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Clinical and radiological risk factors associated with the occurrence of acute compartment syndrome in tibial fractures: a systematic review of the literature

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- *Introduction:* Acute compartment syndrome (ACS) is an orthopedic emergency that may lead to devastating sequelae. Diagnosis may be difficult. The aim of this systematic review is to identify clinical and radiological risk factors for ACS occurrence in tibial fractures.
- *Methods:* PubMed® database was searched in accordance with the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines. Additional articles were found by a manual research of selected references and authors' known articles.
- *Results:* The identification process individualized 2758 via database and 30 via other methods. After screening and eligibility assessment, 29 articles were included. Age, gender, occupation, comorbidities, medications, habits, polytrauma, multiple injuries, mechanism, sports, site, open vs closed, contiguous lesion, classification, and pattern were found to be related to ACS occurrence.
- *Conclusions:* Younger age and male gender are strong independent risk factors in tibial plateau and shaft fractures. High-energy fractures, polytrauma, more proximal fractures and fractures with contiguous skeletal lesions are aggravating risk factors; higher AO/OTA and Schatzker classification types, increased displacement of the tibia relative to the femur, and increased tibial joint surface width are associated risk factors in tibial plateau fractures; higher AO Foundation/Orthopaedic Trauma Association classification types and subgroups and more proximal fractures within the diaphysis are associated risk factors in tibial shaft fracture. Open fractures do not prevent ACS occurrence. Increased fracture length is the only factor suggesting a higher risk of ACS in tibial pilon fractures. The presence of each independent predictor may have a cumulative effect increasing the risk of ACS occurrence.

Keywords

- acute compartment syndrome
- proximal tibial fracture
- tibial plateau fracture
- tibial diaphyseal fracture
- tibial shaft fracture
- tibial pilon fracture
- distal tibial fracture
- risk factor

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Introduction

Acute compartment syndrome (ACS) of the lower leg is a condition in which muscle intra-compartmental pressure (ICP) rises above a level which may cause irreversible muscle and nerve lesion (1). The development of muscle and nerve damage depends on both magnitude and duration of ACS (2, 3, 4). Muscle necrosis may appear after 3 h, neurapraxia after 4 h and neurotmesis after 8 h. The critical threshold to adequately treat ACS and avoid definitive neurologic (sensitive loss, motor deficit, chronic pain) and muscular (contractures, stiffness, deformities) sequelae is generally acknowledged as a duration of symptoms of no more than 6 h (5, 6). The only recognized treatment of ACS is emergent surgical fasciotomy, which consists in a wide incision of muscle fasciae, decreasing ICP in pathological compartments (7, 8, 9).

The most common cause of ACS is a fractured limb segment, most often the leg, then the forearm, thigh, hand, and foot (10, 11). Another cause of ACS might be an insult to the soft tissues without a fracture (direct blow, crush, reperfusion after ischemia, bleeding disorder) (8, 10).

The diagnosis of ACS primarily relies on clinical examination. The most consistent symptom is pain, which is increasing, out of proportion compared to the underlying injury, resistant to standard analgesics and aggravated by passive stretching of the affected compartment muscles (8, 9, 12, 13). Pathological compartments may be tense to palpation. Paresthesia, paresis, pallor, and pulselessness may also be present. Some of these features (pain, paresthesia, paresis, pain on passive movements) have high specificity and high negative predictive values; thus, when absent, ACS is less likely to occur (14). However, these same features have low positive predictive values on their own, suggesting that they are poor solo indicators of ACS; the positive predictive value increases when more than one of these features is present at the same time (14). Furthermore, clinical examination alone is not sufficient in those patients with equivocal clinical signs and with locoregional anesthesia, or in intubated, sedated, or obtunded patients. In these cases, invasive ICP monitoring is necessary (1, 7, 8, 15, 16, 17, 18, 19, 20). The current threshold to diagnose ACS is a differential pressure (diastolic blood pressure − ICP) of less than 30 mmHg (12, 21, 22) or an absolute ICP value above 30 mmHg (23).

Reported ACS occurrence in tibial plateau fractures reaches 12% and even 53% in higher-energy patterns (24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40). In tibial shaft fractures, ACS occurrence reaches 11.5% (10, 27, 28, 40, 41, 42, 43). The association between tibial pilon fractures and ACS is less obvious with reported occurrence rates under 5% (24, 28, 35, 40, 44).

As ACS is not rare in the setting of a tibial fracture, and as any delay in diagnosis and treatment may lead to devastating and irreversible muscle and nerve sequelae, early recognition of injuries at risk of ACS is essential, especially in patients with equivocal clinical signs or loco-regional anesthesia and in intubated, sedated or obtunded patients. In this perspective, red flags or predictors need to be recognized (45, 46). When present, these risk factors should lead the physician in charge to perform frequent clinical assessments and/or repeated or continuous ICP measures throughout the treatment of tibial fractures, before, during and after surgery, even in the presence of an unremarkable initial examination (47).

The aim of the present literature review is to identify clinical and radiological risk factors for the occurrence of ACS in association with different patterns of tibial fractures (proximal, diaphyseal, and distal). To the authors' knowledge, this review is the first to specifically focus on clinical and radiological risk factors for ACS occurrence in the setting of a tibial fracture.

Methods

Identification

For this systematic review a computerized MEDLINE® database research was performed using PubMed® in accordance with the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines. This research included all articles published either in English, French, Italian, German or Spanish until October 2022 focusing on risk factors for ACS in tibial plateau, shaft and pilon fractures. Twelve different combinations of the following terms were used: risk factor, acute compartment syndrome, compartment syndrome, fracture, tibia, leg, plateau, and pilon, as shown in Table 1. No other database was searched.

There was no study design, publication date, geographical, or journal restrictions. Articles in languages other than English, French, Italian, German, and Spanish were not taken into consideration.

After excluding duplicates, the authors examined titles and excluded comments on studies and publications including pediatric population, chronic compartment syndrome, and leg lengthening. The remaining publications were kept for further evaluation.

A manual research was performed by both authors looking for relevant articles potentially missed during the computerized search. This additional analysis was made on selected studies' references found in the remaining publications kept for evaluation and in articles already known by the authors on this topic.

Screening

All selected available abstracts were fully read and evaluated to determine relevancy to the topic. Both authors independently selected articles potentially reporting original research (prospective, retrospective, animal, or cadaver studies) on clinical or radiological risk factors for the occurrence of ACS in case of tibial fractures. All abstracts selected by at least one of the authors were incorporated into the full-text evaluation process.

Inclusion

Full available texts of eligible articles were read and included in the present study if they were reporting

Table 1 Research strategy using different terms with PubMed® and numbers of publications found after step 1 (showing total number of publications found) and step 2 (showing number of publications left after excluding duplicates and reading titles) in the identification process.

PubMed® search term combinations		Step 1	Step 2
Number	Combination		
1	RF + ACS + tibia + fracture	33	20
2	RF + ACS	289	4
3	ACS + tibia + fracture	154	25
4	ACS + leg + fracture	121	6
5	ACS + pilon + fracture	6	0
6	ACS + plateau + fracture	14	1
7	RF + CS + tibia + fracture	78	6
8	RF + CS	895	3
9	CS + tibia + fracture	652	38
10	CS + leg + fracture	427	2
11	CS + pilon + fracture	14	0
12	CS + plateau + fracture	75	1
Total		2758	106

ACS, acute compartment syndrome; CS, compartment syndrome; RF, risk factor.

clinical or radiological risk factors for the occurrence of ACS in case of tibial fractures. Studies on treatment options and techniques, pediatric population, chronic compartment syndrome and leg lengthening were not included. Review articles and metanalysis were not considered for results analysis. Figure 1 shows the PRISMA flow diagram of this systematic review.

The following data from the selected articles were independently extracted by both authors: type of study, level of evidence if stated (if not stated, this was interpreted by the authors), type of tibial fracture, potential risk factors analyzed, univariate analysis results, results after adjustment, multivariable analysis results, any variable confirmed as being or not being a risk factor.

At each step, any disagreement was settled by consensual discussion between the authors. Risk factors for ACS in tibial fractures were divided in three main categories: patient related, type of trauma related, and fracture related; and then each risk factors was thoroughly considered.

Results

The identification step of the computerized research led to 2758 results. Title reading and duplicates exclusion individualized 106 articles (Table 1). The manual research added 30 publications leading to 136 studies. Abstract evaluation left 62 publications. After full-text examination of available studies, a total of 29 articles were kept for this review (10, 24, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 43, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58). Among these only one article was found with the manual research (36). Table 2 shows included articles and their characteristics, and Table 3 shows which articles evaluated each risk factor.

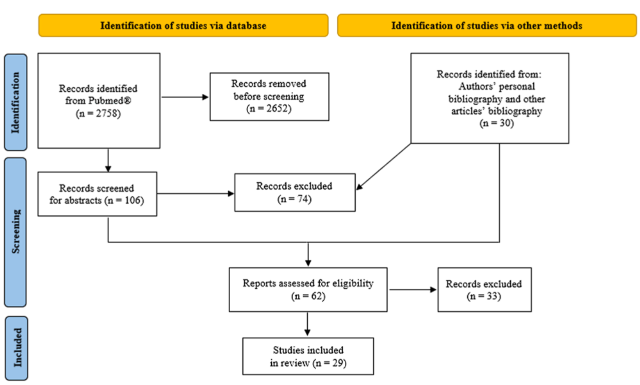

Figure 1
PRISMA flow diagram.

Patient-related risk factors

Age

All tibial fractures (plateau, shaft, and pilon) Bouklouch *et al.* retrospectively evaluated 203500 fractures and Beebe *et al.* 2885 fractures: they both found younger age to be associated with ACS in their multivariate analysis (49, 51). Gamulin *et al.* in a smaller retrospective series found similar results in their univariate analysis (40). These studies identified mean or median age of patients developing ACS being between 36 and 38, and between 43 and 45 for those not developing ACS (40, 49, 51). Additionally, Branco *et al.* retrospectively evaluated 10315 upper and lower extremity traumas with or without fracture and also found younger age to be associated with ACS (33).

Tibial plateau fractures Deng *et al.* in their retrospective study with 1119 intra-articular tibial plateau fractures reported a mean age of 36 years in patients developing ACS and of 43 years in patients not developing ACS (multivariate analysis, $P = 0.003$) (39). Marchand *et al.* in a smaller series with 513 intra-articular tibial plateau fractures found a mean age of 39 years in patients with ACS, and of 47 years in patients without ACS (multivariate analysis, $P=0.003$) (34). Gamulin *et al.* in another smaller retrospective study of 269 intra-articular tibial plateau fractures found age <45 years being associated with ACS in their univariate analysis ($P = 0.014$) (32). Two other studies did not find age being a risk factor for ACS occurrence in intra-articular tibial plateau fractures (31, 37).

Tibial shaft fractures McQueen *et al.* in their retrospective series with 1388 tibial shaft fractures reported the highest prevalence of ACS (20–21%) in patients younger than 29 years old when compared to older patients (multivariate analysis, $P < 0.001$) (41). Park *et al.* in their retrospective study of 173 tibial shaft fractures found that the mean age of patients developing ACS was 27 years, and 39 years for those not developing ACS (multivariate analysis, $P = 0.006$) (28). McQueen *et al.* retrospectively described a cohort of tibial shaft fractures and found that 6% of the fractures were associated with ACS in patients <35 years old, while only 2% had this association in patients >35 years old ($P < 0.001$) (10, 54). Two other retrospective studies found similar results in their univariate analysis (42, 43).

Tibial pilon fractures The authors found no clear data in the reviewed literature on this topic.

Gender

All tibial fractures (plateau, shaft, and pilon) Bouklouch *et al.* and Beebe *et al.* in their retrospective studies with

Table 2 Articles included and their characteristics.

Articles included	Study type	LOE‡	Number of Fractures	Number of Patients	Site of fracture studied
McQueen *et al.* (10)	RCS	NS (IV)	59†	164*	Upper and lower limb, with and without fracture (sub analysis tibial shaft)*
Allmon *et al.* (24)	RCS	III	978	NS	All (plateau + shaft + pilon)
Menetrey *et al.* (27)	RCS	NS (IV)	100	NS	All (plateau + shaft + pilon)
Park *et al.* (28)	RCS	NS (III)	433	414	All (plateau + shaft + pilon), sub analysis shaft
Stark *et al.* (29)	RCS	NS (IV)	67	67	Plateau
Wahlquist *et al.* (30)	RCS	NS (IV)	28	28	Plateau (Schatzker IV)
Ziran *et al.* (31)	RCS	II	162	159	Plateau
Gamulin *et al.* (32)	RCS	II	269	265	Plateau
Branco *et al.* (33)	RCS	NS (III)	NS	10315	All bone fractures
Marchand *et al.* (34)	RCS	III	513	502	Plateau
Gonzalez *et al.* (36)	RCS	NS (III)	393	321	All (plateau + shaft + pilon)
Smolle *et al.* (37)	RCS	NS (IV)	253	243	Plateau
Acklin *et al.* (38)	RCS	NS (III)	356	NS	Plateau
Deng *et al.* (39)	RCS	NS (IV)	1119	1119	Plateau
Gamulin *et al.* (40)	RCS	III	725	711	All (plateau + shaft + pilon)
McQueen *et al.* (41)	RCS	II	1388	1388	Shaft
Shadgan *et al.* (42)	RCS	IV	1125	1100	Shaft
Wuarin *et al.* (43)	RCS	II	273	270	Shaft
Altay *et al.* (48)	PRM	NS (I)	40	40	Proximal extra-articular
Beebe *et al.* (49)	RCS	III	2885	2778	All (plateau + shaft + pilon)
Blick *et al.* (50)	RCS	NS (VI)	198	180	Shaft
Bouklouch *et al.* (51)	RCS	NS (III)	203500	NS	All (plateau + shaft + pilon)
DeLee *et al.* (52)	RCS	NS (IV)	104	NS	All (plateau + shaft + pilon)
Herzog et *al.* (53)	RCS	IV	30	30	Shaft + Plateau
McQueen *et al.* (54)	RCS	NS (IV)	58	NS	Shaft
McQueen *et al.* (55)	PCS	NS (I)	67	66	Shaft
Meskey *et al.* (56)	RCS	NS (II)	938	650	All bone fractures
Prather *et al.* (57)	RCS	III	402	NS	All (plateau + shaft + pilon)
Wind *et al.* (58)	RCS	NS (II)	626–	626	All (plateau + shaft + pilon)

‡When LOE was not specified in the study, both authors of this review evaluated it; their evaluation is shown in parentheses; *Study on 164 patients with ACS in the upper or lower limb, with or without a fracture; †Sub analysis on 59 tibial shaft fractures with acute compartment syndrome.
LOE, level of evidence; NS, not specified; PCS, prospective cohort study; PRM, prospective rabbit model; RCS, retrospective cohort study.

more than 1000 fractures and Gamulin *et al.* in their smaller retrospective study with 725 fractures confirmed in their multivariable analysis male gender as an independent risk factor for the development of ACS in tibial fractures (40, 49, 51). Branco *et al.* came to the same conclusion in their retrospective review of 10315 upper and lower extremity traumas with or without fracture (33). No other considered study found out the opposite or did not confirm this finding in their analysis, except Meskey *et al.* who did not find male gender being a risk factor for ACS in their retrospective review of 938 civilian ballistic fractures of any bone (56).

Tibial plateau fractures Marchand *et al.* and Smolle *et al.* in their retrospective investigations on tibial plateau fractures confirmed in their multivariable analysis male gender as a risk factor for ACS occurrence (34, 37), as well as Gamulin *et al.* in their univariate analysis (32), while Ziran *et al.* and Deng *et al.* did not (31, 39).

Tibial shaft fractures Park *et al.*, McQueen *et al.* and Shadgan *et al.* in their retrospective investigations on tibial shaft fractures did not find any association between male gender and ACS occurrence in their multivariate analysis (28, 41, 42), while Wuarin *et al.* found an association in their univariate analysis (43). McQueen *et al.* found a preponderance of male patients in a cohort of tibial shaft fractures with ACS (without control group), but no statistical analysis was performed to support this result (10, 54).

Tibial pilon fractures No clear data was found on this topic.

Occupation

McQueen *et al.* in their retrospective investigation on tibial shaft fractures found that manual laborers had more risk to develop ACS when compared to educated workers, whereas social deprivation was not a predictor of ACS (41). No other study was found on this topic.

Comorbidities, medications, and habits

Blood pressure was investigated by various authors. McQueen and al. postulated that hypertension may have a protective effect against ACS by making a differential pressure threshold of less than 30 mmHg more difficult to reach (10). This theory was confirmed by Bouklouch *et al.* in their study on overall tibial fractures (51), but not by three other retrospective

Table 3 Risk factors evaluated and related included articles.

Risk factors	All	Plateau	Shaft	Pilon
Patient-related				
Age	Branco *et al.* (33), Gamulin *et al.* (40), Beebe *et al.* (49), Bouklouch *et al.* (51)	Ziran *et al.* (31), Gamulin *et al.* (32), Smolle *et al.* (37), Deng *et al.* (39)	Park *et al.* (28), McQueen *et al.* (41), Shadgan *et al.* (42), Wuarin *et al.* (43)	None
Gender	Branco *et al.* (33), Gamulin *et al.* (40), Beebe *et al.* (49), Bouklouch *et al.* (51), Meskey *et al.* (56)	Ziran *et al.* (31), Gamulin *et al.* (32), Marchand *et al.* (34), Smolle *et al.* (37), Deng *et al.* (39)	McQueen *et al.* (10), Park *et al.* (28), McQueen *et al.* (41), Shadgan *et al.* (42), Wuarin *et al.* (43), McQueen *et al.* (54)	None
Occupation	McQueen *et al.* (41)			
Comorbidities, medications, habits	McQueen *et al.* (10), Park *et al.* (28), Smolle *et al.* (37), Deng *et al.* (39), McQueen *et al.* (41), Bouklouch *et al.* (51), McQueen *et al.* (54)			
Type of trauma-related				
Polytrauma and multiple injuries	Park *et al.* (28), Branco *et al.* (33), Smolle *et al.* (37), Shadgan *et al.* (42), Wuarin *et al.* (43), Beebe *et al.* (49)			
Injury mechanism	McQueen *et al.* (10), Menetrey *et al.* (27), Park *et al.* (28), Gamulin *et al.* (32), Branco *et al.* (33), Marchand *et al.* (34), Gonzalez et *al.* (36), Deng *et al.* (39), Gamulin *et al.* (40), McQueen *et al.* (41), Shadgan *et al.* (42), Wuarin *et al.* (43), Blick *et al.* (50), Bouklouch *et al.* (51), McQueen *et al.* (54), McQueen *et al.* (55), Meskey *et al.* (56), Prather *et al.* (57)			
Sports injuries	Menetrey *et al.* (27), McQueen *et al.* (41), Wind *et al.* (58)			
Fracture-related				
Site	McQueen *et al.* (10), Allmon *et al.* (24), Menetrey *et al.* (27), Park *et al.* (28), Gamulin *et al.* (40), McQueen *et al.* (41), Shadgan *et al.* (42), Wuarin *et al.* (43), Beebe *et al.* (49), Bouklouch *et al.* (51)			
Open/closed	Branco *et al.* (33), Beebe *et al.* (49), Bouklouch *et al.* (51)	Ziran *et al.* (31), Gamulin *et al.* (32), Marchand *et al.* (34), Smolle *et al.* (37), Deng *et al.* (39), Gamulin *et al.* (40)	Park *et al.* (28), McQueen *et al.* (41), Shadgan *et al.* (42), Altay *et al.* (48), Blick *et al.* (50), DeLee *et al.* (52), McQueen *et al.* (55), Prather *et al.* (57)	None
Other contiguous lesions	Allmon *et al.* (24), Park *et al.* (28), Gamulin *et al.* (32), Branco *et al.* (33), Marchand *et al.* (34), Gamulin *et al.* (40), Wuarin *et al.* (43), Beebe et *al.* (49), Herzog *et al.* (53)			
Classification and pattern		Allmon *et al.* (24), Stark *et al.* (29), Wahlquist *et al.* (30), Ziran *et al.* (31), Gamulin *et al.* (32), Marchand *et al.* (34), Smolle *et al.* (37), Acklin *et al.* (38), Deng *et al.* (39), Beebe *et al.* (49), Bouklouch *et al.* (51)	Wuarin *et al.* (43), Beebe *et al.* (49), Bouklouch *et al.* (51)	Allmon *et al.* (24)

studies on either all tibial or tibial plateau fractures (28, 37, 39). Smolle *et al.* found higher BMI to be associated with ACS occurrence in tibial plateau fractures in their univariate analysis, but this was not confirmed by the multivariate analysis (37). The same study did not find diabetes mellitus, renal insufficiency, and American Society of Anesthesiologists (ASA) score to be risk factors for ACS development. Deng *et al.* also did not find diabetes mellitus to be a risk factor for ACS development in tibial plateau fractures, nor steroid use (39). Bouklouch *et al.* found tobacco use to have a positive association with ACS occurrence in overall tibial fractures (51), but Smolle *et al.* and McQuenn *et al.* did not (37, 41). McQueen *et al.* found bleeding disorders or anticoagulants in 10 to 17% of patients affected by ACS after a limb injury without a fracture, but they did not report comparable results for ACS occurring after tibial fractures (10, 54).

Type of trauma-related risk factors

Polytrauma and multiple injuries

Several retrospective publications found an association or a trend between polytrauma and occurrence of ACS in upper and lower extremity traumas with or without fracture (33), in tibial plateau fractures (37) and in tibial shaft fractures (28, 43). Other similar publications did not find any association (42, 49).

Injury mechanism

A relationship between higher energy mechanisms and ACS development was found in many studies (10, 28, 32, 39, 41, 42, 43, 54), while others did not (27, 34, 40, 50, 55). Indirect markers of high-energy mechanisms, such as crush injuries or penetrating wounds, were found to be risk factors for ACS in extremity injuries (33, 36, 51, 56, 57).

Sports injuries

Three retrospective studies have pointed out an association between ACS occurrence and sporting injuries (27, 41, 58).

Fracture-related risk factors

Fracture site: tibial plateau, shaft, pilon

Reported occurrences of ACS in tibial fractures vary depending on the injury site: around 12% for tibial plateau fractures, reaching up to 53% in higher energy patterns (24, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40) and up to 11.5% in tibial shaft fractures(10, 27, 28, 40-43). Reported ACS occurrences in tibial pilon fractures are under 5% (24, 28, 40). Decreasing rates of ACS from proximal to distal tibial location (tibial plateau, then shaft and finally pilon fractures) have been reported by multiple publications using multivariate analysis (24, 40, 49, 51). The same seems to be true within tibial shaft fractures (proximal versus distal shaft) (43). However, two other studies without multivariate analysis did not find similar results (27, 42).

Open vs closed fracture

Several retrospective studies did not find any association between ACS and open or closed overall tibial (49), tibial plateau (31, 32, 34, 37, 39), and tibial shaft fractures (28, 41, 42, 55, 57). A prospective study came to the same conclusion on rabbit extra-articular proximal tibia fractures (48). Two retrospective studies found an association between ACS and open overall tibial fractures in their multivariate analysis (33, 51), as well as a third study only in intra-articular tibial plateau fractures (40). Similarly, two older publications on tibial shaft fractures found that an open fracture would not prevent ACS occurrence, with open fracture severity actually being directly proportional to ACS incidence (50, 52).

Other contiguous lesions

Multilevel tibial fractures (intra-articular tibial plateau +/– shaft +/– pilon fracture) as well as concomitant intra-articular tibial plateau fracture with knee dislocation or fibular fracture were found to be a risk factor for the occurrence of ACS in multivariate analysis of several retrospective studies (24, 32, 33, 34, 40, 43). However, a concomitant fibular fracture in tibial shaft or pilon fractures and segmental shaft fractures were not associated with ACS (24, 28, 43, 49). A descriptive analysis found that ACS occurred in 20% of intra-articular tibial plateau fractures and in 27% of tibial shaft fractures with an associated proximal tibiofibular dislocation (53).

Fracture classification and pattern

Intra- and extra-articular tibial plateau fractures Several fracture patterns have been highlighted as potential risk factors for ACS in multiple retrospective studies using multivariate analysis: higher AO Foundation/Orthopaedic Trauma Association (AO/OTA) classification types (C vs B vs A) (32, 34, 49, 51), higher Schatzker classification grades (IV–VI) (24, 31, 34, 37, 39) with 53% ACS reported in medial plateau fracture–dislocations and 18% in Schatzker VI fractures (29), and increased fracture length (24, 34). Wahlquist *et al.* focusing on Schatzker IV fractures demonstrated that the more lateral the fracture lines were the higher the rates of ACS (14% for fracture lines exiting medial, 33% through and 67% lateral to the intercondylar eminence) (30). Acklin *et al.* did not find a difference in ACS rates between fracture–dislocation patterns and nondislocated fracture patterns (38). Fracture displacement on standard radiographs was evaluated by Ziran *et al.*, Gamulin *et al.* and Marchand *et al.* with similar results (31, 32, 34): while the direction of displacement of the tibia relative to the femur did not relate to ACS occurrence (31, 32, 34), an increased amount of displacement of the tibia relative to the femur was associated with ACS (31, 32) as well as an increased fracture-related widening of the tibial plateau (31, 32, 34).

Tibial shaft fractures Several fracture patterns have been highlighted as potential risk factors for ACS by the multivariate analysis of different retrospective studies: higher AO/OTA classification types and subgroups (49, 51) and proximal fractures with fracture center location at 15 cm or more from the talar dome (43). This last study was not able to find any association with either the distance from the talar dome to the middle of the fibular fracture or between the middle of tibial and fibular fractures, fracture angulation, translation, or overriding.

Tibial pilon fractures The only factor reported to be associated with ACS occurrence in tibial pilon fractures is an increased fracture length (24).

Discussion

This review analyzed a total of 29 articles related to ACS occurrence in tibial fractures in order to highlight risk factors which may help the treating surgeon in its daily work. Risk factors were divided in three main categories: patient related, trauma related, and fracture related. Each risk factor was then analyzed and, when possible, subcategories based on fracture location were further studied.

Patient-related risk factors

Younger age seems to be a strong independent risk factor for the development of ACS in all fractures and especially in tibial plateau and shaft fractures. Reported at-risk age range appears to be the thirties or younger. Possible explanations for this finding may be linked with the fact that younger patients have higher muscle volumes and increased fascial thickness with higher collagen and collagen links density rendering the fascial envelope tighter and less elastic (10, 34, 39, 41, 42, 49). Younger patients may also be more likely involved in specific high-risk work, physical or behavioral activities exposing them to high-energy trauma (10, 32, 49). In contrast, older patients may have smaller muscle volumes due to sarcopenia and decreased activity, as well as less collagen and collagen links density in their fasciae and they may have a more sedentary lifestyle preventing them from sustaining high-energy trauma.

Male gender seems to be a strong independent risk factor for the occurrence of ACS in tibial plateau fractures, but it is a less strong predicting factor for ACS in tibial shaft fractures. Male patients may be more likely involved in specific work, physical and behavioral activities exposing them to high-energy trauma (32, 41) and may also have higher muscle volumes and tighter and thicker fasciae (10, 34, 39, 41, 42, 49).

Only one retrospective study on tibial shaft fractures was found on occupation reporting manual laborers to be more at risk for developing ACS when compared to educated workers. Manual labor still typically involves young, male adults which are both independent risk factors for the development of ACS and may expose them to high-energy trauma-related accidents.

Many studies have investigated on patients' characteristics such as comorbidities, medications and habits. These investigations found confounding results leaving some questions still open especially about the following conditions: hypertension (which might have a protective effect against ACS), higher BMI, tobacco use, and bleeding disorders (which might all be associated with ACS occurrence).

Type of trauma-related risk factors

Several retrospective publications found an association between polytrauma and ACS, but other similar publications did not. The major bias in evaluating polytrauma as a risk factor is the lack of consistent definition throughout different studies, using either variable Injury Severity Scores (ISS) thresholds or even global subjective evaluation. Future studies on this topic should include a solid and validated definition of polytrauma like the Berlin definition (59). Since ACS might be difficult to assess because these patients are often intubated, sedated, or obtunded, a high degree of suspicion is needed.

High- vs low- energy mechanism of injury might be problematic to assess on a retrospective basis thus explaining why this result is still debated with some studies not finding a relationship between higher energy mechanisms and ACS development, while others do. Indirect markers of high-energy mechanisms, such as crush injuries and penetrating wounds which were found to be risk factors for ACS in extremity injuries point out the importance of the energy transmitted to the bone and released within the soft tissue envelope in the physiopathology of both skeletal and soft tissue injuries. The injury mechanisms remain important to alert the treating surgeon to possible risk of ACS development.

Sport accident injuries have been pointed out as potential risk factor for ACS occurrence, but this finding was strongly confounded with lower age (41) and might be related to muscle volume augmentation during physical activity (27).

Fracture-related risk factors

Reported occurrences of ACS decrease from proximal to distal tibial location: tibial plateau, then shaft and finally pilon fractures. The same seems to be true within tibial shaft fractures: from proximal to distal shaft. These findings could be explained by the bulkier muscle mass surrounding the proximal tibia and its diaphysis as well as by the proximity to bigger vascular bundles which can be injured at the same time (28, 36, 43).

There has been a long-lasting controversy on the role of open wounds in the setting of tibial fractures. One theory stipulates that an open fracture would decompress the compartments through the fascial wound, thus protecting against the development of ACS (60), while another states that a skin wound close to a fracture should be recognized as a sign of major trauma to the underlying fascia and muscles, thus potentially increasing the risk of ACS (40, 51). This review suggests that an open fracture does not seem to provide adequate muscle compartment decompression and protection against ACS (48, 52). Clinicians should not be wrongly reassured by an open fracture. A skin lesion in a fractured limb should be recognized as a sign of major trauma to the underlying fascia and muscles, potentially increasing the risk of ACS (40, 51).

Table 4 Literature review key points.

	Factors associated with ACS	
	Clinical	Radiological
Proximal tibial fractures	Younger age (<40 years old) Male gender Polytrauma High-energy fractures and sports injuries Open fractures	Contiguous skeletal lesion* Higher AO/OTA and Schatzker classification types Increased tibiofemoral displacement Increased tibial joint surface width Increased fracture length
Diaphyseal tibial fractures	Younger age (<40 years old) Male gender Polytrauma Manual laborers High-energy fractures and sports injuries Open fractures	Contiguous skeletal lesion† Higher of AO/OTA classification types and subgroups Proximal shaft fractures
Distal tibial fractures	No clear data	Increased fracture length

*Shaft or pilon tibial fracture, knee dislocation, fibular fracture, proximal tibiofibular dislocation; †Plateau or pilon tibial fracture, proximal tibiofibular dislocation. ACS, acute compartment syndrome.

Multilevel tibial fractures as well as concomitant intra-articular tibial plateau fracture with knee dislocation, fibular fracture, or proximal tibiofibular dislocation were found to be a risk factor for the occurrence of ACS. The presence of another skeletal lesion in the same limb segment is suggestive of higher energy injury mechanism and should alert the treating surgeon for a higher risk of ACS occurrence.

Indirect signs of higher energy trauma (higher AO/OTA classification, higher Schatzker types, increased fracture length, femorotibial displacement, and tibial widening) may all indicate a higher risk of ACS occurrence.

Literature review summary

To the authors' knowledge, this review is the first to specifically focus on clinical and radiological risk factors for ACS occurrence in the setting of a tibial fracture. Table 4 summarizes the results of this literature review.

Some of these risk factors (younger age, male gender, higher AO/OTA, types, high-energy mechanism of injury) are in line with another recent review which takes into account extremity injury as a whole: upper and lower extremity including foot injury and gunshot wounds with or without associated fractures (61).

Limitations to this study are many. First, this review lacks a statistical comparison among results, this was difficult to assess due to the heterogeneity of studies founds comprising many different studies designs and protocols. Secondly, studies we included were nearly all retrospective cohort studies and their level of evidence was often not indicated, and it was interpreted by the authors.

Conclusions

This review was able to highlight different clinical and radiological risk factors for the occurrence of ACS in tibial plateau, shaft, and pilon fractures (Table 4). The presence of each independent predictor may have a cumulative effect increasing the risk of ACS occurrence when more than one variable is present (32, 34). Actively searching for these risk factors may help the treating surgeon to evaluate the risk of ACS and the necessity of frequent clinical assessments and/or repeated or continuous ICP measures throughout the treatment of tibial fractures, before, during, and after surgery, especially in patients with equivocal clinical signs or loco-regional anesthesia and in intubated, sedated, or obtunded patients.

ICMJE Conflict of Interest Statement
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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