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# Two-leg alternate loading model – A different approach to biomechanical investigations of fixation methods of the injured pelvic ring with focus on the pubic symphysis

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## ABSTRACT

The dorsal component of the pelvic ring is considered to be the most essential element for the stability of the pelvic ring. None of the current biomechanical set-ups include the effect of shear stresses by alternating loads that the pelvic ring has to withstand during walking. We hypothesize that a biomechanical test set-up with two-leg alternate loading will lead to stress imitation at the pubic symphysis that are more similar to existing strains than other test set-ups, and would, therefore, be more adequate for biomechanical testing of fixation methods.

A new biomechanical two-leg standing test set-up with an alternate pelvic loading was constructed and was validated with six human pelvises from fresh frozen cadavers. Three-dimensional motion tracking was performed. The specimens were subjected to a non-destructive quasi-static test and a non-destructive cyclic test with progressive load amplitude from 170 N to 340 N over 1000 cycles.

The initial rotational 'range of motion' and 'mean displacement' around the vertical axis for a pre-load of 170 N was about 0.3° and 0.2°, respectively, increasing by 0.1–0.2° at a load of 340 N. The rotation around the vertical axis and the translation along the frontal horizontal axis confirmed the stability of the pubic symphysis. The rate of ascend of displacements decreased, once the rotation reached 1° or the translation reached 1 mm.

The current biomechanical test set-up was compared with previous clinical findings, and the method was found valid for measuring inter-segmentary movements at the pubic symphysis.

## 1. Introduction

The biomechanics of the pelvic ring have been of great interest for almost three decades. Many researchers have tried to quantify the physiological movements of the pelvic ring and the involved joints (Becker et al., 2010; Gnat et al., 2013; Meissner et al., 1996; Pool-Goudzwaard et al., 2012; Walheim and Selvik, 1984; Walheim et al., 1984a). However, research was focused either on the biomechanical outcome of different fixation methods (Decker and Ruf, 1988; Kamhin et al., 1980; Kim et al., 1999; Leighton et al., 1991; Pohlemann et al., 1993; Ponson et al., 2002; Simonian et al., 1994a,b) or on the functional outcome after surgical treatment after an injury (Gruen et al., 1995; Matta and Tornetta, 1996; van Den Bosch et al., 1999). The dorsal component of the pelvic ring is considered to be the central element for its stability (Pool-Goudzwaard et al., 2003; Snijders et al., 1993a,b; van Wingerden et al., 1993; Vleeming et al., 1989a,b, 1996, 2002). Therefore, many investigations have evaluated different fixation methods in this region (Berber et al., 2011; Kraus et al., 1998; Kim et al., 1999; Leighton et al., 1991).

Various biomechanical test set-ups have been developed to analyze the complex mechanical behavior of the pelvic ring, but each study has been hampered by limitations. The attempted test set-ups include the *one-leg stance* set-up, in which the force was applied to the pelvic ring via a single femur (Berber et al., 2011; Kraus et al., 1998; MacAvoy et al., 1997; Pohlemann et al., 1993);

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and the *two-leg stance* set-up with simultaneous load application on both hips (Kim et al., 1999; Simonian et al., 1994a; Varga et al., 1995; Vleeming, 1990), among others. Other studies are limited to the anterior pelvic ring (Meissner et al., 1996). Although Vleeming, Snijders and colleagues (Gnat et al., 2013; Ponson et al., 2002; Pool-Goudzwaard et al., 2003, 2004, 2012; Snijders et al., 1993a,b; van Wingerden et al., 1993; Vleeming et al., 1989a,b, 1996, 2002, 2013) have investigated the internal deformation of the innominate due to external forces, the stability of the dorsal ligaments and muscle forces, as well as the stiffness of the sacroiliac joint (SIJ), we believe that the existing test set-ups still do not provide a thorough description of the movements at the pubic symphysis and especially testing of fixation methods with respect to external forces, when the load is transferred from one leg to another. Therefore, in the first step of the experiment, a new pelvic test set-up for biomechanical testing with two-leg alternate loading was developed and evaluated. In the second step, after the evaluation of the test set-up, biomechanical investigations of different fixation methods of the pubic symphysis are planned, which are not subject of this paper.

## 2. Material and methods

### 2.1. Specimen preparation

Seven human pelvises, including proximal femora and the vertebra L5 with no gross evidence of bone and soft tissue pathology, were harvested from fresh frozen cadavers (−20 °C, 4 males and 3 females, age 75.8 ± 6.2 years). Radiological imaging was performed to exclude defects affecting the integrity of the pelvic structure. The specimens had been thawed for two days prior to preparation and mechanical testing. The soft tissue was removed, preserving the pubic symphysis, sacroiliac ligaments, iliolumbar ligaments, proximal femoral ligaments and the hip joints with their capsulae. The vertebra L5 was separated and used for measurements of bone mineral density (BMD), and underwent high-resolution peripheral quantitative computed tomography (HR-pQCT, XtremeCT™ Scanco Medical, Brüttisellen, Switzerland) with a resolution of 123 μm and a volume of interest defined as a cylinder with a length of 6 mm and a diameter of 15 mm in the vertebral body. The proximal femora were cut at a length of 200 mm measured from the lesser trochanter. The sacrum was equipped with a 10 mm petroleum jelly-coated stainless steel rod, passing through a hole drilled from the base of the sacrum to the S3–S4 region. Subsequently, the sacrum was embedded in polymethylmethacrylate (PMMA; Beracryl®, W. Troller Kunststoffe AG, Switzerland), which reinforced the bone to hold sufficient load during the mechanical testing. Finally, five clusters of four infrared light-reflecting markers were attached to either side of the pubic symphysis, the sacrum and the left and right iliac crest of each specimen for 3D motion tracking.

### 2.2. Biomechanical testing

A new test set-up for biomechanical testing was constructed as shown in Fig. 1. The test frame was based on the biaxial servo-hydraulic testing machine, MTS Mini Bionix II 858 (MTS Systems Corp., USA), using a 25 kN/250 Nm load cell (662.20D-05, MTS Systems Corp., Eden Prairie, MN, USA). In the preparation of the biomechanical testing, each specimen was mounted horizontally on the test frame, so that it represented a two-leg stance standing set-up (Figs. 1 and 2). The proximal femora were placed in such a way that the femoral shafts formed an angle of 9° (SD: 2°), while they were unloaded or symmetrically loaded, based on the angle between the femoral shaft and the vertical axis in the coronal plane (Curtis, 2004; Holla's, 2005). Next, both ends were attached to the sliding post, using a bolt at the distal end of each femur (1, in Fig. 2). This fixation allowed the application of axial load in the direction of the mechanical axis of each leg (Fig. 1). The 10 mm stainless steel rod holding the sacrum in place was fixed in the sacral holder, which is shown as (2) in Fig. 2. The rod was part of a jig which was constructed to enable the pelvis to be fixed to the test frame, so that it could rotate around the axis which was parallel to the sacral line (Choufani et al., 2009). Subsequently, the sacrum was mounted on the *sacral-angle* jig (3, in Fig. 2), which enables the free rotational movement of the pelvis with respect to the sacrum. The *sacral-angle* jig possesses an angular adjustor to achieve a sacral angle of approximately 35° (Choufani et al., 2009). The jig was locked before the start of test cycle and attached to the test frame via a load cell (9347C, Kristler®, Switzerland) which was free to translate anteroposteriorly (4, in Fig. 2). This enabled the monitoring and measurement of the load at the attachment point to ensure symmetric loading on both legs. The pelvis of each specimen was free to rotate in all degrees of freedom at the hip joints, while the femora were able to slide on the rails (5, in Fig. 2). Each femur of every specimen was preloaded by attaching a weight of 5 kg to its distal end (6, in Fig. 2) in order to hold the femora in place, or bring them in place while the load is being applied on the contralateral side using the torsional actuator (7, in Fig. 2).

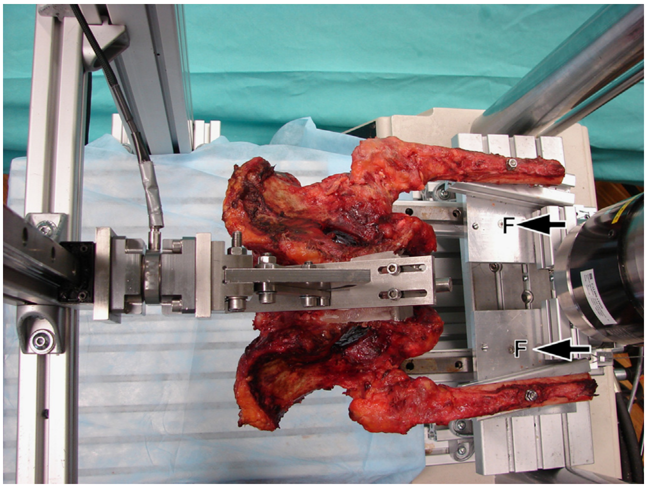

**Fig. 1.** Posterior view of a specimen mounted on the testing frame for two-leg alternate pelvic loading via the torsional machine actuator. Arrows (F) point in the direction of the applied alternating force.

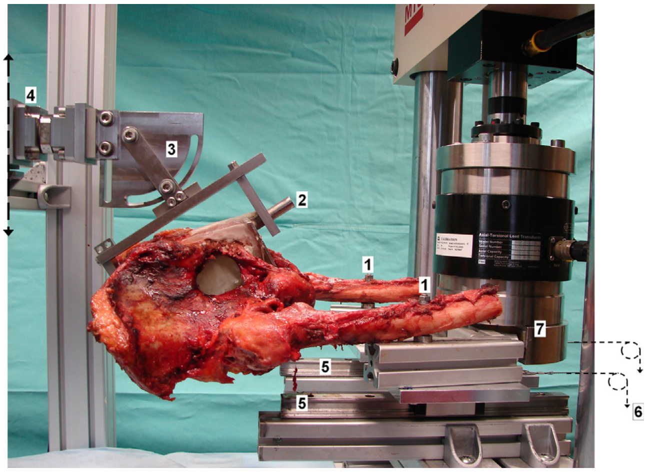

**Fig. 2.** Sagittal view of a specimen mounted on the testing frame for two-leg alternate pelvic loading via the torsional machine actuator. Details of the annotations are provided in the main part of the manuscript.

The specimens were subjected to a non-destructive quasi-static test with an axial ramp load of up to 170 N, applied on each femur at a rate of 17 N/s, followed by a non-destructive cyclic test with an axial sinusoidal loading at a rate of 1 Hz and progressive load amplitude, starting from 170 N and increasing to 340 N over 1000 cycles at a rate of 0.17 N/cycle. Such axial load was found to be within the safe limits, so that any instability or disruption is avoided (MacAvoy et al., 1997; van Den Bosch et al., 2003), as was confirmed in a pilot test with one of the specimens.

### 2.3. Data acquisition and analysis

The axial load was continuously recorded by the testing machine controllers at 128 Hz. Inter-segmental movements were registered optically in all six degrees of freedom through 3D motion tracking and by monitoring the marker clusters on the specimens with five infrared digital cameras (ProReflexMCU, Qualisys AB, Gothenburg, Sweden) at a rate of 100 Hz (Fig. 3). The three-dimensional coordinate system that was used for the pubic symphysis is shown in Fig. 4 (Walheim and Selvik, 1984). It was adopted according to the usage in biomechanics and human anatomy (Panjabi et al., 1974, 1981). The frontal, transverse and sagittal planes were defined as *XY*, *XZ* and *YZ*, respectively. The axes perpendicular to these planes were called *Z* (sagittal horizontal axis), *Y* (vertical axis) and *X* (frontal horizontal axis), respectively.

Based on the translational and rotational movements in all the degrees of freedom at the pubic symphysis, along and around these axes that were calculated