 year, and the mean Tegner score was 6.0. Exact determination of return-to-sport time points was not possible, as most of the athletes reported that they returned to climbing gradually during the rehabilitation process under awareness and care for the injured knee. In contrast to contact sports requiring running or jumping, climbing is a mostly predictable noncontact sport, which allows the athlete to perform it with reduced stress on the leg. Some athletes might even reach their preinjury climbing level while still gently using the affected knee in some movements. This might be the reason for a relatively quick return to sport for our athletes.

Between-group comparison of competitive and noncompetitive athletes revealed 2 interesting findings. First, noncompetitive athletes had significantly more medial meniscal tears and a slightly higher UIAA injury score. Hypothetically, this could be due to a lower level of body awareness and control in the noncompetitive group. Second, the noncompetitive group underwent more surgical procedures than the competitive group. The reasons remain unclear but might be influenced by the significantly lower age and body weight of the competitive group; as medial meniscal tears increase in prevalence with age,

asymptomatic preexisting meniscal lesions should also be considered.

To prevent reinjury of the affected knee during the return-to-sport process, rope climbing should be preferred to bouldering to avoid falls and direct impact on the knee. In case of bouldering activities with a previously injured knee, "down climb" (cautious descent) or "top out" (alternative easy descent) should be preferred to jumping down on the mat after the successful ascent. Rope climbing on an overhanging wall has been described as having a lower injury risk for the lower extremities[17] and should therefore be preferred to rope climbing on vertical walls. Falls on overhangs are stopped exclusively by the rope, whereas falls during rope climbing on a vertical wall can cause a swing into the wall.[17]

Based on the current findings, it may be possible to develop training programs for noncompetitive and competitive climbing athletes to address muscle weaknesses not trained exclusively through climbing. Most climbers neglect the leg muscles completely in their training routine. Active training of the knee stabilizers for improved joint control and stretching techniques (eg, iliotibial band) may be advisable. As an effect of this addition, excessive load on the knee during the described climbing techniques might be reduced. Improved psychomotor skills and body control might better manage and reduce the risk of injury during falls.

Study Limitations

This study has several limitations. The patient population was not fully homogeneous, as most of the athletes came from the local climbing areas but a few were from farther away. The kind of climbing performed in certain regions and the accessibility to climbing/bouldering gyms might influence the type of injuries. The main limitation might be the fact that there is a bias within the patient population: athletes who experience severe knee trauma most likely seek help at the closest medical facility, especially in cases of fractures or acute ligament injuries, rather than consulting a facility specialized on climbing injuries. The number of severe knee injuries, particularly in indoor bouldering, is expected to be even higher than presented in this study. Conclusions cannot be reached about the incidence of the injuries among the climbing and bouldering population at large, and the injury distribution may not be generalizable to other populations. Injury mechanisms were based on athletes' descriptions and could not be independently verified. However, this is the first study that highlights the knee injuries resulting directly from rock climbing and bouldering.

CONCLUSION

We identified 4 distinctive traumatic MOIs of knee injuries, referred to as the *high step, drop knee, heel hook*, and (uncontrolled) *fall*. Meniscal tears, iliotibial band sprains, and ACL injuries were the leading diagnoses, and the return to sport was quick overall. Noncompetitive athletes had significantly more medial meniscal tears than competitive athletes and underwent more surgical procedures.

Increased attention should be placed on the climber's knee, especially given the worldwide rise of indoor bouldering. Sport-specific awareness training programs for noncompetitive and competitive climbing athletes to avoid excessive load on the knee should be developed, and sports medical supervision is mandatory.

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