INTRODUCTION
Osteoporotic fractures have become a global social and financial challenge due to the worldwide aging population [1]. Because of the poor bone quality, these fractures are difficult to treat and often lead to complications requiring a revision surgery which imply additional risks and pain for the patient. Hence, they need to be treated more effectively to prevent any further complications. For this, bone augmentation can be used in which polymethyl-methacrylate (PMMA) is injected into osteoporotic bones to reinforce the weak trabecular network. PMMA has been used for several years to treat vertebral compression fractures by injecting it into the trabecular network of fractured vertebral bodies to regain some of their original height and load bearing capacity [2]. Recently, bone augmentation has also been applied in combination with orthopedic screws mainly targeted for fixation of vertebral bodies to treat spinal instability [3]. Augmented bone screws show increased pull-out strength, stiffness and energy to failure compared to non-augmented specimens [4]. Nevertheless, bone screw augmentation is a quite new surgical procedure and it is not clear what factors contribute to increased stability and how PMMA changes the biomechanical properties in the trabecular network. Furthermore, it is not known how augmentation is affected by inter- and intra-individual differences in bone macroarchitectures. Motivated by these open questions, the aim of this study was to conduct non-destructive mechanical tests on the same set of bone specimens before and after augmentation, and to quantify the role of bone microstructure.

METHODS
Thirty-one bone samples were core drilled from 8 bovine femoral heads. A precision saw was used to remove the cortical bone and to obtain parallel loading surfaces with a specimen dimension of 16 mm in height (15.99±0.05 mm) and in diameter (16.00±0.04 mm). For guided screw insertion, a pre-hole of 2.7 mm in diameter was drilled into the samples. Pulsed jet lavage with 5 bar air pressure was used to wash out residual bone marrow and debris in the trabecular network. A cannulated titanium screw (Synthes, Solothurn, Switzerland) of 14 mm in length and 3.5 mm in diameter was inserted 9 mm into the bone leaving a gap of 1 mm between screw tip and the bottom of the pre-hole. For the first set of non-destructive compression tests (Zwick-Roell Z2050 TN), a preload of 50 N and 19 pre-conditioning cycles between 0 and 0.4 % strain were applied. Stiffness, defined as the resulting force divided by the prescribed displacement and a reliable predictor for pull-out strength [5], was computed at the 20th compression cycle using a linear fit through the top 10% of the unloading curve. All samples were augmented with polymethylmethacrylate (PMMA) (Vertecem V+, Synthes, Solothurn, Switzerland) according to the manufacturer’s guidelines. Maximum injection volumes through the cannulated screws were attempted during injection. After augmentation, all samples were scanned using a micro-CT (µCT 100, Scanco Medical, Bassersdorf, Switzerland) at a nominal isotropic resolution of 20 µm. The images were reconstructed, filtered and segmented with three different threshold values for bone, cement and screw (Fig. 1). Morphometric parameters, such as bone volume fraction (BV/TV), trabecular spacing (Tb.Sp.), trabecular thickness (Tb.Th.) and connectivity density (Conn.D.) were assessed to quantify the microarchitecture of the trabecular network as well as the injected cement volume (CV).

RESULTS
BV/TV ranged from 0.03 to 0.29 ml and correlated only poorly to BV/TV (R²=0.15). Visual inspection of the specimens revealed highly variable cement distributions even for similar PMMA volumes (Fig. 1). The average stiffness of augmented bone-implant constructs (6891 N/mm) was increased compared to their non-augmented state (5934 N/mm; p<0.0001) by 957 N/mm (SD = 427 N/mm) in absolute and 17% (SD = 8.4%) in relative numbers, respectively. The injected cement volume showed a low predictability for absolute stiffness increase (ΔSabs; R²=0.16) and an only slightly higher one for relative stiffness increase (ΔSrel; R²=0.24). The correlation between CV and ΔSrel was improved using a multilinear regression model taking CV and BV/TV into account (R²=0.42): Adding Tb.Sp., Tb.Th. and Conn.D. to the analysis only slightly improved the correlation (R²=0.48).

DISCUSSION
The present work shows the feasibility to image heterogeneous and complex distribution structures of PMMA augmented screws and to quantify their volume in trabecular bone on a micro-structural level. Furthermore, the apparent mechanical properties of bone-implant constructs before and after augmentation were quantified. PMMA volume and morphometric bone parameters only partially explain the stiffness increase. We suspect that the location and distribution of the cement as well as the contact area between PMMA/bone and PMMA/screw are further factors that affect the mechanical competence of augmented trabecular bone-implant constructs. Micro-CT image-based finite-element analysis could be a useful tool to investigate these factors on a macro- and microstructural level.

SIGNIFICANCE
We conducted biomechanical tests to quantify stiffness in trabecular bone specimens before and after augmentation, and used micro-CT imaging to assess bone microarchitecture and cement distribution. This combined approach will enhance our understanding of the bone and cement factors influencing the mechanical properties of augmented implants and could potentially be used to optimize primary implant stability which in turn reduces the risk of revision surgery.

REFERENCES