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In vivo application of an optical segment tracking approach for bone loading regimes recording in humans: A reliability study

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ABSTRACT

This paper demonstrates an optical segment tracking (OST) approach for assessing the *in vivo* bone loading regimes in humans. The relative movement between retro-reflective marker clusters affixed to the tibia cortex by bone screws was tracked and expressed as tibia loading regimes in terms of segment deformation. Stable *in vivo* fixation of bone screws was tested by assessing the resonance frequency of the screw-marker structure and the relative marker position changes after hopping and jumping. Tibia deformation was recorded during squatting exercises to demonstrate the reliability of the OST approach. Results indicated that the resonance frequencies remain unchanged prior to and after all exercises. The changes of Cardan angle between marker clusters induced by the exercises were rather minor, maximally 0.06°. The reproducibility of the deformation angles during squatting remained small (0.04°/m–0.65°/m). Most importantly, all surgical and testing procedures were well tolerated. The OST method promises to bring more insights of the mechanical loading acting on bone than in the past.

1. Introduction

The loading patterns of bones constitute an important determinant for their current geometry and mechanical properties [1]. Further understanding of the bone loading patterns would improve our comprehension of the mechanical adaptation process of bones [2–4]. Certainly, bone loading patterns can be experimentally assessed in some particular cases. A series of classic animal studies in the 1980s investigated long bone loading patterns using typically three strain gauges attached around the mid-shaft of the bone's surface [5,6]. However, substantial prediction error may be induced using strain gauge approaches [7]. Beyond that, the strain gauge approaches may not be suitable for application in many other species, including humans. Despite its invasiveness, the regular muscle function may be disturbed if strain gauges have to be attached around the bone [7,8]. To our knowledge, the current understanding of long bone loading pattern in humans during activities remains limited due to the technical difficulties.

In our previous publication, we proposed a new concept of optical segment tracking (OST) approach for assessing *in vivo* long bone loading pattern, in terms of segment deformation regimes [9]. The idea was to affix clusters with sets of retro-reflective markers to different sites of the bone, and to track the trajectories of these markers with a motion capture system during different locomotor tasks. Bone segment deformation, *i.e.* bending and torsion, can then be assessed from the relative movement between the markers. Since the OST approach is based on coordinate tracking of the markers, its resolution, accuracy, and repeatability entirely rely on the performance of the adopted optical system. Mock-testing with the optical system has demonstrated that a resolution of <20 μm can be achieved with high accuracy and precision within a volume of 400 mm × 300 mm × 300 mm [9]. High repeatability of the OST approach in recording minute tibia deformations was also demonstrated in a human cadaveric testing (supplementary material). However, whether or not the OST approach is practically feasible in humans still remains to be determined. The general toleration of the test subjects to the OST approach has been reported previously [10]. In this paper, firstly, the stability of bone screws in

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the tibia throughout several exercises was evaluated using resonance frequency analysis. Secondly, the *in vivo* reliability of the OST approach was demonstrated using the tibia deformation results of a squatting exercise.

2. Materials and methods

Five healthy male subjects (26–50 years old) volunteered to participate in the study. The study protocol was approved by the relevant ethics bodies, and written informed consent was obtained from all subjects before inclusion into the study. The operations and the *in vivo* exercise battery were performed at the Department of Orthopedic and Trauma Surgery of the University Hospital of Cologne.

2.1. Surgical and bone visualization technique

On the right shank of each subject, surgical implantation and explantation of the bone screws were performed under local anesthesia by injecting Xylocain 1% and Carbostesin 0.5% into the skin and the periosteum. Prior to that, Ibuprofen (600 mg) and Cefuroxime (1500 mg) were administered [10]. Further details regarding the surgical technique have been reported previously [10]. Approximately one week prior to the *in vivo* experiments, transverse MRI (Magnetic Resonance Imaging, sequence: 601, slice thickness/distance: 5/5.5 mm, resolution: 0.27 mm, 1.5 T, Philips, Best, The Netherlands) images of the entire tibia were obtained to select those sites of the tibia where the cortex was at least 4 mm thick for bone screw installation. Eventually, the antero-medial aspect sites of tibia were selected at mid-site of the tibia diaphysis, approximately 10 cm below the tibia plateau and above the medial malleolus, respectively. Surgical incisions of approximately 1 cm length were made (Fig. 1A), and holes were drilled 2–3 mm into the tibia cortex with a 2.1 mm diameter drill (Stryker Leibinger GmbH & Co. KG, Germany) into which the bone screws (Asnis Micro cannulated titanium screws, ∅3 mm, total/thread length: 24/6 mm, Stryker Leibinger GmbH & Co. KG, Germany) were implanted.

Bone screw removal after the testing took place between 6 and 8 h later. Bone screw positions were documented using 6 scans by peripheral quantitative computed tomography (pQCT) with a XCT 3000 (slice thickness/distance: 2.5/1.5 mm, pixel size: 0.4 mm, Stratec Medizintechnik, Pforzheim, Germany) after screw removal (Fig. 1D).

2.2. OST approach

Onto each bone screw, a marker cluster, with a set of three non-collinear, high surface quality retro-reflective markers (∅5 mm, Géodésie Maintenance Services, Nort Sur Erdre, France) was mounted using tiny screws for fixation (Fig. 1C). A Vicon MX optical motion capture system with eight Vicon F40 cameras (Vicon Motion System Ltd., LA, USA) was used to capture the trajectories of the marker clusters at 300 Hz (Fig. 1B). In order to obtain optimal accuracy and precision, the optical system was configured as previously proposed [9]. Of note, by keeping the full resolution of the cameras (maximum sampling rate with full resolution is 370 Hz), a much higher sampling frequency than in the previously proposed configuration was realized to capture the relatively fast movements of the markers during the *in vivo* experiments. Compared to previous surface tracking approaches that use skin-attached markers, the OST approach totally avoids the potential influence of the relative movement between skin and bone on the recorded results.

2.3. Stability of bone screws: resonance frequency

The resonance frequency of the screw-marker structure from two subjects was assessed prior to and after the exercises, including approximately 10 min of walking, 10 min of running, 30 cycles of double legs hopping, 30 cycles of single leg hopping, 3 drop jumps and 3 countermovement jumps. The proximal screw-cluster structure was excited by flipping with a finger of the same lab staff while the subject was in sitting position with the shank free of any loading. The marker trajectories were simultaneous recorded at 1000 Hz.

2.4. Stability of bone screws: relative movement between the tibia-affixed markers

The constancy of the relative position between the marker clusters across the repetitions of the most intense exercises, *i.e.* hopping

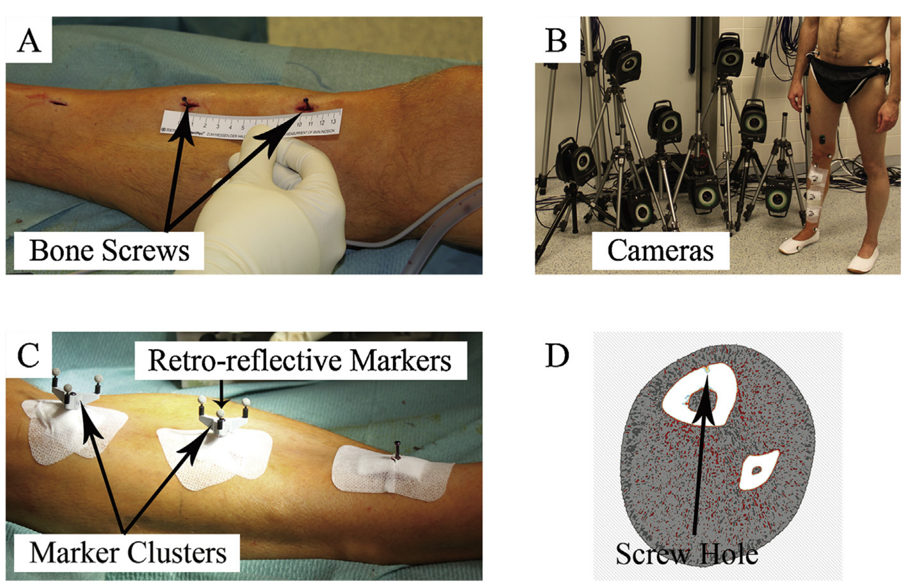

Fig. 1. Illustration of the surgical technique and the OST approach in this study. (A) Bone screw implantation into the tibia cortex. (B) The motion capture system with 8 high resolution cameras to track the retro-reflective markers. (C) Marker clusters were fixed on the top of the bone screws. (D) The pQCT image of the cross section area of the shank. The black arrow indicates the screw hole after the bone screw being removed.