PhD Thesis

Effect of different fixation techniques for the treatment of tibial plateau impression fractures

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Thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

PhD program Musculoskeletal Sciences

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Innsbruck, May 2016
I would like to thank Assoc. Prof. Werner Schmölz for his professional and friendly mentoring through my Ph.D. programme. I have learned a great deal from him for my future career and life and have pleasant memories of my time in his laboratory.

I would also like to thank Dipl. Ing. Christian Heinrichs, who was doing his Ph.D. at the same time as me. We immediately developed a fruitful collaboration, with productive discussions during lunchtimes.

My thanks also go to Prof. Blauth, who made my Ph.D. possible and supported my research with questions and ideas.

I am also grateful to the Department of Anatomy at the Medical University of Innsbruck for their outstanding scientific cooperation. I would like to thank individuals who donated their bodies and tissues for the advancement of education and research. Special thanks go to Mr. Romed Hörmann for providing the detailed anatomical illustrations for my thesis.

Finally, I would like to thank my whole family, who have always given me their support, and particularly my father, Dr. arch. Karl Mayr, for his constant encouragement and backing.
I hereby declare that this thesis and the research reported in it have been written entirely by me. Information derived from other published and unpublished sources is clearly marked with references. I declare that I contributed to each aspect of the thesis (conception of idea, experiments, data analysis and manuscript writing).

The results of the present PhD study have been published in the Journal of Clinical Biomechanics under the title “Effect of additional fixation in tibial plateau impression fractures treated with balloon reduction and cement augmentation,” and parts of the text have been adapted from the publication.

Innsbruck, 18 May 2016

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Raul Mayr, M.D.
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1. ABSTRACT

Purpose:

Anatomical reduction of tibial plateau impression fractures is essential for avoiding post-traumatic knee arthritis. Isolated impression fractures of the tibial plateau are typically found in elderly patients with decreased bone quality. Minimally invasive surgery and early patient mobilization improve the outcome in this group of patients. Tibial plateau impression fractures can be reduced in a minimally invasive fashion by using a percutaneous balloon inflation system. The fracture is augmented with a cement injection in order to support the reduced subchondral bone. In clinical practice, additional fixation using screws or plates is commonly performed. Parallel screws (a screw raft) can be placed percutaneously, and this represents a fully minimally invasive surgical technique in combination with balloon reduction and cement augmentation of tibial impression fractures. Placement of a plate may be more invasive, although it provides angular stability for the screws. However, there is no evidence on whether additional fixation as such, and if so which methods of fixation, are necessary in the treatment of isolated tibial plateau impression fractures. The purpose of the present biomechanical study was to compare a locking plate and a screw raft for additional fixation after balloon reduction and cement augmentation in isolated tibial plateau impression fractures. After testing, the additional fixation was removed and loss of reduction was analyzed with cement augmentation of the fracture alone.

Methods:

In this biomechanical study, eight matched pairs of human fresh-frozen tibiae were used for testing. Pure impression fractures were created by pushing an indenter into the lateral tibial plateau. Fractures were reduced using a balloon inflation system (Kyphon-Medtronic). The subchondral bone void created was filled with injectable cement (VertecemV+, Synthes). In the first group, a lateral locking plate (3.5 mm, Synthes) was used for fixation. In the second group, a raft consisting of four 3.5-mm cortical screws was inserted through the cement cloud. Specimens underwent cyclic loading with 5000 cycles per interval, and loads of 20–240 N, 20–360 N and 20–480 N were applied to the lateral tibial plateau. The applied load magnitudes simulated postoperative weight-bearing of 66%, 100% and 133%. Subsequently, the additional fixation (plate or screw raft) was removed and the last cyclic interval (20–480 N) was repeated in order to assess fracture stabilization in the cement cloud alone.
Radiographs were taken between each loading interval and loss of fracture reduction was assessed by measuring the subsidence of the subchondral bone and cement mass.

Results:

With both additional fixations, the initial reduction was maintained at a comparable magnitude during cyclic loading at 240 N and 360 N. Fractures treated with plate fixation showed significantly less subsidence during cyclic loading at 480 N (0.9 ± 0.6 mm) in comparison with screw raft fixation (1.5 ± 0.8 mm) \((P = 0.039)\). No movement in the implant or cement was observed in the group with plate fixation. In the group with screw raft fixation, subsidence of the cement was observed in one case and subsidence of the cement with the attached screw in two cases. Loss of reduction significantly increased after implant removal to 1.3 ± 0.7 mm and 1.9 ± 0.9 mm in the groups with plate and screw raft fixation, respectively \((P = 0.002, P = 0.003)\). After implant removal, subsidence of the cement was observed in five out of eight specimens in both groups.

Conclusions:

Angularly stable plate fixation of tibial plateau impression fractures showed less loss of reduction at higher loads in comparison with screw raft fixation. After removal of the additional fixation, the rate of cement cloud subsidence and loss of reduction significantly increased. The results of the present study suggest that after balloon reduction and cement augmentation of tibial plateau impression fractures, additional fixation should be carried out. Angularly stable plate fixation may be recommendable for minimizing postoperative loss of reduction, especially in cases of severe osteoporosis, with a large fracture surface and soft-tissue conditions permitting an open surgical approach. After fracture treatment using the fully minimally invasive technique with percutaneous screw raft insertion, partial weight-bearing should be recommended to the patient.
2. ZUSAMMENFASSUNG

Fragestellung:


Methodik:

ZUSAMMENFASSUNG

Zementwolke alleine analysiert. Nach jedem Lastintervall wurden Röntgenbilder angefertigt und das Absinken der Fraktur und der Zementwolke vermessen.

Ergebnisse:

Nach der zyklischen Belastung mit 240N und 360N blieb die initiale Reposition mit beiden Osteosynthesetechniken in vergleichbarem Ausmaß erhalten. Die Frakturversorgung mit Platte zeigte signifikant weniger Repositionsverlust nach Belastung mit 480N (0.9±0.6mm) verglichen mit der Frakturversorgung mit Schrauben (1.5±0.8mm) (P=0.039). Die Präparate mit Plattenosteosynthese zeigten keine Bewegung der Schrauben oder Zementplombe unter Belastung. In der Gruppe mit Schraubenosteosynthese wurde in zwei Fällen ein Absinken der Zementplombe mitsamt der fixierenden Schraube und in einem Fall ein isoliertes Absinken der Zementplombe beobachtet. Die Entfernung der Osteosynthese erhöhte den Repositionsverlust signifikant in beiden Gruppen auf 1.3±0.7mm und 1.9±0.9mm für Platten- und Schraubenosteosynthese (P=0.002, P=0.003). Nach Entfernung der Osteosynthese wurde ein Absinken der Zementplombe bei fünf von acht Präparaten in jeder Gruppe beobachtet.

Schlussfolgerungen:

3. INTRODUCTION

3.1. Anatomy of the proximal tibia

The proximal tibia, also known as the tibial head, consists of the tibial plateau, tibial condyles and tibial metaphysis. The tibial head forms the distal part of the knee joint.

3.1.1. Bone

The tibial head has a medial and lateral condyle with an oval shape. The condyles have a cartilage surface that forms the tibial plateau, with a medial and lateral articular part. They have a concave surface, which is more pronounced on the medial condyle. The two articular surfaces are separated by the intercondylar eminence, which has a medial and lateral intercondylar tubercle (Fig. 1A). The tibial plateau has a dorsal slope to the proximal tibial anatomical axis of 7–13°.1,2

At the metaphysis, the tibia acquires a triangular shape. Centrally at the ventral side, the tibial tuberosity goes over into the anterior margin of the tibia. More laterally and proximally, the less prominent bony Gerdy's tubercle is located (Fig. 1B). This is the insertion site for the iliotibial band. The articular surface of the proximal tibiofibular joint is located on the dorsolateral side of the tibial head.

![Fig. 1. Proximal tibial bone. A. Axial view on the tibial plateau of a left tibia. * Medial tibial plateau, + lateral tibial plateau, # intercondylar eminence, > tibiofibular joint. B. Frontal view of the tibial head. * Tibial tuberosity, + Gerdy's tubercle, # intercondylar eminence. (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)](image-url)
3.1.2. Femorotibial Joint

The knee joint is a compound joint that consists of the femorotibial and femoropatellar joints. The femorotibial joint has a medial and lateral compartment, each consisting of a femoral and tibial condyle. The femoral condyles do not have a constant curvature on the sagittal plane. The curvature radius steadily decreases from anterior to posterior (Fig. 2). This also increases the surface incongruence between the femoral and tibial condyles. As the lateral tibial condyle is slightly convex, the incongruence is more pronounced at the lateral compartment and the lateral compartment undergoes more translational and rotational movement in comparison with the medial compartment.

**Fig. 2.** Distal femoral bone (right side). A. Axial view from caudal on the femoral condyles. * Medial femoral condyle, + lateral femoral condyle, # intercondylar fossa, ∨ trochlea. B. Lateral femoral condyle. * Lateral epicondyle. C. Medial femoral condyle. * medial epicondyle, + adductor tubercle (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)
INTRODUCTION

The tibial condyles are partly covered by the menisci, which decrease the articular surface incongruence between the femoral and tibial condyles. The medial meniscus lies along the medial border of the medial tibial condyle. Its anterior and posterior horns insert at the anterior and posterior intercondylar area, respectively. At the intermediate zone, the basis of the medial meniscus is attached to the femur and tibia by the meniscofemoral and meniscotibial ligaments. They form the deep layer of the medial collateral ligament (MCL). The meniscotibial ligament inserts at the edge of the articular cartilage of the medial tibial plateau. The anterior horns of the lateral and medial menisci are connected with the transverse meniscomeniscal ligament. The lateral meniscus has a more circular shape and covers the lateral tibial condyle to a greater extent in comparison with the medial meniscus (Fig. 3). The anterior and posterior horn inserts at the intercondylar area anteriorly and posteriorly. The posterior horn is additionally attached to the medial femoral condyle by the meniscofemoral ligaments (Humphry and Wrisberg). In the intermediate zone, the lateral meniscus is not attached to the femur or tibia. Thus, the lateral meniscus undergoes more translation during knee motion than the medial meniscus\textsuperscript{3,4}.

Fig. 3. Axial view of the tibial plateau of a right knee. * Medial plateau with medial meniscus, + lateral plateau with lateral meniscus, \(\wedge\) tibial insertion of the anterior cruciate ligament (ACL), # tibial insertion of the posterior cruciate ligament (PCL). (Image reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)
3.1.3. Knee joint ligaments

The capsule–ligament system of the knee can be divided clinically and functionally into the central compartment and the collateral ligament system. The central compartment consists of the anterior and the posterior cruciate ligaments (ACL, PCL), while the collateral ligament system comprises the medial and lateral collateral ligaments (MCL, LCL), as well as the muscle-connected ligaments in the posteromedial and posterolateral part of the joint.

The ACL is an intra-articular, but extrasynovial, band of dense connective tissue. It is enveloped by the synovium. It follows an oblique course in the anterior-medial-distal direction: proximally, it attaches to the posteromedial edge of the lateral femoral condyle, whereas distally it attaches to the anterior intercondylar fossa of the tibial plateau. The ACL consists of two functional individual fibrous bundles, anteromedial (AM) and posterolateral (PL) bundles, named after their insertion points on the tibial footprint (Fig. 4)\(^5\).

**Fig. 4.** A. Anterior view into the right knee after removal of the patella and anterior capsule. * Medial meniscus with meniscotibial attachment, + lateral meniscus, AM,PL anteromedial and posterolateral bundles of ACL, # PCL. (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck). B. Oblique view of the medial wall of the lateral femoral condyle, right knee. AM bundle (red), PL bundle (blue).

The PCL originates from the lateral wall of the medial femoral condyle and inserts at the posterior intercondylar area. A thick part of the ligament runs over the posterior tibial border and inserts at the posterior wall of the tibia. The PCL has a ligamentous connection to the posterior horn of the lateral meniscus. Two functional bundles, the anterolateral and...
posteromedial bundle, can be identified. The anterior meniscofemoral ligament (Humphry ligament) runs anteriorly, and the posterior meniscofemoral ligament (Wrisberg ligament) runs posteriorly from the anterolateral bundle of the PCL to the lateral femoral condyle (Fig. 5).

![Image](image.png)

**Fig. 5.** Posterior view of a left knee joint. * Medial meniscus, + lateral meniscus with the posterior meniscofemoral ligament (Wrisberg), \(\wedge\) ACL, # PCL, LCL lateral collateral ligament, POL posterior oblique ligament. (Image reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

The MCL is a broad ligament that originates at the medial femoral condyle and inserts at the medial aspect of the proximal tibia. The tibial insertion lies anteriorly to the medial tibial margin and posteriorly to the insertion of the superficial pes anserinus. The MCL runs obliquely at an angle of 15–20° to the tibial axis in full extension. The ventral part of the MCL runs over the knee capsule. A bursa separates the ventral MCL from the joint capsule in
order to allow sliding of the structures. The ventral MCL does not have any connection to the medial meniscus. The dorsal part of the MCL has a superficial and deep layer. The superficial layer has long parallel ligamentous fibers and inserts at the tibia. The deep layer has shorter fibers running from the medial femoral epicondyle to the base of the medial meniscal (meniscofemoral ligament) and from the meniscus to the tibia (meniscotibial ligament). Dorsally, the MCL continues in the posterior oblique ligament (POL). Its origin is the adductor tubercle and it inserts at the posterior articular capsule and posteromedial tibia (Fig. 6A).\(^7\)

The lateral collateral ligament (LCL) is a round ligament with its origin at the lateral femoral condyle, and it inserts at the fibular head. The LCL has no connection to the lateral knee capsule or meniscus (Fig. 6B).\(^8\)

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**Fig. 6.** Collateral ligaments of a left knee joint. **A.** Medial view of the medial collateral ligament (MCL). The ventral part is formed by the superficial MCL (sMCL). The posterior part of the ligament is formed by the posterior oblique ligament (POL). **B.** Lateral view of the lateral collateral ligament (* LCL) and lateral meniscus (+). (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)
INTRODUCTION

The dorsal part of the knee is composed of strong ligaments that are tensioned in full extension. They limit knee hyperextension and stabilize the knee against varus or valgus moments in full extension. The semimembranosus tendon inserts at the posteromedial corner of the knee. Its broad insertion is called the deep pes anserinus and consists of five insertions: oblique popliteal ligament, a strand to aponeurosis of the popliteus, a strand to the dorsal tibia, a strand to the posteromedial tibia and a strand to the POL and medial meniscus (Fig. 7). The oblique popliteal ligament runs at the dorsal articular capsule and inserts at the dorsal femur under the head of the lateral gastrocnemius muscle and plantaris muscle.

The popliteus muscle originates anteriorly from the lateral femoral epicondyle (Fig. 7). The strong popliteus tendon passes through the posterior horn of the lateral meniscus, and the muscle inserts at a broad area at the dorsal tibia proximal to the soleal line. The arcuate popliteal ligament originates at the fibular head and inserts at the lateral meniscus, popliteus tendon, fabella and dorsal tibia. The connection between the popliteus muscle and the arcuate popliteal ligament provides dynamic stabilization of the posterolateral corner of the knee.

Fig. 7. Posterior aspect of a right knee joint. * Popliteus tendon, LCL lateral collateral ligament, # insertion of the lateral gastrocnemius muscle, + semimembranosus tendon with its five insertion strands forming the deep pes anserinus (dotted lines). (Image reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)
### 3.1.4. Muscles

The muscles acting on the knee joint are divided into an extensor group and a flexor group. Whereas the extensor group predominantly exerts knee extension, the flexor muscles exert knee flexion and either internal or external rotation of the lower leg (Fig. 8)\(^d\). A summary of the active muscles required for various motions is given in Table 1.

**Table 1.** Summary of the knee joint muscles and the movements they exert.

<table>
<thead>
<tr>
<th>Extension</th>
<th>Flexion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps femoris</td>
<td>Biceps femoris</td>
</tr>
<tr>
<td>Tensor fasciae latae</td>
<td>Semimembranosus</td>
</tr>
<tr>
<td></td>
<td>Semitendinosus</td>
</tr>
<tr>
<td></td>
<td>Gracilis</td>
</tr>
<tr>
<td></td>
<td>Sartorius</td>
</tr>
<tr>
<td></td>
<td>Popliteus</td>
</tr>
<tr>
<td></td>
<td>Gastrocnemii</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal tibial rotation</th>
<th>External tibial rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimembranosus</td>
<td>Biceps femoris</td>
</tr>
<tr>
<td>Semitendinosus</td>
<td>Tensor fasciae latae</td>
</tr>
<tr>
<td>Gracilis</td>
<td>Medial gastrocnemius</td>
</tr>
<tr>
<td>Popliteus</td>
<td></td>
</tr>
<tr>
<td>Lateral gastrocnemius</td>
<td></td>
</tr>
</tbody>
</table>

The general active range of motion in the knee joint is 130° of flexion, 0–10° of hyperextension, and 10° internal and 30° external rotation\(^3,11\).
Fig. 8. The knee joint muscles with their insertions at the knee. A. Ventral side. 1. Rectus femoris, 2. vastus medialis, 3. vastus lateralis, 4. sartorius, 5. gracilis, 6. tensor fasciae latae, 7. superficial pes anserinus, 8. quadriceps tendon, 9. patellar tendon. (Image reproduced with permission from the Department of Anatomy, Medical University of Innsbruck). B. Dorsal side. 1. Biceps femoris, 2. semimembranosus, 3. semitendinosus, 4. gracilis, 5. sartorius, 6. popliteus, 7. lateral head of the gastrocnemius, 8. medial head of the gastrocnemius. (Image adapted from the Pernkopf atlas of anatomy)
3.2. Tibial plateau fractures

3.2.1 Etiology
Around one per cent of fractures in adults involve the tibial plateau. Tibial plateau fractures typically result from axial compression mechanism on the tibial head. This can be either isolated or combined with a rotatory moment. The axial compression leads to the impression of the articular surface with or without a split of the outer cortex. The rotatory moment causes associated ligament injuries to the knee joint, which occur in up to 30% of tibial head fractures.

Tibial head fractures can be caused by low-energy and high-energy traumas. Low-energy traumas occur during normal everyday activities such as a fall in the domestic environment or during walking. Older patients with diminished bone quality are mainly affected. High-energy traumas may result from traffic accidents, high falls and sports injuries. These typically involve younger, active patients. Moore et al. analyzed the demographic data for 752 patients with tibial plateau fractures and reported that the patients’ average age was 44 years and that they were predominantly male, in 62% of cases.

3.2.2 Classification
Several classification systems have been described for tibial head fractures. The treatment strategy can be defined and the outcome predicted on the basis of these classifications.

3.2.2.1 Schatzker

Schatzker classified 1979 tibial plateau fractures according to their anatomical locations and the extent of the concomitant injuries. Fractures are divided into six types: type 1 fractures are split fractures of the lateral tibial plateau; type 2 are split-impression fractures of the lateral tibial plateau; type 3 are pure impression fractures of the lateral tibial plateau; type 4 are fractures of the medial tibial plateau; type 5 are bicondylar fractures; and type 6 are bicondylar fractures with separation of the tibial head from the shaft (Fig. 9).

Schatzker type I fractures are split fractures through the lateral tibial condyle. The fracture displacement is usually less than 4 mm. The fracture results from a valgus moment leading to axial impaction of the lateral femoral condyle onto the lateral tibial condyle. This can lead to a distraction injury on the contralateral medial side involving the MCL, or a medial meniscus separation. This type of fracture is typically seen in younger patients with a high
quality of cancellous bone in the tibial head. The normal anatomy of the tibial plateau can be easily restored by fracture reduction and fixation\textsuperscript{17,18}.

Schatzker \textbf{type II} fractures are split fractures combined with an articular impression at the lateral tibial condyle. This is the most common fracture type, representing 25\% of all tibial plateau fractures\textsuperscript{19}. The fracture mechanism corresponds to type I fractures as above, with a valgus moment on the knee. Patients in the fourth to fifth decades of life with a certain amount of osteopenia are typically involved. Concomitant injuries are distraction injuries of the MCL and medial meniscus. After impression elevation and fracture reduction, a residual defect zone or irregularity on the articular surface sometimes has to be accepted\textsuperscript{17,20}.

Schatzker \textbf{type III} fractures are pure impression fractures of the lateral tibial plateau without splitting of the cortical bone. These mostly result from low-energy trauma, such as falling on stairs, causing an axial compression load on the lateral tibial plateau. Concomitant injuries are lateral meniscus tears, resulting from direct compression. This type of fracture is typically seen in older patients (fourth to eighth decades of life), with diminished bone quality in the cancellous bone of the tibial head. The treatment depends primarily on the depth of the impression and patient factors. Surgical treatment consists of fracture elevation, defect augmentation and additional fixation\textsuperscript{17,21}.

Schatzker \textbf{type IV} fractures are split or impression fractures of the medial tibial condyle. They result from a varus movement, leading to axial impaction of the medial femoral condyle onto the corresponding tibial condyle. Additional knee hyperflexion during injury leads to a posteromedial coronal split fracture. In younger patients, these fractures are caused by high-energy traumas with knee subluxation or luxation with spontaneous reduction. This may cause severe concomitant injuries, especially distraction injuries of the lateral and posterolateral ligamentous structures, peroneal nerve and popliteal artery\textsuperscript{22}. In older patients, low-energy traumas can also lead to this type of fracture, without severe concomitant injuries. Treatment involves reduction and fixation of the fracture with buttress plates or screws\textsuperscript{17,23}.

Schatzker \textbf{type V} fractures are bicondylar split fractures of the medial and lateral tibial plateau. They may be associated with fractures of the intercondylar eminence or bony avulsion of the cruciate ligaments. Type V fractures result from high-energy trauma, with a complex injury mechanism including axial loading combined with varus or valgus stress. Thus, fractures are associated with increased soft-tissue injury, possibly open fractures, and injuries to the neurovascular structures. In bicondylar fractures, the distal attachments of the collateral ligaments are separated from the tibia, causing lateral instability of the knee. The
anchorage of the cruciate ligaments becomes crucial for knee stability. Four-part fractures (bicondylar split with intercondylar eminence separation) must be regarded as grossly unstable joint fractures. A peripheral meniscus detachment is found in about half of patients with type V fractures, and avulsion of the ACL in up to a third of them. The amount of soft-tissue injury determines the surgical treatment flowchart, but early joint stabilization is mandatory.

Schatzker type VI fractures are tibial head fractures with separation of the metaphysis from the diaphysis. They present with a transverse fracture below the bicondylar tibial head and result in a severely unstable fracture. They result from high-energy trauma, and open fractures are present in up to a third of the cases. The fracture morphology at the tibial plateau includes all types of fracture. The amount of soft-tissue injury determines the surgical treatment flowchart, but early joint stabilization is mandatory.
Fig. 9. The Schatzker classification of tibial plateau fractures (adapted from Brunner et al.\textsuperscript{26}).
I. Split fracture, II. split fracture with impression of the articular surface, III. isolated tibial plateau impression fracture, IV. split fracture of the medial condyle, V. bicondylar fracture, VI. tibial head fracture with metaphyseal fracture.
3.2.2.2 AO / OTA classification

Another widely used classification system is the AO/OTA (Arbeitsgemeinschaft für Osteosynthesen/Orthopedics Traumatology Association) classification, which categorizes fractures of the proximal tibia into three main types (A, B and C). Type A fractures are extra-articular fractures involving the metaphysis, with the tibial plateau remaining intact. Types B and C are intra-articular fractures with fracture splits, articular impressions, or defect zones at the tibial plateau\textsuperscript{13}. Each type is further divided into three subgroups depending on the severity of the fracture (Fig. 10).

![AO Foundation](image)

**Fig. 10.** Classification of proximal tibial fractures\textsuperscript{14}.

The first two numbers ("41") describe the anatomical location. Number "4" stands for the tibial bone, number "1" for proximal (out of 1 to 3, standing for proximal, middle and distal third of long bones). "A" fractures refer to extra-articular fractures in which the tibial plateau remains intact. "B" fractures are tibial plateau fractures that involve only one condyle. "C" fractures are bicondylar tibial plateau fractures. The last number (1 to 3) indicates the severity of fracture comminution and articular defects. (Image reproduced from the AO web site: https://www2.aofoundation.org/)
3.2.2.3  Hohl classification

Some tibial plateau fractures result from partial or complete knee luxation, with associated ligamentous injuries. The Hohl classification\(^{27}\) is often more helpful for these fractures in comparison with the Schatzker classification. Fractures are divided into six types. The first three types are similar to the Schatzker classification, including I. a split fracture of the lateral condyle, II. a pure impression of the lateral tibial plateau and III. a split-impression fracture of the lateral condyle. These may be associated with collateral ligament tears, cartilage and meniscal damage. Type IV fractures are medial condylar split fractures (entire condylar fracture) and are associated with lateral–posterolateral knee ligament injuries and possibly with peroneal nerve and popliteal artery lesions. Type V fractures refer to coronal split fractures of the posterior part of the tibial plateau. The mechanism of injury is anterior luxation or subluxation of the tibia, with complete tearing of the ACL. Concomitant injuries to the PCL and collateral ligaments must be suspected. Type VI fractures refer to bicondylar fractures with severe soft-tissue damage, bilateral collateral ligament detachment of the tibia and possible cruciate ligament tears. The mechanism of injury includes axial compression with subluxation or luxation of the tibia in any direction (Fig. 11).
Fig. 11. The Hohl classification\textsuperscript{27} of tibial plateau fractures (adapted from Brunner et al.\textsuperscript{26})
I. Split fracture of the lateral condyle, II. tibial plateau impression fracture, III. split-impression fracture of the lateral condyle, IV. split fracture of the medial condyle (entire condylar fracture), V. posterior coronal split fracture of the tibial plateau, VI. bicondylar fracture.
3.2.2.4 Three-column

The Schatzker and AO/OTA classification systems are based on the appearance of tibial plateau fractures on anteroposterior radiographs. However, they do not fully assess some fracture types. With improvements in radiographic imaging, fractures can now be visualized three-dimensionally using computed tomography (CT). Zhu et al.\textsuperscript{28} introduced a CT-based classification of tibial plateau fractures.

On the axial slices of the CT scan, a section containing most parts of the fibular head is selected. The center of the tibia metaphysis is marked. Lines are then drawn to the tibial tuberosity, the anterior border of the fibula and the posteromedial ridge of the proximal tibia. This divides the tibial plateau into three columns: medial, lateral and posterior (Fig. 12). A fracture line that passes through the column wall is defined as a fracture involving the corresponding column. The three columns are relevant for the surgical treatment in terms of patient position, surgical approach, plate type and plate position. A pure impression fracture of the tibial plateau without rupture of any of the column walls is defined as a zero-column fracture.

\textbf{Fig. 12.} Pattern of the Zhu three-column classification.\textsuperscript{28}

The center of the metaphysis is marked on an axial CT slice, and lines are drawn to the tibial tuberosity, anterior border of the fibula and the posteromedial ridge of the tibia. The lateral, posterior, and medial columns are divided by these lines. In this example, the fracture lines extend into all three columns.
3.2.3 Diagnosis of tibial plateau fractures

At the clinical examination, the patient presents with pain, swelling and an inability to bear axial loading of the knee. On physical examination, hemarthrosis is noted. The extremity must be examined for peripheral perfusion and sensorimotor aspects. The amount of soft-tissue damage can be assessed visually and with palpation.

Standard anteroposterior (AP) and lateral x-rays of the knee joint with the proximal tibia are the primary radiological images for assessing tibial plateau fractures. Undisplaced or minimally displaced fractures may be overlooked, and underestimation of the articular impression is frequent. CT scanning has therefore become the standard for the preoperative assessment of these fractures. Cross-sectional imaging can add important information, with better visualization of the fracture pattern, articular impression and displacement. Studies have reported that the surgical plan based on plain radiographs is altered in up to 60% of cases after CT scanning and in about 21% of cases after magnetic resonance imaging (MRI)\(^29-31\). Preoperative planning can also be carried out using three-dimensional reconstructions of the tibial head. In severe fracture patterns, CT angiography should be performed to assess possible vascular injuries. In most cases, an examination of the knee’s stability is not tolerated by the patient and it may be associated with a risk of fracture dislocation. Additional MRI can be carried out to visualize all ligamentous, cartilaginous and meniscal injuries at the knee joint.

3.2.4 Osteoporosis and osteoporotic fractures

Globally, osteoporosis is the most common type of bone disease\(^32\). Due to demographic changes, the incidence of osteoporotic fractures and tibial plateau fractures in geriatric patients is increasing\(^33,34\). Isolated tibial plateau impression fractures are typical osteoporotic fractures in patients who have a diminished bone quality at the tibial metaphysis. Low-energy trauma such as a fall causes an axial impression of the femoral condyle into the tibial plateau without fracture of the cortical bone.

Osteoporosis can be treated pharmacologically in order to reduce the risk of osteoporotic fractures. Specific surgical treatment strategies are required in the case of osteoporotic fractures and geriatric tibial plateau impression fractures.
3.2.4.1 Osteoporosis and pharmacological treatment

Osteoporosis is defined as a systemic disease in which the bones become fragile and more likely to break. It leads to an abnormally reduced level of bone mineral density (BMD), with impaired bone microarchitecture and strength, increasing the individual’s susceptibility to bone fractures. All forms of osteoporosis are based on an imbalance between osteogenesis by osteoblasts and bone resorption by osteoclasts.

The World Health Organization (WHO) defined manifest osteoporosis using a threshold T-score of less than or equal to –2.5 standard deviations, measured on dual-energy x-ray absorptiometry (DEXA) at the hip. In the past, osteoporosis was mainly diagnosed in accordance with the WHO criteria on the basis of the results of DEXA BMD measurements expressed using the T-score. The T-score describes the number of standard deviations by which a patient’s BMD differs from the mean BMD in a healthy adult female reference population. The WHO criteria are:

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>T-score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>T-score ≥ –1.0</td>
</tr>
<tr>
<td>Osteopenia</td>
<td>T-score –1.0 to –2.5</td>
</tr>
<tr>
<td>Osteoporosis</td>
<td>T-score ≤ –2.5</td>
</tr>
</tbody>
</table>

Osteoporosis can affect women and men in all age groups, but is more common in older women. About half of all women over the age of 50 sustain a hip, wrist, or spine fracture during their lives. General risk factors can be divided into four groups: genetic, lifestyle, hormonal and pharmacological (Table 2). Osteoporosis is a major socioeconomic problem that causes annual direct healthcare costs of €31.7 billion in Europe.

Osteoporotic fractures mainly affect the spine, wrist, proximal humerus and hip. The mortality rate after a proximal femur fracture is about 13% within the first 6 months and about 25% within 12 months after the injury. About only half of the patients are able to recover the same activity level in everyday life as before the injury. About 25% remain immobile and 50% become unable to leave the house independently or without assistance.

In the past, decision-making on whether to carry out preventive measures or treatment was often made on the basis of the T-score alone. However, prediction of osteoporotic fractures can be optimized by combining certain risk factors with the BMD. The “10-year osteoporotic fracture risk” can be predicted using the “fracture risk assessment tool” (FRAX), taking into account risk factors identified in epidemiological studies and meta-analyses (Table 3). This allows a clearer indication for osteoporosis treatment, but treatment guidelines differ between countries. In Austria, treatment should be initiated when the risk for hip fracture is more than 3–5%.
Table 2. General risk factors can be divided into four groups: genetic, lifestyle, hormonal and pharmacological.

**Genetic**
- Ethnic
- Sex
- Asthenic body shape
- Osteoporosis in parents
- Genetic polymorphism
  - Men: mutation of the protein A4 gene \([GJA4]\)\(^{29}\)
  - Women: mutation of the adipocyte-derived leucine aminopeptidase [ALAP] gene\(^{29}\)

**Lifestyle**
- Smoking
- Alcohol abuse
- Low weight
- Lack of exercise
- Immobilization
- Nutrition
- Vitamin D deficiency
- Lack of sunlight exposure

**Hormonal**
- Primary or secondary oligomenorrhea/amenorrhea
- Premature menopause
- Hypogonadism
- Hyperthyroidism

**Pharmacological**
- Hormonal (steroids, LHRH agonists/antagonists, aromatase inhibitors, antiandrogens, anticonvulsants)
- Immunosuppressive medication
- Chemotherapeutic agents
- Other (hydantoins, heparin, glitazones)
Table 3. Risk factors for predicting the “10-year osteoporotic fracture risk” in accordance with the fracture risk assessment tool (FRAX)\(^{31}\).

<table>
<thead>
<tr>
<th>Risk Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Age</td>
</tr>
<tr>
<td>2. Previous fracture</td>
</tr>
<tr>
<td>3. Femoral neck fracture in one parent</td>
</tr>
<tr>
<td>4. Steroid therapy</td>
</tr>
<tr>
<td>5. Alcohol or tobacco consumption</td>
</tr>
<tr>
<td>6. Rheumatoid arthritis</td>
</tr>
<tr>
<td>7. Decreased BMI</td>
</tr>
</tbody>
</table>

Prevention of osteoporosis consists mainly of lifestyle modifications, including nutrition with calcium-rich food, sun exposure and muscle training. However, the recommended minimum levels of daily intake are 1000–1300 mg calcium and 600–800 IU vitamin D\(^{40}\). These levels cannot always be reached by lifestyle modifications alone, and oral supplementation with calcium–vitamin D should be initiated. Severe vitamin D deficiency must be assumed in geriatric or immobilized patients in particular.

A daily intake of a minimum of 1200 mg calcium combined with 800 IU vitamin D represents the basic treatment for preventing manifest osteoporosis. The calcium intake can be increased to 2000 mg per day, which has been shown to be safe in relation to the risk of cardiopulmonary events in a long-term follow-up study of older female patients\(^{41}\). Monotherapy with calcium may only reduce the fracture risk in patients with severe calcium deficiency and is less effective than combination therapy with calcium and vitamin D. Vitamin D is involved in calcium absorption in the duodenum, and monotherapy with vitamin D may be ineffective in patients with calcium deficiency. The vitamin D dosage can be temporarily increased until normal 25(OH)D levels are reached.

In patients with manifest osteoporosis, however, the basic therapy has to be combined with additional osteoporotic medications. The guidelines for osteoporotic treatment recommend an antiresorptive bisphosphonate drug for first-line additional medication\(^{35}\). Bisphosphonates are resorbed by osteoclasts during phagocytosis, causing a lifetime reduction of osteoclasts.

Alternative drugs include a human monoclonal antibody that binds the receptor activator of nuclear factor-κB ligand (RANKL). This inhibits interaction with the receptor (RANK) on the surface of osteoclasts.
In patients with postmenopausal osteoporotic fractures, selective estrogen receptor modulators (SERMs) are indicated for therapy. These stimulate the estrogen receptor at osteoblasts, leading to reduced expression of interleukin-6 (IL-6), which is a strong stimulator for osteoclasts.

3.2.4.2  Surgical treatment of osteoporotic fractures

The main challenge in the surgical treatment of osteoporotic fractures is to achieve a sufficient fixation quality in the intraoperative fracture reduction. There is a high risk of implant loosening and movement. The thin cortical bone and the low density of cancellous bone in patients with osteoporosis require special attention when osteosyntheses are performed, and special implants or surgical techniques have been developed to address these problems. Cement is widely used for bone filling or augmentation of the osteosynthesis material in geriatric trauma centers\textsuperscript{37-42}. Generally, there are two techniques for screw augmentation. Either the borehole is filled with cement and the screw is inserted afterwards, or cannulated screws are used that can be augmented “in situ” at the screw tip after screw insertion. Several biomechanical studies have shown that cement augmentation can significantly increase implant purchase\textsuperscript{18,41-45}.

Treatment options with augmentation for some of the most common geriatric fractures (vertebral body, humerus and femur) are listed below.
Compressive fractures of the vertebral body are one of the most common types of osteoporotic fracture. In the majority of cases, they remain stable and can be treated conservatively. However, with severe osteoporosis, the vertebral body tends to collapse entirely. This leads to a painful situation, with immobilization and severe kyphosis of the spine. Surgical treatment can be carried out using a minimally invasive surgical technique with a percutaneous balloon inflation system\(^\text{36}\). The vertebral body is reduced by balloon expansion and the bone void created is filled with bone substitute via the same cannula (Fig. 13).

Fig. 13. Kyphoplasty of a compressive fracture of vertebral body T12 (89 years, female).

A. Preoperative x-ray, showing almost complete collapse of the vertebral body. The patient could not be mobilized. Subsequent kyphosis deformity in the spine would lead to persistent pain. B. Postoperative x-ray. The height of the vertebral body has been increased and augmented by cement injection. Postoperatively, the patient managed to become mobile and pain was reduced. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
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Proximal humerus fractures in elderly patients are treated conservatively or surgically, mainly depending on fracture dislocation and patient-related factors. Surgical treatment may be indicated in fractures with a humeral head angulation of more than 45°, tuberosities displaced more than 5 mm, or shaft fragments displaced more than 20 mm\(^3\). After open reduction, an angular stable plate is commonly applied. In order to achieve the best fixation, the screw length should be as long as possible in order to reach the denser subcortical bone. A defect zone in the calcar region poses a greater risk of loss of reduction, in terms of varus head subsidence\(^3\). An allogenic bone graft can be used to reinforce the calcar with a cancellous bone block\(^4\). In patients with severe osteoporosis, screw anchorage can be increased using screws augmented with cement\(^43,45\). (Fig. 14)

![Fig. 14](image1.png)

**Fig. 14.** Proximal humerus fracture treated with plate fixation and augmentation (74 years, female).  
**A.** Preoperative x-ray, showing a three-part fracture with subcapital and major tubercle fracture lines. The head is displaced posteriorly, suggesting glenohumeral dislocation (AO 11-B3). **B.** Postoperative x-ray, showing the reduced fracture treated with a plate (Philos Synthes Inc., West Chester, Pennsylvania, USA) and cement augmentation of the cannulated screws entering the humeral head.  
(X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
Pertrochanteric femoral fractures represent up to 50% of all hip fractures\(^4^4\). They require early surgical stabilization in order to allow early patient mobilization and reduce the mortality rate. A femoral nail with a blade passing into the femoral head is a commonly used implant. Implant failures include blade cut-out from the femoral head. The blade anchorage can be significantly increased by cement augmentation of the blade, as shown in a human cadaveric study by Erhart et al.\(^4^6\) (Fig. 15).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{pertrochanteric_femoral_fracture_treated_with_proximal_femur_nail_and_cement_augmentation.png}
\caption{Pertrochanteric fracture treated with proximal femur nail and cement augmentation (77 years, female). \textbf{A.} Preoperative x-ray, showing a pertrochanteric fracture (AO 31-A1). \textbf{B.} Postoperative axial x-ray, showing the reduced fracture stabilized with a proximal femur nail (TFNA, Synthes Inc., West Chester, Pennsylvania, USA). The cannulated blade in the femoral head was augmented with cement. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)}
\end{figure}
INTRODUCTION

Distal femoral or periprosthetic fractures are commonly stabilized using angular stable plates and screws, which can be augmented with cement (Fig. 16).

Fig. 16. A distal femur fracture treated with plate osteosynthesis and cement screw augmentation (82 years, female). **A.** Preoperative x-ray, showing a distal peri-implant fracture. The patient had previously been treated with a proximal femur nail with blade augmentation. **B.** Postoperative x-ray, showing fracture reduction using a LISS plate (Synthes Inc., West Chester, Pennsylvania, USA). The distal screws were augmented by injecting the cement into the borehole before screw insertion. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
3.2.5 Treatment of tibial plateau fractures

The goal of treatment with tibial plateau fractures is to achieve bone healing in anatomic position in order to obtain a good functional outcome for the patient. Generally, tibial plateau fractures can be treated conservatively or surgically, depending on various factors including the type of fracture, bone quality, associated injuries, patient expectations and the surgeon’s preferences and experience.

3.2.5.1 Conservative treatment

Nondislocated and stable fractures with an articular impression of less than 2 mm can be treated conservatively\(^{18,47}\). Primary treatment consists of swelling reduction (RICE: rest, ice, compression, elevation) and pain medication. Knee motion should be started as soon as tolerated, using a continuous passive motion (CPM) brace. Early mobilization with no weightbearing, with frequent radiological check-ups, should be performed. If there is secondary dislocation, surgical reduction and osteosynthesis are indicated.

3.2.5.2 Surgical treatment

Displaced tibial plateau fractures are typically treated surgically, with fracture reduction and fracture fixation\(^{48}\). The surgical approach must allow fracture reduction and application of the osteosynthesis\(^{94}\). Open surgical approaches are mainly classified into medial, lateral and posterior approaches on the basis of the triangular contours of the tibia. Minimally invasive open approaches or stab incisions for percutaneous screw insertion have been described in the literature\(^{51,47}\).

3.2.5.2.1 Fracture reduction techniques

Displaced fractures are typically reduced using large clamps, which can be also placed percutaneously. If an open reduction is performed, the reduction can be temporarily stabilized with K-wires. Anatomical reduction is controlled using fluoroscopy, and depending on the surgeon’s preference, additionally checked with arthroscopy. Split fractures may be reduced percutaneously using reduction clamps or with open reduction. Displaced posterior coronal split fractures must be addressed using an open approach.

Articular impressions are conventionally reduced using an open cortical window approach. A cortical window is created at the lateral aspect of the proximal tibia using an osteotome. Through the cortical window, cylindrical metal bone tamps or other instruments can be introduced to elevate the depressed articular surface. Alternatively, reduction can be performed using an inflatable balloon\(^{49-56}\). Under fluoroscopy, the entry point, mostly from the anteromedial aspect of the tibia, is chosen. Through a small skin incision, the corticals is tapped with a 3.2-mm manual drill, and a cannula can be introduced into the tibial
metaphysis. A smaller manual drill is introduced and inserted below the entire impression zone (Fig. 17). The drill is then removed, and the deflated balloon is inserted centrally below the impression fracture. The top and bottom of the balloon are indicated with radiographic markers (Fig. 18A). After correct placement, the balloon is expanded with an isotonic water and contrast medium using a syringe inflation system. The balloon pressure can be detected and is typically below 250 psi (1.7 MPa)\(^50,55\). If there is high balloon pressure and a disproportionate balloon shape, the procedure has to be carefully re-evaluated. The reasons for it may be hard bone around the balloon, trapped fragments, or incorrect tool placement\(^57\). The balloon can be supported caudally with K-wires in order to direct the expanding force of the balloon upwards (Fig. 18B). Particularly in very osteoporotic bone, the balloon may expand more in the caudal direction, removing the porous cancellous bone more easily than raising the subcortical articular plateau\(^54,58\). Possible complications of balloon reduction may include breakage of the lateral or posterior cortex (Fig. 21). If the cortex is not intact, a plate fixation should be performed (Fig. 22). In general, cement augmentation must be performed very carefully due to the risk of cement leakage into the surrounding tissue. Cement filling should be always controlled under fluoroscopy and performed in a stepwise fashion, as cement leakage through the articular surface can occur\(^54\) (Fig. 22, 23).

Arthroscopically assisted reduction of tibial plateau fractures has been described by several authors\(^21,59,60\). Direct visualization of the reduction is possible and may be helpful for precise anatomic reduction. However, soft-tissue swelling and compartment syndrome can develop due to fluid extravasation. Knee arthroscopy of tibial plateau fractures should be performed without a pressure pump. If there is extensive soft-tissue swelling after arthroscopy, any open surgical approaches may be associated with a greater risk of postoperative healing disturbances\(^60\).
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**Fig 17.** Tapping of the lateral cortex using a manual drill. Schematic figure showing the manual drill with the cannula introduced below the lateral tibial plateau, in the anteroposterior view (A) and lateral view (B) (from Medtronic Inc., Inflatable FX™, Tibial Plateau Surgical Technique Guide 2012). C. Intraoperatively, the plate can already be placed on the lateral side in order to secure the lateral cortex. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 18.** Balloon placement and expansion (Kyphon; Medtronic, Sunnyvale, California, USA). A. The deflated balloon is positioned below the lateral tibial plateau impression. The two round markers indicate the primary expansion distance of the balloon. B. Balloon expansion is monitored using contrast medium. After the final expansion, the balloon has expanded completely. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
Fig. 19. A patient with a posterolateral tibial plateau impression fracture (85 years, female). Preoperative x-rays, showing the impression fracture in the anteroposterior view (A), and lateral view (B). (x-rays: Department of Trauma Surgery, Medical University of Innsbruck)

Fig 20. Elevation of the impressed articular surface. A. The balloon is supported with two K-wires introduced below the cannula. B. Balloon inflation at the posterior part of the lateral tibial plateau in order to elevate the posterior impression. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
Fig 21. Cement augmentation after balloon reduction. The cement has completely filled the subchondral void, but has extruded at the posterolateral cortex. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

Fig 22. Final intraoperative x-ray in the anteroposterior (A) and lateral (B) views. An angular stable plate with small fragment screws (3.5-mm proximal lateral tibia plate, Synthes Inc., West Chester, Pennsylvania, USA) was used for additional fixation after balloon reduction and cement augmentation. The posterior screws from the proximal plate row pass through the cement cloud. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)
**Fig. 23.** Comparison of the preoperative and postoperative CTs. A. Preoperative lateral impression fracture, with a severe increase in the tibial dorsal slope. B. On the postoperative CT scan, the lateral tibial plateau has been reduced anatomically and the slope corrected. A small amount of cement has penetrated into the joint at the posterior fracture line. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

3.2.5.2.2 Void fillers

Trauma causing tibial plateau fractures results in an impression on the joint line, with disruption and compression of the trabecular bone structure. At surgery, the bony defect is filled with autograft bone or artificial bone fillers in order to support the articular surface above it.

3.2.5.2.2.1 Autogenous and allogeneous bone graft

The autogenous bone graft is the gold standard for filling up fracture defects\(^{61}\). The bone graft is typically harvested from the iliac crest, and pure cancellous bone can be compacted, or a corticocancellous bone graft can be trimmed to the desired size to fit the defect. However, graft harvesting is associated with morbidity and complications due to the additional operation site, longer operating time, postoperative pain and blood loss. In addition, due to fatty degeneration, particularly in older patients, it is not always possible to harvest bone of sufficient quality for proper defect filling\(^{62}\). Postoperative mobilization is sometimes impaired due to pain at the iliac crest wound and the drain. Although autogenous bone has the best osteoconductive and osteogenetic properties, it does not offer enough mechanical stability to allow for early postoperative full weightbearing by the patient. Thus,
full weightbearing is usually allowed after the fracture has been healed completely. Some surgeons prefer allogeneous bone graft in order to minimize surgical trauma and decrease operating time. As with the use of autogenous bone grafts, full weightbearing may be allowed after the fracture has healed completely. There are problems with allograft bone healing, in connection with inconsistent incorporation or rejection.

3.2.5.2.2 Artificial bone substitute materials (aBSM)

Using artificial bone substitute materials (aBSM) may reduce the operating time and minimize surgical trauma, with no additional bone harvesting and a shorter time to full weightbearing.

Injectable bone-graft substitutes are used in several clinical situations, such as screw augmentation in osteoporotic fractures, maxillofacial surgery and bony defect filling after fracture reduction. Usually, a dry powder is dissolved in water or a phosphate solution in the operating room and the mixed cement-like paste can be injected. This makes defect filling much more effective in comparison with blocks or granules made of hydroxylapatite (HA) or beta-tricalcium phosphate (β-TCP). Solidification of the cement with the adjacent bone leads to a more stable time zero situation in comparison with autogenous bone grafts, blocks or granules of HA, calcium phosphate, or calcium sulfate in the bony defect. The working time with the cement is a few minutes, depending on the chemical reaction in the materials. There are two general types of injectable cement: Calcium phosphate cements (CPCs) and calcium sulfate cements (CSCs).

CPCs are biocompatible and osteoconductive materials. They can be classified into two subgroups: apatite and brushite CPCs. Apatite CPCs are precipitated hydroxyapatite and are osteoconductive but slowly resorbable materials. It has been reported that this material is biocompatible, with no adverse reactions after implantation. Histological studies have shown that fibrovascular tissue can ingrow into HA particles, form new bone and result in strong connective tissue. In contrast, brushite CPCs consist of dicalcium phosphate dehydrates, which are resorbed and degraded faster, leading to earlier loss of mechanical strength at the defect site. After implantation, a high compressive strength (20-60 MPa) is reached within 4–8 hours, but the strength in tension and shear is much lower. Gisep et al. investigated the resorption pattern of CPCs in sheep bone. In a tibial defect model, new cancellous bone formation occurred, but no cortical bridging. Cement cracks were observed at the site of greater bending loads, leading to the conclusion that CPCs should be used in addition with mechanically stable fixations.
CSCs have been used for bone defect filling for more than 100 years\textsuperscript{71}. Good biocompatibility has been observed, and degradation of the material starts immediately after implantation. It has been reported in clinical studies that the CSC resorption was faster than bone formation, leaving a bone defect after cement degradation\textsuperscript{72}. In general, CSCs are more brittle and weak in comparison with CPCs. Also, if high initial compressive loads (up to 100 MPa) are present, the material strength may decrease rapidly due to the rapid resorption. Hybrid materials composed of fast-resorbing CSCs and slow-resorbing CPCs (apatite) may allow early vascular infiltration and bone formation while providing sufficient mechanical support\textsuperscript{73}. Using CSCs allows antibiotics or growth factors to be delivered, due to the rapid degradation.

In recent years, implant augmentation with polymethylmethacrylate (PMMA) has become more widely used to increase implant purchase in osteoporotic bones and reduce implant cut-out. In a rabbit model, Hisatome et al\textsuperscript{74} investigated the effect on the cartilage of cement injection at the medial femoral condyle. A bone void was created, leaving a 2-mm subchondral surface, and was filled either with PMMA or calcium phosphate (CaPO$_4$) cement. Degeneration of the articular cartilage developed in the PMMA group after 12 weeks, while the group with CaPO$_4$ did not show any degeneration. In contrast, Goetzen et al.\textsuperscript{75} reported no articular degeneration after PMMA injection close to the articular cartilage. When a balloon is used for reduction of the impression of the tibial plateau, a metaphyseal void is created. The distance to the articular cartilage is clearly more than 2 mm in most of the cases reported in the literature\textsuperscript{52,53,56,58}. However, during cement injection, radiological control of the cement position must be carefully observed. After the cement has filled up the bone void, further pressure may lead to cement penetration into the fractured articular surface spaces. This can lead to a short distance between the cement and the articular cartilage. One concern with PMMA augmentation is potential heat necrosis of bone tissue during polymerization. An ex vivo study has shown that the temperature during cement curing after injection does not exceed the threshold of 47 °C for bone tissue injury\textsuperscript{76,77}.

Negative features of injectable cements, such as material brittleness and potentially unpredictable resorption time, have led to research on other artificial bone substitutes. Bioactive glass is made of silicate glass, mainly composed of silica, sodium, calcium and phosphate. Bioactive glass has been reported to be an alternative osteoconductive and biocompatible bone substitute, with osteocytes binding and proliferating on the glass surface. The angiogenic potential of bioactive glass has been described only on the basis of in vitro findings, and it is stimulated by combination with vascular epithelial growth factors (VEGF)\textsuperscript{78}. Carbonated HA is formed inside and on the glass surface. Sodium, silica, calcium and
phosphate ions are released from the glass surface, increasing the pH and osmotic pressure. A silica gel is formed, and calcium phosphate precipitates on the bioactive glass surface. Calcium phosphate then crystallizes into HA, which initiates osteostimulative processes. The resorption time of the bioactive glass depends on its chemical composition and the granule size. In vitro antibacterial activity has been demonstrated in previous studies, associated with locally increased pH and osmotic pressure. Successful treatment of chronic osteomyelitis in clinical practice has been reported in the literature. Heikillä et al. reported a randomized controlled study of 25 patients with tibial plateau fractures. After anatomical reduction, the defect was filled with bioactive glass or autologous bone graft. No differences in the clinical outcome or radiological findings were noted between the two groups at follow-up after 1 year. In summary, bioactive glass may represent an attractive artificial bone substitute for tibial plateau fractures with articular impression.

3.2.5.2.3 Fracture fixation

After open reduction and temporary fixation with clamps and wires, additional fixation is performed (Fig. 24A). Isolated split fractures (Schatzker I) can be addressed using two lag screws in young patients with good bone quality. A buttress plate can be used to achieve more stable fixation. The plate is formed around the cortical bone and compressed against the bone with the screws. This allows fragment compression, and the plate avoids fragment sliding during axial loading (Fig. 24B).

Fig 24. A. Schematic image showing clamp reduction of a pure lateral split fracture (AO 41-B1). B. Buttress plating with fragment compression using lag screws passing through the fracture. The compression direction is indicated by the blue arrow, and the buttress plate support against dislocation of the distal fragment by the green arrow. (Images adapted from Rüdi et al., AO Principles 38)
In split fractures with a comminuted fracture zone or with decreased bone quality, it may be beneficial to use an angular stable plate. Conventional plates are pressed against the bone by the screw, and the screw can move within the plate hole. In angular stable plates, the screw heads are locked into the plate via a thread in the screw head (Fig. 25A). The fracture fragments are fixed in a determined position without screw loosening, thus avoiding secondary displacement (Fig. 25B).

**Fig. 25.** A. Conventional plate and screw (left). Screw insertion causes plate compression against the bone surface. Angular stable plate (right). The screw heads are locked into the plate via a thread in the screw head. The plate is not compressed, and the periosteal blood supply to the bone is not compromised. B. In conventional plates, the screw can move (green arrows). In angular stable plates, the screw is locked into the plate and fixed at a defined angle. (Images from Rüdi et al., AO Principles).

In contrast to conventional plates, the angular stable plate does not need to be compressed against the bone, and blood flow in the periosteum is not compromised. In addition, this means that the plate does not have to be contoured perfectly to the bone curvature. This makes it possible to save operating time, and even though the plate is not contoured directly to the bone, good fixation strength can be achieved. The angular stable plate makes it possible to transmit the load completely, with the implant protecting the comminuted fracture zone (Fig. 26). Particularly in osteoporotic bone, angular stable plates show better fixation in comparison with non-locking plates.
Bicondylar tibial head fractures (OTA/AO 41, Type C) usually result from high-energy trauma and younger patients with good bone quality are involved. These fractures are associated with severe soft-tissue damage.

The management of bicondylar fractures starts in many cases with the application of a joint-spanning external fixator for fracture stabilization. This should ensure joint stability, anatomical length and axis. After the soft tissue has settled (usually 3–10 days), internal fixation using dual plating is thought to be the best method of mechanical stabilization\textsuperscript{15,87}. Buttressing the medial and lateral condyle is mandatory in cases with a comminuted intercondylar fracture zone (OTA/AO C2). On the lateral side, a precontoured angular stable plate has become standard, as it provides the best stability when used as a buttress, with additional angular stable screws. On the medial side, a posteromedial conventional buttress plate is mostly used. If there is a medial split fracture without comminution or intercondylar fragment, isolated lag screw fixation over stab incisions can be performed\textsuperscript{48}. If the soft tissue is severely compromised and conversion to internal fixation cannot be performed, the external fixator can be converted to an Ilizarov ring fixator for definitive treatment\textsuperscript{48}. 
After anatomical reduction and bone void filling of isolated tibial plateau impression fractures, additional fixation is commonly performed. Screws can be placed to support the articular surface against subsidence of the subchondral bone. They are commonly placed percutaneously through a stab incision at the lateral side. A parallel screw configuration, also called a “raft of screws”, can be placed directly under the subchondral bone or through the cement cloud if cement augmentation is performed (Fig. 27A). Screws can also be placed in the anteroposterior direction in order to support the lateromedially directed screws. This technique was first described by Petersen et al. and termed the “jail screw configuration” (Fig. 27B). In clinical practice, the use of cannulated screws may facilitate proper screw positioning. Screws can also be placed through a lateral plate, which may improve fixation strength, due to the angular stability of the screws (Fig. 27C).

Fig 27. Fixation methods after tibial plateau impression fracture reduction.  
A. Parallel screws placed through the cement cloud. Up to four screws are placed, depending on the fracture area (from Craiovan et al.). B. Screws placed in the anteroposterior direction, supporting the lateromedial screws in the “jail technique” (from Petersen et al.). C. Lateral locking plate fixation with angular stable screws (Department of Trauma Surgery, Medical University of Innsbruck)
3.3. Biomechanics of the knee joint

One of the major functions of the tibia is to transmit the body’s weight from the hip down to the feet. Like all long bones, the tibia has larger dimensions in the vicinity of the joints in comparison with the mid-section. At the proximal tibia, the cortical bone is thin and the metaphysis is filled with trabecular bone, while the diaphysis has thick cortical bone and is hollow inside. These anatomical differences make the tibial head more deformable in comparison with the tibial diaphysis, and short peak forces can be absorbed by bone deformation. With the waisted shape at the proximal tibia, a larger surface area for force transmission is created (Fig. 28). In summary, these bone properties reduce pressure on the joint surface when loads are applied.

![Fig. 28. Radiograph of the left knee. The waisted shape at the metaphysis of the femur and tibia increases the articulating surfaces at the knee joint. (Department of Trauma Surgery, Medical University of Innsbruck)](image)

In large joints, the bone surfaces do not match precisely, leading to incongruence on the articular surfaces. This is most pronounced in the knee joint, with convex and convoluted femoral condyles, an asymmetrical tibial plateau and a dorsal tibial slope of 7°–13°. Contact
between the femur and tibia only occurs at points or along lines, so that pressures on the contact areas are accordingly high. The menisci between the femur and the tibia increase the pressure-transmitting area and reduce focal contact pressures (Fig. 29A,B). The location of the contact areas between the femur and tibia changes during joint motion. Without menisci, the size of the contact areas is decreased by a factor of 3–5 (Fig. 29C).

Fig. 29. A. Image showing the triangular cross-section of the meniscus. During axial loading between the round articular surfaces of the femur and tibia (blue arrows), the meniscus is pushed outside (black arrow). B. Image showing the longitudinal load distribution along the meniscus (blue arrows) and the radial load distribution directed toward the joint capsule (black arrows). C. Contact areas between the femur and tibia, shown with and without menisci at full extension and 45° and 75° of flexion. Without menisci, the size of the contact areas is decreased by a factor of 3–5. (Images adapted from Brinkmann et al., Musculoskeletal Biomechanics)
During knee motion, the center of rotation changes in different joint positions. This is caused by the convoluted, asymmetric condyles and different tension pattern of the knee ligaments. The motion of the knee joint is not confined to a frontal plane, and the description of the knee joint as a hinge joint is only an approximation. In the last 20° of knee extension, the tibia performs an external rotation of 15°. This is called the “screw-home” movement, and it has been postulated that it is caused by the tibial eminences entering into the asymmetric intercondylar fossa of the femur. Other authors have postulated that this movement is caused because the length of the medial femoral condyle is greater than the that of the lateral condyle. In full extension, the knee is considered as locked and secured.

For a stable maintaining posture, static equilibrium is necessary and the center of gravity of the body is located above the area of support (Fig. 30). Muscle forces are required to balance the moment of the gravitational force of the body, and the joint load depends on these muscle forces.

**Fig. 30.** Image showing the static equilibrium of a person in a semi-squatting position. The body’s center of gravity is located perpendicular to the area of support. The joint loads depend on the muscle forces needed to maintain the equilibrium. r1 describes the moment arm between the rotation center of the knee and the center of gravity. In a fully standing person, r1 is nearly 0 and the muscle forces around the knee (e.g., at the quadriceps muscle) are kept to a minimum. (Image adapted from Brinkmann et al., Musculoskeletal Biomechanics)
If the knees are bent, the body’s center of gravity is located dorsally from the knee joint. The moment arm $r_1$ is indicated by the perpendicular distance of the line of the gravitational force from the center of rotation. In symmetrical knee bending of both legs, the force $F_1$ is half of the gravitational force of the body mass. In order to maintain this static position, the quadriceps muscle has to generate a moment equal to $F_1 \times r_1$. The generated tensile force of the patellar tendon $F_2$ acts with the moment arm $r_2$, the perpendicular distance from the patellar tendon force to the center of rotation (Fig. 31A).

To calculate the compressive force between the femur and the tibia, the equilibrium of forces on the tibia is considered in the sagittal plane (Fig. 31B). All of the muscles, except the force of the quadriceps muscles, ligaments and the gravitational force of the lower leg and foot, are ignored. In this equilibrium of forces, the force on the tibia is the resulting force $F_3$ of the gravitational force of the body weight $F_1$ (or the force from the floor on to the foot) and the force of the patellar tendon $F_2$. This oversimplified model assumes that force $F_3$ is directed perpendicularly to the tibial plateau, although in reality the tibial plateau has a dorsal slope. In this case, additional accelerating forces are generated and may be compensated by the knee ligaments, especially the ACL and PCL.

**Fig. 31.** The forces acting at the knee in static symmetric knee bending position **A.** The gravitational force of half of the body mass $F_1$ produces a moment with a moment arm $r_1$. The quadriceps muscle must generate the tensile force of the patellar tendon $F_2$ acting with the moment arm $r_2$. **B.** The compressive force between the femur and the tibia $F_3$ is equal to the sum vector of the gravitational force of body weight $F_1$ and the force of the patellar tendon $F_2$. (Images adapted from Brinkmann et al., *Musculoskeletal Biomechanics*)
INTRODUCTION

The force at the tibia can be also calculated using the equilibrium of forces in the frontal plane when the individual is standing on one leg. The ground reaction force $F_1$ (gravitational force of the body weight or force from the floor on to the foot) creates a moment in the frontal plane relative to the center of rotation of the knee. This moment has to be balanced by the combined force of the gluteus maximus muscle and the tensor fasciae latae $F_2$. With increasing knee varus, the medial lever arm increases, requiring an increased lateral reaction to prevent the joint from opening. In other words, the medial moment has increased, and force $F_2$ must increase as well. Thus, the resulting force on the tibia $F_3$ also increases (Fig. 32A). The lateral ligaments will elongate over time, leading to a joint gap, and force is transmitted via the medial compartment of the knee. Over the longer term, this results in medial knee arthritis, with increasing varus deformity (Fig. 32B). With valgus deformity, overloading on the lateral knee compartment leads to laterally pronounced knee arthritis (Fig. 32C). With a physiological leg axis (valgus 0–2°), the distribution between the medial and lateral knee compartments has been reported to be 60:40%\textsuperscript{95} or 55:45%\textsuperscript{96} in the literature.

Fig. 32. Equilibrium of forces in the frontal plane when the individual is standing on one leg. A. The ground reaction force $F_1$ creates a moment in the frontal plane relative to the center of rotation of the knee. This moment has to be balanced by the force on the fasciae latae $F_2$. With increasing knee varus, the medial lever arm increases, requiring an increased lateral reaction to prevent the joint from opening. This results in an increased force on the tibia $F_3$. (Images adapted from Brinkmann et al., Musculoskeletal Biomechanics\textsuperscript{11}) B. Long leg radiograph on the right side, showing varus deformity. The mechanical axis runs through the medial compartment. The medial arthritis with joint-space narrowing is visible. C. Long leg radiograph of a right-sided valgus deformity. The mechanical axis runs through the lateral compartment and increases lateral joint loads. (Department of Trauma Surgery, Medical University of Innsbruck)
The dynamic load on the knee joint has been calculated from gait analysis. The input data are mass, location of the center of gravity and temporary course of “lower leg” and “foot”, and the force between the floor and the foot\textsuperscript{11}. The load acting on the knee can be determined using a model of the knee joint with directions and moment arms for all muscles and ligaments. At approximately 60% of the gait cycle, there is contact between the foot and the floor (Fig. 33). In a simplified model (based on electromyography (EMG) measurements), Paul\textsuperscript{97} showed 1976 that peak load values are reached during the “heel on” and the “toe off” phases. With increasing gait velocity, the maximum values increase and reach values of four times the body’s weight.

\textbf{Fig. 33.} Load on the tibiofemoral joint during fast, normal and slow walking, based on Paul et al.\textsuperscript{97} The x-axis describes the gait cycle in percentages. Foot contact with the floor occurs 60% of the gait cycle. The y-axis describes the load on the joint percentages of body weight. (Image adapted from Brinkmann et al., Musculoskeletal Biomechanics\textsuperscript{11})
4. AIM AND HYPOTHESES

The purpose of this study was to compare a locking plate and a screw raft for additional fixation after balloon reduction and cement augmentation in isolated tibial plateau impression fractures. Loss of reduction was also analyzed after the additional fixation was removed.

The first hypothesis was that a screw raft is biomechanically equivalent to a lateral locking plate in tibial plateau impression fractures reduced by balloon inflation and cement augmentation.

The second hypothesis was that removing additional fixation results in increased loss of reduction and cement cloud subsidence.
5. MATERIAL AND METHODS

5.1. Specimens

Eight matched pairs of human fresh-frozen tibiae were used for testing (mean age: 78 years, six female). The specimens were randomly assigned to one of the two fixation techniques: lateral locking plate or screw raft.

The specimens were obtained from the Department of Anatomy at the Medical University of Innsbruck. The individuals had given written consent to donate their bodies and tissues for the advancement of education and research prior to death\(^{86,99}\). The specimens were double-sealed in plastic bags and stored at –20°C.

5.2. Bone mineral density

CT scans were performed using a GE LightSpeed VCT (GE Healthcare, Milwaukee, Wisconsin, USA). True axial slices were obtained using a multiplanar reconstruction tool from IMPAX EE (Agfa HealthCare, Belgium). The coronal and sagittal planes were adjusted parallel to the tibial shaft axis. Circular regions of interest (ROI) were placed 5, 10 and 15 mm below the lateral articular surface of the tibia. A diameter of 20 mm was chosen for the ROI. The ROI was placed in the lateral plateau in cancellous bone (Fig. 34). The European Forearm Phantom (EFP) calibration equation was used to convert the measured Hounsfield units (HU) into mg/cm\(^3\) (Fig. 39). The EFP was placed beside the specimens\(^{100}\). Four HU measurements were performed in each section of the EFP; section I (200 mg/cm\(^3\)), section II (100 mg/cm\(^3\)), section III (50 mg/cm\(^3\)), and section V (water equivalent). The mean HU values for each EFP section were calculated. The average HU value for the ROI in the lateral tibial head was pasted into the calibration template. A linear calibration equation carried out automatic calculations from HU to BMD (Fig. 35).
Fig. 34. BMD measurement locations using a multiplanar reconstruction tool from IMPAX EE (Agfa HealthCare, Belgium). The coronal and sagittal planes were adjusted parallel to the tibial shaft axis. Circular regions of interest (ROI) with a diameter of 20 mm were placed 5, 10 and 15 mm below the lateral articular surface of the tibia.
Fig. 35. The European Forearm Phantom (EFP) calibration equation. The mean value of the four HU measurements for each section was calculated and pasted into the calibration template. The BMD was automatically calculated using a linear calibration equation.
5.3. Specimen preparation

Specimens were thawed overnight in the refrigerator at 6 °C before testing. At room temperature, all soft tissue was removed and the proximal tibiofibular joint was separated, leaving the isolated proximal tibial bone. The tibia was cut at mid-diaphysis 20 cm distal to the tibial plateau using an oscillating saw. The tibia was orientated with the long axis of the tibial shaft at a 5° angle on the coronal plane and held with an adjustable clamp. This was intended to simulate the physiological leg alignment, with a slight valgus orientation of the proximal tibia\textsuperscript{62,101}. The tibia was embedded using PMMA (Technovit 3040, Heraeus Kulzer, Wehrheim, Germany), resulting in a free specimen length of 15 cm (Fig. 36).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{image.png}
\caption{Specimens were embedded with 5° valgus and a free specimen length of 15 cm.}
\end{figure}
5.4. Fracture creation

Pilot studies were performed to establish the fracture model. In order to avoid an additional split fracture, it was necessary to arrange several predetermined breaking points at the lateral tibial plateau\textsuperscript{62,101}. Twelve drill holes with a 2-mm diameter were arranged in a circle with a diameter of 14 mm (Fig. 37A). The indenter was positioned in the center of the arranged predetermined breaking points. The impression fracture was created by pushing a cylindrical indenter with a diameter of 14 mm into the lateral tibial plateau surface to a depth of 8 mm. The indenter was pushed at a speed of 1 mm/sec using a servohydraulic materials testing machine (MTS Mini- Bionix II 858; MTS, Eden Prairie, Minnesota, USA) (Fig. 41B). After fracture creation, anteroposterior x-ray images were taken to document the fracture shape (Fig. 37C).

Fig. 37. Fracture creation. A. Circular arrangement of the predetermined breaking holes. B. Photograph of the fracture and the indenter. C. Anteroposterior (AP) radiograph after fracture creation, showing a lateral impression fracture.
5.5. Balloon reduction and cement augmentation

At the anteromedial aspect of the tibia, proximal to the insertion site of the superficial pes anserinus, the cortex was tapped with a manual 3.2-mm drill. The primary cannula was introduced into the center of the metaphysis, facilitating instrument insertion. The precision drill was further introduced through the cannula close to the lateral cortex. The drill was removed and the deflated balloon was introduced into the prepared tunnel (Fig. 38A). The lateral and medial ends of the balloon (when introduced horizontally) are visualized with two x-ray markers. With confirmation on the AP and lateral x-ray views, the balloon was positioned centrally under the impressed subchondral bone (Fig. 38B,C). The impression fracture was reduced using stepwise inflation of the balloon inflation system (Kyphon-Medtronic, Sunnyvale, California, USA). Anatomical repositioning was achieved with balloon expansion and controlled with fluoroscopy and direct visualization of the tibial plateau (Fig. 39). The volume of contrast solution used to inflate the balloon was noted and determined the amount of cement that was subsequently injected into the void (VertecemV+, Synthes, Paoli, PA). The powder and the liquid components of the cement were mixed in a bowl using a spatula for about 40 seconds. Cannulas containing 1.5 mL of cement were filled and introduced through the primary cannula into the bone void. The cement was pushed into the void, starting at the lateral end of the void and moving the working cannula toward the medial end of the void. According to the manufacturer, the application time for the cement is about 27 minutes.
Fig. 38. Balloon placement. **A.** The cannula is introduced from the medial cortex proximal to the insertion of the pes anserinus. The balloon's position is checked fluoroscopically in the AP (**B**) and lateral views (**C**).

Fig. 39. Balloon inflation and reduction. **A.** The balloon is inflated using a contrast solution. Reduction and balloon expansion is controlled with fluoroscopy. **B.** Direct view of the reduced fracture.
5.6. Fixation

The lateral locking plate (3.5 mm, Synthes, Paoli, Pennsylvania, USA) was provisionally positioned ventral to the articular surface of the proximal tibiofibular joint (Fig. 40). In the craniocaudal direction, the plate position was chosen in such a way that at least one proximal screw passed centrally through the cement cloud. The plate was fixed with K-wires and one distal screw.

Fig. 40. The lateral plate is provisionally placed at the lateral cortex. The drill sleeves are mounted at the proximal plate holes in order to visualize the direction of the screws after drilling. The plate position is adjusted until the drill sleeves are directed through the center of the cement cloud. The plate is then fixed with one distal screw and thin K-wires at the proximal plate.
**5.6.1. Plate fixation**

In the group with plate fixation, locking screws (3.5 mm, Synthes, Paoli, PA) were inserted with four proximal screws, one kickstand screw and one diaphyseal screw (Fig. 41). The plateau width was measured in line with the four proximal drill sleeves. The screw length was chosen 5 mm shorter than the plateau width in order to avoid perforation of the medial cortex. Relative to the round shape of the tibial head, the anterior and posterior screws were shorter (55–65 mm) than the two central screws (65–75 mm). The proximal holes were drilled first, and screws were inserted while the cement still had a doughy consistency. The kickstand screw had a consistent length of 70 mm, in accordance with the manufacturer’s recommendations. The diaphyseal screw was placed bicortically, with a length of 35–40 mm.

![Fig. 41. A fracture treated with a lateral plate and angular stable screws, seen from frontal (A) and lateral (B). Radiographs showing a right tibia before biomechanical testing in the AP (C) and axial views (D). The yellow circle marks the cement cloud.](image-url)
5.6.2. Raft fixation

The lateral locking plate was provisionally fixed and used as a drill guide. The plateau width was measured in line with the four proximal drill sleeves. The screw length was chosen 5 mm shorter than the plateau width in order to avoid perforation of the medial cortex. Within each pair of specimens, the raft screws had the same length as the proximal screws in the plate fixation group. The screw holes for the fixation of the raft were drilled using the four proximal holes of the locking plate. The plate was then removed and four self-cutting 3.5-mm cortical screws (Synthes, Paoli, Pennsylvania, USA) were inserted through the lateral tibia while the cement still had a doughy consistency. (Fig. 42).

Fig. 42. A fracture treated with screw raft fixation, seen from frontal (A) and lateral (B). Radiographs showing a left tibia before biomechanical testing in the AP (C) and axial views (D). The yellow circle marks the cement cloud.
5.7. Biomechanical test setup

The femoral component of a hemi-TKA (Stryker; Triathlon, Duisburg, Germany) was rigidly attached to the actuator of the servohydraulic material testing machine (Fig. 43). The embedded specimen was mounted on an x–y bearing table in order to ensure uniform loading across the reduced impression fracture.

![Fig. 43. A. Photograph showing the test set-up. B. The femoral component of a hemi-knee arthroplasty (Stryker; Triathlon, Duisburg, Germany) was positioned at the lateral tibial plateau.](image)

The cyclic loading protocol consisted of three loading intervals of overall 15,000 load cycles at 20–240 N, 20–360 N and 20–480 N (5000 load cycles per interval) applied at 2 Hz, representing physiological gait loads ranging from partial to more than full weightbearing. Load magnitudes were chosen on the basis of the following considerations: firstly, during gait, the net joint contact force for a single leg stance is reported to be three times body weight. Secondly, load-sharing between the medial and lateral compartments is 55% to 45%. Thirdly, in comparison with the native femoral condyle, a hemi-TKA reduces the
contact area to 30% and the force for the hemi-TKA was reduced correspondingly in order to apply a comparable contact pressure to that in the native femoral condyle.

The above considerations are summarized in the following calculation:

$$784.5 \text{ N} \times 3 \times 0.45 \times 0.3 = 353 \text{ N}$$

To approximate the calculation, a load magnitude of 360 N was chosen to simulate load-bearing on the lateral tibiofemoral compartment of 100% for a patient weighing 80 kg. Loads of 240 N and 480 N simulate 66% and 133% of load-bearing, respectively.

To evaluate the stabilizing effect of an additional fixation on subsidence of the cement cloud in the cancellous bone, the additional fixation was removed after 15,000 cycles. The last cyclic interval (20–480 N) was applied for another 5000 load cycles.

Standardized radiographs (Siremobil 2000, Siemens Healthcare, Erlangen, Germany) with the C-arm in a constantly identical position around the femur were taken at a load of 20 N initially and at the end of each loading interval for radiographic documentation of the tibia plateau reduction and implants (Fig. 44).

**Fig. 44.** Radiographs were taken after each loading interval at 20 N.
5.8. Data evaluation

5.8.1. MTS measurements
During cyclic loading after every 250 cycles, four cycles were recorded at a sampling rate of 50 Hz. The cyclic amplitude was calculated and describes the elastic deformation of the construct. The permanent displacement of the hemi-TKA in the tibia plateau was calculated every 5000 cycles during the course of cyclic loading. The minimum displacement value during the four recorded cycles was defined as the permanent displacement of the hemi-TKA.

5.8.2. Radiographic measurements
Cartilage thickness, subsidence of the lateral plateau reduction and subsidence of the cement cloud were measured on radiographs using an image-processing program (icoview 3.5, ITH-icoserve). A line was drawn connecting the medial and lateral borders of the tibial plateau. Perpendicular to it, a line was drawn across the center of the impression fracture.

The cartilage thickness was defined as the distance between the hemi-TKA and the subchondral plate at the initial 20 N load (Fig. 45).

Fig. 45. Measurement of cartilage thickness. A line was drawn connecting the medial and lateral borders of the tibial plateau. Perpendicular to it, a line was drawn across the center of the impression fracture. The distance between the hemi-TKA and the subchondral bone (h) was measured at a constant load of 20 N before cyclic loading.
The distance between the line of the tibial plateau and the subchondral bone was measured along the perpendicular line across the fracture. Subsidence of the subchondral bone was defined as an increase in distance (from the tibial plateau to the subchondral bone) during each loading interval in relation to the initial radiograph before cyclic loading. Subsidence of the subchondral plate was defined as a parameter for loss of reduction. Subsidence of the cement cloud was defined as an increase in the distance between the line on the tibial plateau and the border of the proximal cement cloud (Fig. 46).

Fig. 46. Subsidence of the subchondral bone and cement cloud were measured on radiographs taken after each loading interval. A line was drawn connecting the medial and lateral borders of the tibial plateau. Perpendicular to it, a line was drawn across the center of the impression fracture. The distances between the lines of the tibial plateau, the subchondral bone (x) and proximal border of the cement cloud (y) were measured along the perpendicular line across the fracture.
5.9. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics 22.0 (IBM Corporation, Armonk, New York). Differences in BMD, cement volume and cartilage thickness between the two groups were compared using the Student’s t-test. Differences between the two groups in displacement measured on MTS and subsidence measured on radiographs were compared using the paired Student’s t-test. The Pearson correlation coefficient was calculated to evaluate the correlation between cartilage thickness and displacement/subsidence data for both test groups. P values below 0.05 were considered significant.
6. RESULTS

Isolated impression fractures were successfully created in all specimens. The fractures were reduced by single insertion and inflation of the balloon below the impressed articular surface.

6.1. BMD
Local BMD measurements showed a mean BMD of 102.8 ± 50.0 mg/cm³, 90.0 ± 30.0 mg/cm³, 74.1 ± 36.2 mg/cm³ at the ROI 5, 10,15 mm below the articular surface, respectively. In the group with plate fixation, the mean BMD was 87.9 ± 36.1 mg/cm³, 93.7 ± 27.1 mg/cm³, 67.8 ± 35.6 mg/cm³ at the ROI 5, 10,15 mm below the articular surface, respectively. In the group with raft fixation, mean BMD was 117.9 ± 59.7 mg/cm³, 86.3 ± 34.1 mg/cm³, 80.4 ± 38.0 mg/cm³ at the ROI 5, 10,15 mm below the articular surface, respectively. These differences were not significant (P = 0.247, P = 0.636, P = 0.508).

6.2. Cement volume
The mean cement volume injected was 2.7 ± 1.0 mL (range: 1.5 to 5 mL) for the group with a plate and 2.1 ± 0.6 mL (range: 1.3 to 3.0) for the group with screw raft fixation (P = 0.178). After anatomic reduction, the distances from the subchondral plate to the proximal border of the cement cloud were 5.0 ± 1.6 mm (range: 1.2 to 6.6 mm) and 4.6 ± 1.7mm (range: 0.7 to 6.6 mm) (P = 0.687).

6.3. Cartilage thickness
The cartilage thickness was 2.1 ± 1.3 mm (range: 0.4 to 4.3 mm) in the group with plate fixation and 2.7 ± 0.8 mm (range: 1.7 to 4.1 mm) in the group with screw raft fixation (P = 0.343).

Displacement data measured by the MTS showed a good correlation with cartilage thickness for all three load intervals (240 N: r = 0.54, P = 0.032; 360 N: r = 0.57, P = 0.023; 480 N: r = 0.58, P = 0.018) (Fig. 47).

The subsidence measured on the radiographs showed no correlations with cartilage thickness for all three load intervals with additional fixation (240 N: r = −0.19, P = 0.478; 360 N: r = −0.86, P = 0.750; 480 N: r = −0.02, P = 0.939) (Fig. 48).
Fig. 47. Scatter plots showing the displacement data measured by the MTS in relation to the cartilage thickness. The $R^2$ correlation lines indicate a positive correlation between displacement and cartilage thickness.

Fig. 48. Scatter plots showing the subsidence data measured on radiographs for each load cycle in relation to the cartilage thickness. The $R^2$ correlation lines do not indicate any significant correlation between displacement and cartilage thickness.

### 6.4. Displacement measured by the MTS

The group with plate fixation showed mean displacements of $1.4 \pm 0.6$ mm (range: 0.6 to 2.3 mm), $1.8 \pm 0.6$ mm (range: 0.9 to 2.9 mm) and $2.1 \pm 0.8$ mm (range: 1.1 to 3.5 mm) during cyclic loading at 240 N, 360 N and 480 N, respectively. The group with raft fixation showed mean displacements of $1.6 \pm 0.7$ mm (0.6 to 2.8 mm), $2.1 \pm 0.7$ mm (range: 0.9 to 3.3 mm) and $2.6 \pm 0.8$ mm (range: 1.3 to 3.8 mm) during cyclic loading at 240 N, 360 N and 480 N, respectively. These differences between the two groups for all three load intervals were not significant ($P = 0.986$, $P = 0.999$, $P = 0.869$) (Fig. 49, Fig. 50).
RESULTS

Fig. 49. An example cyclic protocol on the MTS. Three load cycles (20–240 N, 20–360 N and 20–480 N, 5000 load cycles per interval) are applied over the course of the cyclic protocol, shown by the axial force (blue). The displacement over the course of the three cyclic intervals shown in red.

Fig. 50. Displacement of the loading piston with additional fixation (plate or raft), presented as box plots with medians and interquartile ranges (25–75%). The differences between the two groups were not significant.
RESULTS

The group with plate fixation showed mean cyclic amplitudes of $0.20 \pm 0.02$ mm (range: 0.18 to 0.26 mm), $0.26 \pm 0.03$ mm (range: 0.21 to 0.32 mm) and $0.32 \pm 0.06$ mm (range: 0.25 to 0.42 mm) during cyclic loading at 240 N, 360 N and 480 N, respectively. The group with raft fixation showed mean cyclic amplitudes of $0.22 \pm 0.05$ mm (range: 0.13 to 0.26 mm), $0.27 \pm 0.04$ mm (range: 0.20 to 0.31 mm) and $0.32 \pm 0.04$ mm (range: 0.26 to 0.38 mm) during cyclic loading at 240 N, 360 N and 480 N, respectively. These differences between the two groups for all three load intervals were not significant ($P = 0.330$, $P = 0.253$, $P = 0.818$) (Fig. 51).

**Fig. 51.** Amplitude of the loading piston during cyclic loading with additional fixation, presented as box plots with medians and interquartile ranges (25–75%). The differences between the two groups were not significant.

After plate removal, displacement increased significantly to $3.0 \pm 0.9$ mm (range: 2.1 to 4.6 mm) during cyclic loading at 480 N, compared with displacement with plate fixation during loading at 480 N ($2.1 \pm 0.8$ mm, range: 1.1 to 3.5 mm, $P = 0.000$).

After screw raft removal, displacement significantly increased to $3.6 \pm 1.0$ mm (range: 2.3 to 5.2 mm), compared with displacement with screw raft fixation during loading at 480 N ($2.6 \pm 0.8$ mm, range: 1.3 to 3.8 mm, $P = 0.000$) (Fig. 52).
RESULTS

Fig. 52. Displacement of the loading piston with plate or screw raft fixation during cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

After plate removal, the mean cyclic amplitude decreased significantly to $0.29 \pm 0.07$ mm (range: 0.24 to 0.44 mm) during cyclic loading at 480 N, compared with the amplitude with plate fixation during loading at 480 N ($P = 0.024$).

After screw raft removal, the mean cyclic amplitude was $0.31 \pm 0.07$ mm (range: 0.23 to 0.46 mm), compared with the amplitude with screw raft fixation during loading at 480 N ($0.32 \pm 0.04$ mm, range: 0.26 to 0.38 mm, $P = 0.335$) (Fig. 53).
RESULTS

Fig. 53. Amplitude of the loading piston with plate or screw raft fixation during cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

6.5. Subsidence measured on radiographs

The group with plate fixation showed a mean subchondral bone subsidence of $0.6 \pm 0.4$ mm (range: 0.0 to 1.2 mm) and $0.8 \pm 0.5$ mm (range: 0.2 to 1.4 mm) during cyclic loading at 240 N and 360 N, respectively. The group with screw raft fixation showed a mean subsidence of $0.8 \pm 0.6$ mm (range: 0.0 to 1.4 mm) and $1.0 \pm 0.6$ mm (range: 0.1 to 1.7 mm) during cyclic loading at 240 N and 360 N, respectively. These differences were not significant ($P = 0.174$, $P = 0.206$). The group with plate fixation showed significantly less subsidence during cyclic loading at 480 N ($0.9 \pm 0.6$ mm, range: 0.2 to 1.7 mm) in comparison with the group with screw raft fixation ($1.5 \pm 0.8$ mm, range: 0.3 to 2.5 mm) ($P = 0.039$) (Fig. 54).
RESULTS

![Diagram showing subsidence of subchondral bone with additional fixation, presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).]

Fig. 54. Subsidence of the subchondral bone with additional fixation, presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

No implant breakages were observed in either group. The screws and cement cloud remained stable in all specimens with plate fixation. In the group with screw raft fixation, after loading at 360 N and 480 N one specimen showed cement cloud subsidence without screw subsidence, and two specimens showed subsidence of the cement cloud with the attached screw (Fig. 55). Measured subsidence of the cement cloud during cyclic loading at 480 N was minimal in both groups without significant differences (plate: $0.1 \pm 0.3$ mm, range: 0.0 to 0.3 mm; raft: $0.1 \pm 0.1$ mm, range: 0.0 to 0.3 mm, $P = 0.833$ ).
**RESULTS**

**Fig. 55.** **A.** Radiographs taken after cyclic loading at 240 N (left) and 480 N (right). **B.** The superimposed image shows the small movement of the screw head (arrow) from the attached screw in the cement cloud.
RESULTS

After plate removal, subsidence of the subchondral bone increased significantly to $1.3 \pm 0.7$ mm (range: 0.7 to 2.4 mm) during cyclic loading at 480 N in comparison with subsidence with plate fixation during loading at 480 N ($0.9 \pm 0.6$ mm, range: 0.2 to 1.7 mm, $P = 0.002$). Subsidence of the cement cloud increased significantly after plate removal from $0.1 \pm 0.3$ mm (range: 0.0 to 0.3 mm) to $0.4 \pm 0.4$ mm (range: 0.0 to 1.1 mm) ($P = 0.032$).

After screw raft removal, subsidence of the subchondral bone increased significantly to $1.9 \pm 0.9$ mm (range: 0.4 to 2.8 mm) in comparison with subsidence with screw raft fixation during loading at 480 N ($1.5 \pm 0.8$ mm, range: 0.3 to 2.5 mm, $P = 0.003$) (Fig. 56). Subsidence of the cement cloud increased significantly after screw raft removal from $0.1 \pm 0.1$ mm (range: 0.0 to 0.3 mm) to $0.4 \pm 0.2$ mm (range: 0.0 to 0.7 mm) ($P = 0.005$).

In both groups, subsidence of the cement cloud was observed in five out of eight specimens after removal of the additional fixation.

![Subsidence of the subchondral bone with plate or screw raft fixation after cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).](image-url)
7. DISCUSSION

In the present human cadaveric study, a lateral locking plate was compared with screw raft fixation after balloon reduction and cement augmentation of isolated tibial impression fractures using a cyclic loading protocol. Subsequently, the stability of the cement cloud without the additional fixation was analyzed.

7.1. Hypotheses

The two groups showed comparable loss of reduction during cyclic loading simulating partial and full weight bearing, while at higher loads the group with screw raft fixation showed significantly more loss of reduction. In the group with screw raft fixation, a higher subsidence of the cement cloud with the attached screw was observed. Thus, the first hypothesis of biomechanically equivalency of the two additional fixations was rejected.

After removal of the additional fixations, the loss of reduction and subsidence of the cement cloud significantly increased. Therefore, the second hypothesis about the stabilizing effect of the additional fixation was accepted.

7.2. Surgical technique

7.2.1. Fracture reduction — balloon technique

Reduction of tibial plateau impression fractures is conventionally performed using an open cortical window approach and elevating the depressed articular segments with a metal tamp or elevator. Recently, reduction using a balloon inflation system has become more widely used for several reasons. First of all, it represents a minimally invasive technique adapted from spine surgery to restore vertebral body height after kyphotic vertebral compression fractures (kyphoplasty). A small skin incision is performed, and the cortex only has to be tapped with a manual drill of 3.2 mm. A cortical window approach performed with an oscillating saw can be avoided. Use of an inflatable balloon has shown better anatomic reduction in comparison with conventional metal tamps\textsuperscript{50,88}. Particularly in comminuted articular surface depression, the conventional instruments can easily perforate into the joint and irregular reduction can result. In contrast, the balloon has a larger elevating surface and
balloon expansion may lead to a more homogeneous reduction. Broome et al.\textsuperscript{50} investigated fracture reduction of tibial plateau and distal radius impression fractures, comparing balloon reduction with conventional metal tamp reduction. The fractured and reduced articular surface was analyzed on micro-CT scans and more over-reduction was observed with the conventional reduction technique. In a cadaveric study, Heiney et al.\textsuperscript{88} performed tibial plateau split-impression fractures, and the knee capsule was closed after fracture creation. In this manner, the surgeons performed fracture reduction without direct vision on the tibial plateau, using either a metal tamp or an inflatable balloon under fluoroscopy. The reduction was then rated using fluoroscopy and directly inspected by independent, blinded observers. In the majority of pairs, the observers rated the side reduced by balloon inflation as “better” than the contralateral side reduced with conventional tamps (direct inspection: 9 of 14 pairs “balloon better”, fluoroscopy: 11 of 14 pairs “balloon better”). They also calculated the residual defect size, using three-dimensional multiplanar fluoroscopic imaging. Fractures reduced with balloon inflation showed less over-reduction and under-reduction in comparison with the conventional reduction technique.

7.2.2. Bone void filling - cement augmentation

Reduction using the balloon inflation system creates a symmetrical bone void below the articular surface. This is typically filled with an injectable bone substitute and avoids bone grafting from the iliac crest. The iliac bone graft is associated with some harvest-side morbidity, such as pain, blood loss, and a risk of postoperative hematoma and infection. Postoperative mobility may therefore be significantly better if no bone harvesting is performed, and older patients can be mobilized earlier. While bone grafting is usually performed in young patients, in older patients with osteoporosis the iliac bone graft may be of low bone graft quality due to fatty degeneration, and bone substitutes are widely used\textsuperscript{105}.

Cement augmentation has been compared with cancellous bone grafts in tibial plateau fractures with articular impression and has consistently shown greater initial strength in biomechanical studies\textsuperscript{88,106-109}. Less subsidence during cyclic loading and increased ultimate loads for tibial plateau fractures treated with cement augmentation instead of autologous bone grafts have been reported in the literature\textsuperscript{88,106,107}. Using cement injection, the defect can be filled completely and is consolidated within the trabecular bone structures\textsuperscript{108}. If autogenous bone grafting is performed, bone healing must first occur before the autogenous bone will sufficiently resist loading. Weightbearing therefore has to be avoided or permitted only to a minimum during the first postoperative weeks. In reality, this cannot be achieved by most of the older patients, and injectable bone substitutes should be used instead.
7.3. Previous biomechanical studies on tibial plateau fractures

Secure fixation after tibial plateau fracture reduction is essential to avoid secondary loss of reduction, which can lead to early post-traumatic knee arthritis. Several biomechanical studies have therefore been performed in order to optimize fracture augmentation and fixation.

7.3.1. Specimens

Most studies have used fresh frozen human cadaveric bone, which can be considered the gold standard for in vitro studies investigating periarticular fracture fixation\textsuperscript{110}. Ali et al.\textsuperscript{111}, Baumann et al.\textsuperscript{112} and Hasan et al.\textsuperscript{113} used synthetic tibiae (Sawbones® Europe, Malmö, Sweden) for a fracture model of bicondylar fractures. They investigated the effect of different techniques of osteosynthesis on the condylar fragment motion, without addressing tibial plateau impressions. In all of these studies, the use of synthetic material is mentioned as a limitation of the study. On the other hand, human cadaveric bone also has limitations. For example, bicondylar fractures typically result from high-energy trauma occurring in young people with significantly better bone quality in comparison with older cadaveric specimens. There is also wide variability in bone quality between human donors, which can influence the fixation strength. Paired comparisons (left – right) should therefore always be carried out if possible \textsuperscript{88,106,107,109,114-117}.

7.3.2. Fracture model

A laboratory fracture model should be reproducible and should create a realistic fracture pattern. The fracture type intended to be simulated determines the fracture methods used.

A split fracture (Schatzker I, OTA/AO 41, B1) was simulated with an osteotomy through the medial or lateral tibial condyle\textsuperscript{117}. A lateral split impression fracture (Schatzker II, OTA/AO 41, B3) model has been described by Karunakar et al.\textsuperscript{114}. Three predetermined breaking points were drilled across the lateral tibial plateau. A drop weight of 48 N was dropped onto the lateral condyle from a height of 1 m (Fig. 57A). The split fracture was then completed using an oscillating saw. Recently, Heiney et al.\textsuperscript{88} have described a fracture model that made it possible to perform a blinded study, since after fracture creation the joint capsule was closed again. They used an oscillating saw for the fracture split. Using a modified captive bolt stunner, an initial impression was created which was further compacted manually using rounded tamps (Fig. 57B).
Fig. 57. A. Split impression fracture created by a dropped weight (from Karunakar et al.\textsuperscript{114}). B. Heiney et al.\textsuperscript{88} created the split using an oscillating saw and a modified captive bolt stunner for the articular impression.

If a pure tibial plateau impression fracture (OTA/AO 41, Type B2) model is used, older cadaveric bone is favored in order to avoid a split fracture of the entire condyle. In the fracture model described by Yetkinler et al.\textsuperscript{109}, predetermined breaking points are drilled in a 15.8-mm circle at the lateral tibial plateau using a 2-mm drill (Fig. 58A). A steel rod with a diameter of 15.8 mm is used as an indenter and is pushed into the tibial plateau to a depth of 12 mm at a speed of 500 mm/min (Fig. 58B). Doht et al.\textsuperscript{62} used the same fracture model with a fracture diameter of 12 mm and a depth of 15 mm.

Fig. 58. Unicondylar pure impression fracture creation. A. Small bore holes are created in a circle on the lateral tibial plateau. B. The resulting circular impression fracture after the indenter has been pushed into the tibial plateau.
Horwitz et al.\textsuperscript{118} described a bicondylar fracture model using three osteotomies, simulating an OTA/AO 41-C2 (Schatzker VI) fracture (Fig. 59). The first cut runs from the intercondylar area to the medial cortex 6 cm distal to the tibial plateau. This simulates the medial condylar fracture. The second cut simulates the lateral condylar fracture and runs from the intercondylar area to the lateral cortex 4 cm distal to the tibial plateau. The two points on the medial and lateral cortex are connected by an osteotomy, simulating metaphyseal separation from the shaft. The metaphyseal triangle-shaped bone block is removed and simulates multiple metaphyseal fragmentation.

![Fig. 59. A. Fracture model presented by Horwitz et al.\textsuperscript{118} B. This fracture model simulates a comminuted bicondylar fracture with intact condylar articular surfaces (AO 41-C2). (Image from AO web site: https://www2.aofoundation.org/)](https://www2.aofoundation.org/)

### 7.3.3. Loading of the fracture

#### 7.3.3.1 Load application

In all of the studies, the specimens were axially loaded using a servohydraulic materials testing machine. The specimens were mounted vertically\textsuperscript{88,111-113,115-117,119,120} or with a slight valgus inclination of 5–7°\textsuperscript{62,109}. The tibial plateau on the lateral view was tilted 5° by Baumann et al.\textsuperscript{112} and Gösling et al.\textsuperscript{121}.

Mueller et al.\textsuperscript{116} performed bicondylar loading using a cadaveric distal femur attached to the actuator of the testing machine in a 10° flexion position (Fig. 60A). The femoral component of a total knee arthroplasty (TKA) has been used by several authors for bicondylar loading\textsuperscript{111,120,122} (Fig. 60B). The femoral component was mounted in a slight valgus position and in full extension\textsuperscript{111} or with 15° of flexion\textsuperscript{122}.

Unicondylar loading has been performed in most of the biomechanical studies of tibial plateau fractures. An attached indenter with a different diameter at the spherical
end or the femoral component of a hemi-knee arthroplasty have been used for axial loading (Fig 60C,D).

Fig. 60. Different methods for loading of tibial plateau fractures described in the literature. A. Bicondylar loading using an anatomic distal femur (from Mueller et al.\textsuperscript{116}). B. Bicondylar loading using the femoral component of a total knee arthroplasty (from Ali et al.\textsuperscript{111}). C. Unicondylar loading to the medial tibial plateau using an indenter with a spherical end (from Egol et al.\textsuperscript{119}). D. Loading on the lateral tibial plateau using the femoral component of a hemi-knee arthroplasty (from McDonald et al.\textsuperscript{106}).

7.3.3.2 Loading protocols

Biomechanical protocols for testing implants and fracture treatment techniques typically consist of cyclic loading with subsequent load-to-failure testing. In the early postoperative phase, the fracture fixation should be able to resist repetitive loading as soon as the patient becomes mobile. This is best simulated with cyclic loading of the study specimens. Displacement of the loaded subject and stiffness during cyclic loading can be calculated. Displacement should be kept to a minimum in order to maintain anatomical reduction before the fracture heals.

In the load-to-failure test, the construct is loaded to failure in displacement or force control. Ultimate failure load and stiffness during load-to-failure can be calculated. The ultimate failure load of an osteosynthesis construct determines its load-bearing capacity and may be of importance in the case of a catastrophic event such as a fall.

The construct stiffness can be calculated after cyclic loading or load-to-failure data. Basically, stiffness determines the amount of interfragmentary movement, which is essential for the progress of successful fracture healing\textsuperscript{122}. Increased stiffness indicates less fracture movement and more stability, but no interfragmentary movement and also excessive interfragmentary movement can delay or impede fracture healing.
The appropriate construct stiffness depends on the fracture type. In the case of tibial plateau fractures with articular impression, early postoperative subsidence is the main risk, rather than delayed fracture healing. In this case, high construct stiffness is mandatory to maintain the anatomical reduction. In comminuted proximal tibial fractures, however, an excessively rigid construct with angular stable plates can suppress bone healing by preventing interfragmentary movement. Using a gradually increasing load protocol allows cyclic loading until construct failure. However, this might imply very long testing times for each specimen, leading to drying-out of the specimens and high costs. Some authors therefore prefer to set a certain amount of load, which is intended to simulate postoperative partial or full weightbearing. Loading on the knee joint and each compartment are assessed on the basis of previous gait analyses.

7.3.4. Measurement systems
Different measurement methods have been used in previous biomechanical studies investigating tibial plateau fractures. Studies focusing on articular impression fractures have measured subsidence of the articular surface indirectly using the displacement of the indenter connected to the testing machine. Yetkinler et al. formed a mold using dental materials and measured the impression after cyclic loading. McDonald et al. measured the impression using a displacement gauge rigidly mounted onto the frame of the testing machine. Studies focusing on condylar split or bicondylar fractures have measured subsidence of the entire condyle by placing displacement gauges at the tibial metaphysis. Other authors have used visual measurement systems, placing markers on the cortex of the tibial head.

7.4. Results of the study – comparison with previous studies on isolated tibial plateau impression fractures

Only two biomechanical studies have investigated pure tibial plateau impression fractures. Yetkinler et al. reduced the impression using a lateral cortical window approach. Fractures were treated either with autogenous bone graft and two screws or with calcium phosphate cement only. In the second part of the study, a more extensive void was prepared and fractures were treated either with calcium phosphate bone cement alone or with calcium phosphate cement in combination with two screws. The three groups with cement augmentation showed significantly less subsidence during cyclic loading and higher ultimate failure loads in comparison with the control group with autogenous bone graft and two...
screws. The group with cement only in an extensive void showed less subsidence in comparison with the group with cement only in a smaller void. This means that removing all cancellous bone under the subchondral plate and replacing it with cement increased the initial stability of the cement augmentation technique. In the two groups with extensive void preparation, additional fixation with two screws did not significantly reduce subsidence during cyclic loading. Cyclic loading was performed with loads of 20–125 N using a steel rod. In the present study, subsidence of the subchondral plate significantly increased after removal of the additional fixation at higher loads. However, the following considerations should be borne in mind when comparing the results of Yetkinler et al.\textsuperscript{109} with the present results: firstly, the load used for cyclic loading was much lower in comparison with the present study, and the results may change at higher loads. Secondly, differences in surgical technique such as using a lateral cortical window approach with extensive void preparation leads to more complete cement filling in comparison with cement augmentation after balloon inflation. In the study by Yetkinler et al.\textsuperscript{109}, the cement was directly in contact with the subchondral plate and was supported by the lateral tibial cortex at the caudal side of the cement. Nevertheless, the results presented by Yetkinler et al.\textsuperscript{109} have implications for surgeons performing balloon reduction of tibial plateau impression fractures. It can be assumed that a close distance from the cranial cement cloud surface to the subchondral bone minimizes postoperative loss of reduction. The effects of subchondral cement injection of the overlying cartilage have still been poorly investigated. Concerns have been raised about cartilage damage caused by heat necrosis and disruption of the cartilage nutrition. Goetzen et al.\textsuperscript{75} recently showed that the injection of PMMA-based bone cement close to the joint line did not appear to damage the adjacent subchondral bone or cartilage in an in vivo sheep model. The authors concluded that cement augmentation in the metaphyseal region appears to be a safe procedure that does not harm the subchondral plate or the adjacent cartilage. The initial balloon position determines the position of the cement cloud. In our opinion, the ideal case would be a cement cloud very near to the subchondral bone, with the additional fixation passing through the cement. In clinical practice, the balloon position is often more distal and the additional screws (with or without plate) are located in the cancellous bone below the subchondral bone without passing through the cement cloud\textsuperscript{49,54,58}. Inflation of the balloon very close to the fracture involves a risk of fragmentation of the impressed articular surface, balloon penetration and cement leakage into the joint\textsuperscript{54}.

Doht et al.\textsuperscript{62} created isolated tibial plateau impression fractures using the same fracture model as Yetkinler et al.\textsuperscript{109}. They compared three groups: In the first group, bone defects were filled with cement only. In the second, defects were filled with cement and additionally secured with four crossing screws in a “jail technique” (two anteroposterior and
lateromedially directed screws). In the third group, fractures were treated with the four crossing screws only. In agreement with the results presented by Yetkinler et al., the additional screws did not significantly reduce loss of reduction during cyclic loading, but significantly increased the ultimate loads in the load-to-failure test. Again, in contrast to the present study, cyclic loading was carried out at lower loads (20–250 N) simulating only partial weightbearing, and the defects were completely filled with cement through a lateral cortical window approach. The results presented by Doht et al. support the present finding that after cement augmentation, additional fixation increases the initial strength at higher loads. Finally, as older patients often have difficulties in managing partial weightbearing, additional fixation should be performed in order to secure the cement augmentation and allow full weightbearing. It should be borne in mind that tibiofemoral compressive forces reach about 4–4.5 times body weight during everyday activities, but may reach up to six times body weight during patient mobilization on stairs.

7.5. Results of the study — interpretation

The displacement measured by the MTS did not show any significant differences in subsidence between the groups with plate and screw raft fixation. After removal of the additional fixation, the displacement measured by the MTS and subsidence measured on radiographs significantly increased showing the stabilizing effect of the additional fixation. The amplitude of the MTS loading piston during cyclic loading decreased after removal of the additional fixation. A possible explanation can be that the cartilage and the subchondral bone were already compressed during the first three cyclic load intervals and the bouncing effect of the screws was removed.

The displacement measured by the MTS correlated with the cartilage thickness. Measurements on radiographs were independent of the cartilage thickness and directly assessed the fracture fragment subsidence. In the present study, therefore, more importance was given to the results from radiographic measurements.

Both additional fixations (plate and screw raft) showed comparable loss of reduction during cyclic loading at load magnitudes simulating partial and full weightbearing. In the group with a lateral locking plate, no subsidence of the cement cloud or screw movement was observed. In the group with screw raft fixation, subsidence of the cement cloud with the attached screw was observed in two out of eight specimens at a load magnitude simulating full
weightbearing. On the basis of this observation, there is a probability of about 25% for implant motion during full weightbearing in a patient treated with the screw raft technique.

7.6. Recommendations for clinical practice

Decisions regarding additional fixation after balloon reduction and cement augmentation of tibial plateau impression fractures should be made on the basis of patient-specific factors, fracture morphology and intraoperative events. The patient’s mobility and everyday activities before the injury must be evaluated in a preoperative discussion. Concurrently, psychological factors and motivation for postoperative rehabilitation should be assessed. The physical examination will make it possible to assess the patient’s physical state. Existing deficits or associated injuries in the upper extremities must be ruled out. All of these patient-specific factors can be helpful in predicting whether the patient will be a candidate for partial weightbearing rehabilitation postoperatively. The extent of existing osteoporosis should be estimated using prior BMD measurements. Special attention should be given to the skin condition in older patients during the physical examination, to estimate the risk of wound healing disturbances after open surgical approaches.

The fracture morphology should be analyzed on the radiographs and CT scan. A large fracture area with multiple fragments in the subchondral plate, a thin cortex and low cancellous bone density with large cavities may indicate a weak fracture situation. The fracture location should also be considered, since it may not be possible to treat very posterior impressions with a lateral locking plate and anteroposterior screws may be more effective.

Intraoperatively, the bone quality of the cortex can be estimated very early during tapping of the cortex to introduce the balloon cannula. Balloon inflation should be carefully observed on fluoroscopy, and the pressure inside the balloon is shown on a pressure monitor. Normally, the balloon pressure increases during balloon expansion, with an operating range of 120–250 psi. In severe osteoporosis, balloon reduction may occur at very low values or without an increase in the pressure. On fluoroscopy, caudal expansion of the balloon without any elevation of the subchondral plate indicates very poor cancellous bone quality. The balloon needs to be supported with K-wires caudally in order to achieve reduction. In these cases, it can be assumed that the cement cloud has very weak support from the surrounding
cancellous bone and should be stabilized with additional fixation. If there is very thin cortex, the screws without a plate might cut through as soon they undergo axial loading.

In summary, a lateral locking plate may be indicated in order to minimize postoperative loss of reduction, particularly in patients who are unable to manage partial weightbearing or who have compromised bone quality, a thin cortex, or severe fracture patterns. In patients presenting with a small homogeneous fracture pattern, a very posterior fracture location, or who have a high risk of soft-tissue complications, screw raft fixation still represents an attractive and valid technique that minimizes surgical trauma and operating time.
8. LIMITATIONS AND FUTURE PLAN

8.1. Limitations

The present study has some limitations. A homogeneous impression fracture was created using a circular subchondral plate pushed into the tibial metaphysis. This resulted in a reproducible fracture and permits data comparison with previous studies, but the results may only be valid for this fracture pattern. The clinical fracture patterns of isolated tibial plateau impression fractures, such as fragmentation of the subchondral plate and irregular shape and depth of the fracture were not simulated in this type of laboratory fracture. Loads were applied directly to the reduced fracture using the femoral part of a hemi-TKA, and the load distribution caused by the lateral meniscus was ignored. One limitation of all the biomechanical studies on tibial plateau fractures mentioned above is that the influence of knee ligaments and menisci were neglected, as they were removed before testing. Loading with anatomic femoral condyles was only performed in few studies. The fracture models described simulate simplified fractures, limiting the ability to extrapolate data to in vivo fractures. In addition, the present study and all of the studies mentioned simplified the in vivo loading pattern of the fracture during postoperative mobilization of the patient as no study applied an axial loading with simultaneous knee flexion and rotation.

The biomechanical protocol used here did not include a load-to-failure test. A load-to-failure test would provide information about resistance to greater loads in case of a catastrophic event such as a fall. However, the postoperative loss of reduction may be primarily caused by repetitive loading during mobilization and can be adequately simulated in a cyclic loading protocol. After cyclic loading, the additional fixation was removed in order to test the cement cloud without additional fixation. However, when one is interpreting these results, it should be borne in mind that the specimens had already been tested for three cyclic load intervals beforehand.
8.2. Future plans

Future studies are planned in order to investigate balloon reduction and cement augmentation in tibial plateau impressions with larger surfaces. In addition, posterior lateral tibial plateau impression fractures are still difficult to treat and stabilize with fixation implants. As the impression fracture is covered by the posterior horn of the lateral meniscus, the impression depth at which a surgical reduction should be performed is still not known. It should be investigated whether a dorsal impression on the lateral tibial plateau alters the knee biomechanics with and without an intact ACL. The biomechanical effect of dorsal impression fractures can be studied before and after reduction using the balloon technique.

A knee simulator is currently being constructed in our biomechanics laboratory. It will enable tibial plateau fractures to be loaded in more physiological conditions, particularly with axial loading combined with flexion or extension and internal or external rotational knee movements.
After balloon reduction and cement augmentation of tibial plateau impression fractures, angular stable plate fixation showed less loss of reduction and no screw subsidence at greater loads in comparison with screw raft fixation. After removal of the additional fixation, the rate of cement cloud subsidence and loss of reduction significantly increased. The results of the present study suggest that after balloon reduction and cement augmentation of tibial plateau impression fractures, additional fixation should be performed. Angular stable plate fixation may be recommended in order to minimize postoperative loss of reduction, particularly in patients with severe osteoporosis or a large fracture surface with soft-tissue conditions that allow an open surgical approach. The pure minimally invasive technique with percutaneous screw raft insertion remains an attractive surgical technique, and postoperative partial weightbearing should be recommended to the patient.
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11. **APPENDIX**

11.1. **Legends**

11.1.1 **Figures**

**Fig. 1.** Proximal tibial bone. **A.** Axial view on the tibial plateau of a left tibia. * medial tibial plateau, + lateral tibial plateau, # intercondylar eminence, > tibiofibular joint. **B.** Frontal view of the tibial head. * Tibial tuberosity, + Gerdy’s tubercle, # intercondylar eminence. (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 2.** Distal femoral bone (right side). **A.** Axial view from caudal on the femoral condyles. * medial femoral condyle, + lateral femoral condyle, # intercondylar fossa, ∨ trochlea. **B.** lateral femoral condyle. * lateral epicondyle. **C.** medial femoral condyle. * medial epicondyle, + adductor tubercle (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 3.** Axial view of the tibial plateau of a right knee. * medial plateau with medial meniscus, + lateral plateau with lateral meniscus, ∧ tibial insertion of the ACL, # tibial insertion of the PCL. (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 4.** **A.** Anterior view into the right knee after removal of the patella and anterior capsule. * medial meniscus with meniscotibial attachment, + lateral meniscus, AM,PL anteromedial and posterolateral bundles of ACL, # PCL (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck). **B.** Oblique view of the medial wall of lateral femoral condyle, left knee. AM bundle (red), PL bundle (blue).

**Fig. 5.** Posterior view of a left knee joint. * Medial meniscus, + lateral meniscus with the posterior meniscofemoral ligament (Wrisberg), ∧ ACL, # PCL, LCL lateral collateral ligament, POL posterior oblique ligament. (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 6.** Collateral ligaments of a left knee joint. **A.** Medial view of the medial collateral ligament (MCL). The ventral part is formed by the superficial MCL (sMCL). The posterior part of the ligament is formed by the posterior oblique ligament (POL). **B.** Lateral view of the
lateral collateral ligament (* LCL) and lateral meniscus (+). (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 7.** Posterior aspect of a right knee joint. * Popliteus tendon, LCL lateral collateral ligament, # insertion of the lateral gastrocnemius muscle, + Semimembranosus tendon with its five insertion strands forming the deep pes anserinus (dotted lines). (Images reproduced with permission from the Department of Anatomy, Medical University of Innsbruck)

**Fig. 8.** The knee joint muscles with their insertions at the knee. A. Ventral side. 1. Rectus femoris, 2. vastus medialis, 3. vastus lateralis, 4. sartorius, 5. gracilis, 6. tensor fasciae latae, 7. superficial pes anserinus, 8. quadriceps tendon, 9. patellar tendon. (Image reproduced with permission from the Department of Anatomy, Medical University of Innsbruck). B. Dorsal side. 1. Biceps femoris, 2. semimembranosus, 3. semitendinosus, 4. gracilis, 5. sartorius, 6. popliteus, 7. lateral head of the gastrocnemius, 8. medial head of the gastrocnemius. (Image adapted from the Pernkopf atlas of anatomy)

**Fig. 9.** The Schatzker classification of tibial plateau fractures (adapted from Brunner et al.26). I. Split fracture, II. Split fracture with impression of the articular surface, III. Isolated tibial plateau impression fracture, IV. Split fracture of the medial condyle, V. Bicondylar fracture, VI. Tibial head fracture with metaphyseal fracture.

**Fig. 10.** Classification of proximal tibial fractures14. The first two numbers (“41”) describe the anatomical location. Number “4” stands for the tibial bone, number “1” for proximal (out of 1 to 3, standing for proximal, middle and distal third of long bones). “A” fractures refer to extra-articular fractures in which the tibial plateau remains intact. “B” fractures are tibial plateau fractures that involve only one condyle. “C” fractures are bicondylar tibial plateau fractures. The last number (1 to 3) indicates the severity of fracture comminution and articular defects.

**Fig. 11.** The Hohl classification27 of tibial plateau fractures (adapted from Brunner et al.26). I. Split fracture of the lateral condyle, II. Tibial plateau impression fracture, III. Split-impression fracture of the lateral condyle, IV. Split fracture of the medial condyle (entire condylar fracture), V. Posterior coronal split fracture of the tibial plateau, VI. Bicondylar fracture.

**Fig. 12.** Pattern of the Zhu three-column classification28. The center of the metaphysis is marked on an axial CT slice, and lines are drawn to the tibial tuberosity, anterior border of the fibula and the posteromedial ridge of the tibia. The lateral, posterior, and medial columns are divided by these lines. In this example, the fracture lines extend into all three columns.

**Fig. 13.** Kyphoplasty of a compressive fracture of vertebral body T12 (89 years, female).
A. Preoperative x-ray, showing almost complete collapse of the vertebral body. The patient could not be mobilized. Subsequent kyphosis deformity in the spine would lead to persistent pain.  
B. Postoperative x-ray. The height of the vertebral body has been increased and augmented by cement injection. Postoperatively, the patient managed to become mobile and pain was reduced. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 14.** Proximal humerus fracture treated with plate fixation and augmentation (74 years, female).  
A. Preoperative x-ray, showing a three-part fracture with subcapital and major tubercle fracture lines. The head is displaced posteriorly, suggesting glenohumeral dislocation (AO 11-B3).  
B. Postoperative x-ray, showing the reduced fracture treated with a plate (Philos Synthes Inc., West Chester, Pennsylvania, USA) and cement augmentation of the cannulated screws entering the humeral head. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 15.** Pertrochanteric fracture treated with proximal femur nail and cement augmentation (77 years, female).  
A. Preoperative x-ray, showing a pertrochanteric fracture (AO 31-A1).  
B. Postoperative axial x-ray, showing the reduced fracture stabilized with a proximal femur nail (TFNA, Synthes Inc., West Chester, Pennsylvania, USA). The cannulated blade in the femoral head was augmented with cement. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 16.** A distal femur fracture treated with plate osteosynthesis and cement screw augmentation (82 years, female).  
A. Preoperative x-ray, showing a distal peri-implant fracture. The patient had previously been treated with a proximal femur nail with blade augmentation.  
B. Postoperative x-ray, showing fracture reduction using a LISS plate (Synthes Inc., West Chester, Pennsylvania, USA). The distal screws were augmented by injecting the cement into the borehole before screw insertion. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 17.** Tapping of the lateral cortex using a manual drill. Schematic figure showing the manual drill with the cannula introduced below the lateral tibial plateau, in the anteroposterior view (A) and lateral view (B) (from Medtronic Inc., Inflate FX™, Tibial Plateau Surgical Technique Guide 2012), C. Intraoperatively, the plate can already be placed on the lateral side in order to secure the lateral cortex. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 18.** Balloon placement and expansion (Kyphon; Medtronic, Sunnyvale, California, USA).
A. The deflated balloon is positioned below the lateral tibial plateau impression. The two round markers indicate the primary expansion distance of the balloon. B. Balloon expansion is monitored using contrast medium. After the final expansion, the balloon has expanded completely. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 19.** A patient with a posterolateral tibial plateau impression fracture (85 years, female). Preoperative x-rays, showing the impression fracture in the anteroposterior view (A), and lateral view (B). (x-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 20.** Elevation of the impressed articular surface. A. The balloon is supported with two K-wires introduced below the cannula. B. Balloon inflation at the posterior part of the lateral tibial plateau in order to elevate the posterior impression. (x-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 21.** Cement augmentation after balloon reduction. The cement has completely filled the subchondral void, but has extruded at the posterolateral cortex. (x-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 22.** Final intraoperative x-ray in the anteroposterior (A) and lateral (B) views. An angular stable plate with small fragment screws (3.5-mm proximal lateral tibia plate, Synthes Inc., West Chester, Pennsylvania, USA) was used for additional fixation after balloon reduction and cement augmentation. The posterior screws from the proximal plate row pass through the cement cloud. (x-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 23.** Comparison of the preoperative and postoperative CTs. A. Preoperative lateral impression fracture, with a severe increase in the tibial dorsal slope. B. On the postoperative CT scan, the lateral tibial plateau has been reduced anatomically and the slope corrected. A small amount of cement has penetrated into the joint at the posterior fracture line. (X-rays: Department of Trauma Surgery, Medical University of Innsbruck)

**Fig 24.** A. Schematic image showing clamp reduction of a pure lateral split fracture (AO 41-B1). B. Buttress plating with fragment compression using lag screws passing through the fracture. The compression direction is indicated by the blue arrow, and the buttress plate support against dislocation of the distal fragment by the green arrow. (Images adapted from Rüdi et al., AO Principles 38)

**Fig. 25.** A. Conventional plate and screw (left). Screw insertion causes plate compression against the bone surface. Angular stable plate (right). The screw heads are locked into the plate via a thread in the screw head. The plate is not compressed, and the periosteal blood
supply to the bone is not compromised. **B.** In conventional plates, the screw can move (green arrows). In angular stable plates, the screw is locked into the plate and fixed at a defined angle. (Images from Rüdi et al., AO Principles\textsuperscript{38})

**Fig. 26.** Bridging the comminuted fracture zone using a locking plate results in relative stability. Micromotion at the fracture site is needed to stimulate indirect bone healing. The load is borne completely by the implant (green arrows). This type of fracture treatment is also used in severely comminuted fractures of the proximal tibia. Images from Rüdi et al., AO Principles\textsuperscript{38}

**Fig 27.** Fixation methods after tibial plateau impression fracture reduction. **A.** Parallel screws placed through the cement cloud. Up to four screws are placed, depending on the fracture area (from Craiovan et al.\textsuperscript{51}). **B.** Screws placed in the anteroposterior direction, supporting the lateromedial screws in the “jail technique” (from Petersen et al.\textsuperscript{21}). **C.** Lateral locking plate fixation with angular stable screws (Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 28.** Radiograph of the left knee. The waisted shape at the metaphysis of the femur and tibia increases the articulating surfaces at the knee joint. (Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 29.** **A.** Image showing the triangular cross-section of the meniscus. During axial loading between the round articular surfaces of the femur and tibia (blue arrows), the meniscus is pushed outside (black arrow). **B.** Image showing the longitudinal load distribution along the meniscus (blue arrows) and the radial load distribution directed toward the joint capsule (black arrows). **C.** Contact areas between the femur and tibia, shown with and without menisci at full extension and 45° and 75° of flexion. Without menisci, the size of the contact areas is decreased by a factor of 3–5. (Images adapted from Brinkmann et al., Musculoskeletal Biomechanics\textsuperscript{11})

**Fig. 30.** Image showing the static equilibrium of a person in a semi-squatting position. The body’s center of gravity is located perpendicular to the area of support. The joint loads depend on the muscle forces needed to maintain the equilibrium. \( r_1 \) describes the moment arm between the rotation center of the knee and the center of gravity. In a fully standing person, \( r_1 \) is nearly 0 and the muscle forces around the knee (e.g., at the quadriceps muscle) are kept to a minimum. (Image adapted from Brinkmann et al., Musculoskeletal Biomechanics\textsuperscript{11})
**Fig. 31.** The forces acting at the knee in static symmetric knee bending position A. The gravitational force of half of the body mass $F_1$ produces a moment with a moment arm $r_1$. The quadriceps muscle must generate the tensile force of the patellar tendon $F_2$ acting with the moment arm $r_2$. B. The compressive force between the femur and the tibia $F_3$ is equal to the sum vector of the gravitational force of body weight $F_1$ and the force of the patellar tendon $F_2$. (Images adapted from Brinkmann et al., Musculoskeletal Biomechanics) 

**Fig. 32.** Equilibrium of forces in the frontal plane when the individual is standing on one leg. A. The ground reaction force $F_1$ creates a moment in the frontal plane relative to the center of rotation of the knee. This moment has to be balanced by the force on the fasciae latae $F_2$. With increasing knee varus, the medial lever arm increases, requiring an increased lateral reaction to prevent the joint from opening. This results in an increased force on the tibia $F_3$. (Images adapted from Brinkmann et al., Musculoskeletal Biomechanics) B. Long leg radiograph on the right side, showing varus deformity. The mechanical axis runs through the medial compartment. The medial arthritis with joint-space narrowing is visible. C. Long leg radiograph of a right-sided valgus deformity. The mechanical axis runs through the lateral compartment and increases lateral joint loads. (Department of Trauma Surgery, Medical University of Innsbruck)

**Fig. 33.** Load on the tibiofemoral joint during fast, normal and slow walking, based on Paul et al. The x-axis describes the gait cycle in percentages. Foot contact with the floor occurs is at 60% of the gait cycle. The y-axis describes the load on the joint percentages of body weight. (Image adapted from Brinkmann et al., Musculoskeletal Biomechanics)

**Fig. 34.** BMD measurement locations using a multiplanar reconstruction tool from IMPAX EE (Agfa HealthCare, Belgium). The coronal and sagittal planes were adjusted parallel to the tibial shaft axis. Circular regions of interest (ROI) with a diameter of 20 mm were placed 5, 10 and 15 mm below the lateral articular surface of the tibia.

**Fig. 35.** The European Forearm Phantom (EFP) calibration equation. The mean value of the four HU measurements for each section was calculated and pasted into the calibration template. The BMD was automatically calculated using the linear calibration equation.

**Fig. 36.** Specimens were embedded with a 5° valgus and a free specimen length of 15 cm

**Fig. 37.** Fracture creation. A. Circular arrangement of the predetermined breaking holes. B. Photograph of the fracture and the indenter. C. Anteroposterior (AP) radiograph after fracture creation, showing a lateral impression fracture.
**Fig. 38.** Balloon placement. **A.** The cannula is introduced from the medial cortex proximal to the insertion of the pes anserinus. The balloon’s position is checked fluoroscopically in the **AP (B)** and lateral views (C).

**Fig. 39.** Balloon inflation and reduction. **A.** The balloon is inflated using a contrast solution. Reduction and balloon expansion is controlled with fluoroscopy. **B.** Direct view of the reduced fracture.

**Fig. 40.** The lateral plate is provisionally placed at the lateral cortex. The drill sleeves are mounted at the proximal plate holes in order to visualize the direction of the screws after drilling. The plate position is adjusted until the drill sleeves are directed through the center of the cement cloud. The plate is then fixed with one distal screw and thin K-wires at the proximal plate.

**Fig. 41.** A fracture treated with a lateral plate and angular stable screws, seen from frontal (A) and lateral (B). Radiographs showing a right tibia before biomechanical testing in the **AP (C)** and axial views (D). The yellow circle marks the cement cloud.

**Fig. 42.** A fracture treated with screw raft fixation, seen from frontal (A) and lateral (B). Radiographs showing a left tibia before biomechanical testing in the **AP (C)** and axial views (D). The yellow circle marks the cement cloud.

**Fig. 43.** **A.** Photograph showing the test set-up. **B.** The femoral component of a hemi-knee arthroplasty (Stryker; Triathlon, Duisburg, Germany) was positioned at the lateral tibial plateau.

**Fig. 44.** Radiographs were taken after each loading interval at 20 N.

**Fig. 45.** Measurement of cartilage thickness. A line was drawn connecting the medial and lateral borders of the tibial plateau. Perpendicular to it, a line was drawn across the center of the impression fracture. The distance between the hemi-TKA and the subchondral bone (h) was measured at a constant load of 20 N before cyclic loading.

**Fig. 46.** Subsidence of the subchondral bone and cement cloud were measured on radiographs taken after each loading interval. A line was drawn connecting the medial and lateral borders of the tibial plateau. Perpendicular to it, a line was drawn across the center of the impression fracture. The distances between the line of the tibial plateau, the subchondral bone (x) and proximal border of the cement cloud (y) were measured along the perpendicular line across the fracture.
Fig. 47. Scatter plots showing the displacement data measured by the MTS in relation to the cartilage thickness. The $R^2$ correlation lines indicate a positive correlation between displacement and cartilage thickness.

Fig. 48. Scatter plots showing the subsidence data measured on radiographs for each load cycle in relation to the cartilage thickness. The $R^2$ correlation lines do not indicate any significant correlation between displacement and cartilage thickness.

Fig. 49. An example cyclic protocol on the MTS. Three load cycles (20–240 N, 20–360 N and 20–480 N, 5000 load cycles per interval) are applied over the course of the cyclic protocol, shown by the axial force (blue). The displacement over the course of the three cyclic intervals shown in red.

Fig. 50. Displacement of the loading piston with additional fixation (plate or raft), presented as box plots with medians and interquartile ranges (25–75%). The differences between the two groups were not significant.

Fig. 51. Amplitude of the loading piston during cyclic loading with additional fixation, presented as box plots with medians and interquartile ranges (25–75%). The differences between the two groups were not significant.

Fig. 52. Displacement of the loading piston with plate or screw raft fixation during cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

Fig. 53. Amplitude of the loading piston with plate or screw raft fixation during cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

Fig. 54. Subsidence of the subchondral bone with additional fixation, presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences ($P < 0.05$) are indicated with brackets and an asterisk (*).

Fig. 55. A. Radiographs taken after cyclic loading at 240N (left) and 480 N (right). B. The superimposed image shows the small movement of the screw head from the attached screw in the cement cloud.
Fig. 56. Subsidence of the subchondral bone with plate or screw raft fixation after cyclic loading at the highest load interval (20–480 N) and after removal of the additional fixation (20–480 N), presented as box plots with medians and interquartile ranges (25–75%). Statistically significant differences (P<0.05) are indicated with brackets and an asterisk (*).

Fig. 57. A. Split impression fracture created by a dropped weight (from Karunakar et al.\textsuperscript{114}). B. Heiney et al.\textsuperscript{88} created the split using an oscillating saw and a modified captive bolt stunner for the articular impression.

Fig. 58. Unicondylar pure impression fracture creation. A. Small bore holes are created in a circle on the lateral tibial plateau. B. The resulting circular impression fracture after the indenter has been pushed into the tibial plateau.

Fig. 59. A. Fracture model presented by Horwitz et al.\textsuperscript{118} B. This fracture model simulates a comminuted bicondylar fracture with intact condylar articular surfaces (AO 41-C2). (Image from AO web site: https://www2.aofoundation.org/)

Fig. 60. Different methods for loading of tibial plateau fractures described in the literature. A. Bicondylar loading using an anatomic distal femur (from Mueller et al.\textsuperscript{116}). B. Bicondylar loading using the femoral component of a total knee arthroplasty (from Ali et al.\textsuperscript{111}). C. Unicondylar loading to the medial tibial plateau using an indenter with a spherical end (from Egol et al.\textsuperscript{119}). D. Loading on the lateral tibial plateau using the femoral component of a hemi-knee arthroplasty (from McDonald et al.\textsuperscript{106}).

11.1.2 Tables

Table 1. Summary of the knee joint muscles and the movements they exert.

Table 2. General risk factors can be divided into four groups: genetic, lifestyle, hormonal and pharmacological.

Table 3. Risk factors for predicting the “10-year osteoporotic fracture risk” in accordance with the fracture risk assessment tool (FRAX)\textsuperscript{31}. 
### 11.2. Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>aBSM</td>
<td>artificial bone substitute materials</td>
</tr>
<tr>
<td>ACL</td>
<td>anterior cruciate ligament</td>
</tr>
<tr>
<td>ALAP</td>
<td>adipocyte-derived leucine aminopeptidase</td>
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<tr>
<td>AM</td>
<td>anteromedial bundle</td>
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<tr>
<td>AO</td>
<td>Arbeitsgemeinschaft für Osteosynthesen</td>
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<tr>
<td>AP</td>
<td>anteroposterior</td>
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<td>β-TCP</td>
<td>beta-tricalcium phosphate</td>
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<tr>
<td>BMD</td>
<td>bone mineral density</td>
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<td>CaPO₄</td>
<td>calcium phosphate</td>
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<td>CPCs</td>
<td>calcium phosphate cements</td>
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<tr>
<td>CPM</td>
<td>continuous passive motion</td>
</tr>
<tr>
<td>CSCs</td>
<td>calcium sulfate cements</td>
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<tr>
<td>CT</td>
<td>computed tomography</td>
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<tr>
<td>DEXA</td>
<td>dual-energy x-ray absorptiometry</td>
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<tr>
<td>EFP</td>
<td>European Forearm Phantom</td>
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<tr>
<td>EMG</td>
<td>electromyography</td>
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<tr>
<td>FRAX</td>
<td>fracture risk assessment tool</td>
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<td>GJA4</td>
<td>Protein A4 gene</td>
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<td>HA</td>
<td>hydroxylapatite</td>
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<tr>
<td>HU</td>
<td>Hounsfield units</td>
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<td>IL-6</td>
<td>interleukin-6</td>
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<tr>
<td>LCL</td>
<td>lateral collateral ligament</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>MCL</td>
<td>medial collateral ligament</td>
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<td>MRI</td>
<td>magnetic resonance imaging</td>
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<tr>
<td>MTS</td>
<td>materials testing machine system</td>
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<tr>
<td>OTA</td>
<td>Orthopedics Traumatology Association</td>
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<tr>
<td>PCL</td>
<td>posterior cruciate ligament</td>
</tr>
<tr>
<td>PL</td>
<td>posterolateral bundle</td>
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<tr>
<td>PMMA</td>
<td>polymethylmethacrylate</td>
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<td>POL</td>
<td>posterior oblique ligament</td>
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<td>RANKL</td>
<td>receptor activator of nuclear factor-κB ligand</td>
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<tr>
<td>RANK</td>
<td>receptor activator of nuclear factor-κB</td>
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<td>ROI</td>
<td>regions of interest</td>
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<tr>
<td>SERMs</td>
<td>selective estrogen receptor modulators</td>
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<td>sMCL</td>
<td>superficial medial collateral ligament</td>
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<td>total knee arthroplasty</td>
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<td>VEGF</td>
<td>vascular epithelial growth factor</td>
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<td>WHO</td>
<td>World Health Organization</td>
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The results of the present PhD study have been published in the Journal Clinical Biomechanics under the title “Effect of additional fixation in tibial plateau impression fractures treated with balloon reduction and cement augmentation”.

13. GRANT SUPPORT

Research for this dissertation was performed with the assistance of the AO Trauma Network. We are grateful for grant funding.