Local osteo-enhancement of the proximal femur in osteoporosis: biomechanical rationale and current evidence

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ABSTRACT

Fragility fractures are a major clinical consequence of osteoporosis and are associated with considerable morbidity and mortality. Hip fractures in particular remain among the most severe complications of skeletal fragility. Although bone mineral density (BMD) is widely used to assess fracture risk, bone strength is also influenced by structural and material properties collectively referred to as bone quality. Age-related deterioration of trabecular architecture in the proximal femur may contribute to localized mechanical weakness and increased fracture susceptibility.

In this context, site-specific bone reinforcement strategies using resorbable biomaterials have been proposed to improve the mechanical competence of osteoporotic bone. Among these, the Local Osteo-Enhancement Procedure (LOEP) is a minimally invasive technique designed to reinforce structurally vulnerable regions of the proximal femur through targeted injection of a resorbable calcium-based biomaterial. This review analyzes the biomechanical rationale and the currently available evidence supporting LOEP. Preclinical studies suggest that injectable biomaterials may increase load-to-failure and energy absorption in osteoporotic bone models. Early clinical studies have reported increases in femoral neck BMD and estimated mechanical strength following LOEP. However, current clinical evidence remains limited and is largely based on surrogate endpoints rather than fracture reduction.

KEYWORDS

Osteoporosis, bone fragility, proximal femur, local osteo-enhancement, biomaterials.

Introduction

Fragility fractures are among the main clinical manifestations of osteoporosis and constitute a major global health problem associated with considerable morbidity, mortality, and socioeconomic burden [1,2]. Proximal femur fractures are particularly significant due to their substantial clinical consequences, including loss of independence, systemic complications, and increased mortality within the first year following the incident. Historically, fracture risk has primarily been evaluated via bone mineral density (BMD) assessed through dual-energy X-ray absorptiometry, but BMD has been recognized to account for only a portion of the variability in bone strength and fracture risk.

Seeman and Delmas, introducing the concept of bone quality, which includes parameters such as trabecular microarchitecture, bone turnover, microdamage accumulation, and degree of mineralization, described bone strength as the result of the interaction between bone quantity and bone quality [3]. Similarly, Bouxsein highlighted how structural and biomechanical factors contribute significantly to bone strength independently of BMD alone [4].

Imaging and morphological studies indicate that age-related trabecular loss in the proximal femur may exhibit heterogeneous regional distribution. In this context, Civinini *et al*. described regional structural alterations of the proximal femur that may contribute to reduced biomechanical strength of the hip [5]. Based on these observations, it has been hypothesized that, in addition to global bone loss, localized structural vulnerabilities may contribute to the reduction of bone mechanical resistance. In this context, experimental focal bone reinforcement strategies have been proposed, based on the injection of resorbable biomaterials into load-bearing regions of osteoporotic bone. Among these approaches, the Local Osteo-Enhancement Procedure (LOEP) represents a relatively recent technique that is attracting growing interest for the treatment of the proximal femur. The LOEP consists of a minimally invasive image-guided percutaneous approach in which access to the proximal femur is obtained using dedicated instrumentation. After local preparation of the targeted cancellous region, a resorbable calcium-based biomaterial is delivered in a controlled manner into structurally vulnerable femoral neck and intertrochanteric areas, with the aim of providing temporary mechanical support while promoting subsequent bone remodeling [6].

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Methods

A literature review was performed to identify and critically evaluate the available evidence regarding focal bone reinforcement strategies employing resorbable biomaterials in skeletal fragility. The literature search was conducted using the PubMed/MEDLINE, Embase, and Cochrane Library databases with combinations of the following terms: "local osteo-enhancement," "focal bone reinforcement," "proximal femur augmentation," "resorbable calcium implant," "osteoporosis," and "bone fragility." Articles published between January 2000 and March 2026 were considered. Titles and abstracts were screened to identify potentially relevant studies; this step was followed by full-text evaluation of eligible articles.

Preclinical studies, biomechanical *ex vivo* investigations, and clinical studies evaluating the use of calcium-based resorbable biomaterials in focal bone reinforcement procedures were included.

Biomechanical rationale for focal bone reinforcement

The mechanical strength of bone is determined by the ability of its trabecular and cortical structures to distribute mechanical loads. BMD, trabecular connectivity, and structural orientation all have a significant influence on bone mechanical behavior under load.

Morgan *et al*. demonstrated that the relationship between BMD and elastic modulus varies across different anatomical sites, highlighting the role of microarchitecture in determining bone mechanical properties [7].

Structural strength in the proximal femur is also determined by femoral neck geometry and the spatial distribution of bone mass along load-bearing trajectories. Experimental studies have shown that the trabecular architecture of the proximal femur is highly anisotropic, and that structural variations have a significant impact on mechanical resistance to hip fracture [8].

These observations highlight the importance of bone microarchitecture and structural organization in determining skeletal strength. Within this biomechanical framework, it has been proposed that targeted reinforcement of structurally vulnerable trabecular regions may modify the mechanical behavior of osteoporotic bone. The concept of local osteo-enhancement is therefore based on improving the load-bearing capacity of fragile bone through the injection of resorbable biomaterials that provide temporary mechanical support and act as osteoconductive scaffolds.

Biomaterials used in focal bone reinforcement procedures

Focal bone reinforcement procedures mainly employ synthetic resorbable calcium-based biomaterials designed to provide temporary mechanical support and promote new bone formation. A review by Giannoudis *et al*. described the main biological and mechanical characteristics of synthetic bone substitutes used in orthopedics, highlighting how chemical composition, porosity, and crystalline structure influence biomaterial behavior [9].

The most commonly used materials include calcium sulfate, characterized by high biocompatibility and rapid resorption [10], and calcium phosphates, which have a chemical composition similar to the mineral phase of bone and exhibit favorable osteoconductive properties [11].

To improve mechanical properties and modulate resorption kinetics, composite formulations combining different calcium phases have also been developed.

In the context of the LOEP, the available clinical studies describe the use of AGN1, a triphasic resorbable calcium-based biomaterial intended for local augmentation of structurally vulnerable regions of the proximal femur. AGN1 has been described as comprising calcium sulfate, brushite (dicalcium phosphate), and β-tricalcium phosphate (β-TCP), components intended to provide complementary biological and mechanical properties [12].

Calcium sulfate is generally characterized by relatively rapid dissolution and may contribute to early implant turnover and initial pore formation within the treated region. Brushite may display intermediate resorption kinetics and could support transitional remodeling during the early phases of biological integration. β-TCP is typically more slowly resorbed and may serve predominantly as an osteoconductive scaffold, thereby potentially helping to provide temporary structural support while permitting bone ingrowth [10-12]. The biomechanical rationale underlying the combination of these three phases is to provide early local mechanical reinforcement while facilitating progressive material resorption and subsequent replacement by newly formed bone over time [12].

Biomechanical evidence

Initial evidence supporting focal bone reinforcement procedures derives mainly from biomechanical studies conducted on *ex-vivo* models. In a study on osteoporotic human vertebrae, Trost *et al*. demonstrated that injection of a triphasic resorbable biomaterial significantly increased load-to-failure compared with untreated controls [13].

Although this study was conducted on vertebrae, it provides important insights into the biomechanical behavior of osteoporotic bone after biomaterial injection, demonstrating the ability of this intervention to modify structural response under load. In parallel, finite element analysis models based on computed tomography imaging have been used to estimate proximal femur strength. Keyak *et al*. showed that strength estimated by finite element modeling strongly correlates with fracture load observed in biomechanical testing [14].

Clinical evidence

Clinical evidence regarding the LOEP currently derives mainly from prospective non-randomized studies.

In a prospective study involving patients with osteopenia

or osteoporosis, Howe *et al*. reported an increase in femoral neck BMD following focal reinforcement of the proximal femur [12]. In the same study, finite element analysis demonstrated an increase in estimated proximal femoral strength, suggesting an improvement in structural load-bearing capacity. These findings may reflect both the immediate mechanical contribution of local biomaterial augmentation and the subsequent biological replacement of the resorbed material by newly formed bone during follow-up. Furthermore follow-up data reported by the same group indicated persistence of femoral neck BMD changes for several years after the procedure, supporting the hypothesis that local structural modification may extend beyond the early post-procedural phase. Additional analyses using quantitative computed tomography, as reported by Chin *et al*., showed localized increases in volumetric BMD in treated regions [15]. These imaging findings may be consistent with sustained regional remodeling after local osteo-enhancement.

Limitations of the available evidence

The currently available evidence on focal bone reinforcement procedures presents several methodological limitations.

Most clinical studies are observational or prospective non-randomized investigations with relatively small sample sizes. Furthermore, many studies rely on surrogate endpoints such as variations in BMD or biomechanically estimated strength. Although these parameters provide relevant information on structural and biomechanical changes in treated bone, their relationship with an actual reduction in hip fracture risk requires further investigation.

Conclusions

LOEP represent an emerging approach in the field of skeletal fragility.

The biomechanical rationale for these techniques is based on the concept that bone strength depends not only on bone mass, but also on the structural organization and regional distribution of bone tissue.

Preclinical evidence and early clinical studies suggest that injectable resorbable biomaterials may induce localized increases in BMD and estimated biomechanical strength. In particular, triphasic calcium-based materials may offer the advantage of combining temporary structural reinforcement with progressive biological integration.

However, the currently available clinical evidence remains limited and relies largely on surrogate endpoints rather than fracture-related outcomes.

Further prospective controlled studies with clinically relevant endpoints will be required to better define the role of focal bone reinforcement techniques in fragility fracture prevention.

If confirmed by future evidence, local osteo-enhancement technique may represent an adjunctive option within comprehensive osteoporosis management. Further studies will be required to clarify the most appropriate clinical indications and target populations.

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