A structural numerical model for the optimization of double pelvic osteotomy in the early treatment of canine hip dysplasia

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Summary
Background: Double pelvic osteotomy (DPO) planning is usually performed by hip palpation, and on radiographic images which give a poor representation of the complex three-dimensional manoeuvre required during surgery. Furthermore, bone strains which play a crucial role cannot be foreseen.

Objective: To support surgeons and designers with biomechanical guidelines through a virtual model that would provide bone stress and strain, required moments, and three-dimensional measurements.

Methods: A multibody numerical model for kinematic analyses has been coupled to a finite element model for stress/strain analysis on deformable bodies. The model was parametrized by the fixation plate angle, the iliac osteotomy angle, and the plate offset in ventro-dorsal direction. Model outputs were: acetabular ventro-version (VV) and lateralization (L), Norberg (NA) and dorsal acetabular rim (DAR) angles, the percentage of acetabular coverage (PC), the peak bone stress, and moments required to deform the pelvis.

Results: Over 150 combinations of cited parameters and their respective outcome were analysed. Curves reporting NA and PC versus VV were traced for the given patient. The optimal VV range in relation to NA and PC limits was established. The 25° DPO plate results were the most similar to 20° TPO. The output L grew for positive iliac osteotomy inclinations. The 15° DPO plate was critical in relation to DAR, while very large VV could lead to bone failure.

Clinical significance: Structural models can be a support to the study and optimization of DPO as they allow for foreseeing geometrical and structural outcomes of surgical choices.

Introduction
Hip dysplasia is a common developmental skeletal disease leading to hip joint surface incongruity with insufficient coverage of the femoral head by the dysplastic acetabulum and secondary subluxation of the femoral head. Its incidence can be estimated to be above 10% with reference to 2005–2010, according to the "Orthopaedic Foundation for Animals" (1). Triple pelvic osteotomy (TPO) and, more recently, double pelvic osteotomy (DPO) are among the surgical procedures commonly performed to manage hip dysplasia in growing dogs (2). According to the latter surgical procedure, only two osteotomies are performed, one on the pubis, with the partial removal of its ramus (see 'A' in Figure 1a), and one on the ilium (‘C’ in Figure 1a), while the ischium is left intact (Figure 1a). The DPO surgical procedure can be critical because it requires bone deformation of the ischium, and loading forces can lead to bone or plate fixation failure in certain circumstances. Therefore, the development of software that could predict stresses, strains, and constraining forces could assist surgeons in the planning of DPO, and more in detail, in determining the inclination of the DPO plate, the orientation of the osteotomy, and the position of the plate over the ilium. In fact, it is actually impossible to foresee the outcome of all the different combinations of these variables ex vivo since this would require a very high number of cadaveric pelves with an unlikely possibility to collect pelves from growing dogs. A virtual model can be a sound alternative, since the outcomes of
DPO performed with different combinations of parameters can be simulated, and the surgery can be optimized in relation to a specific patient.

Methodologies for kinematic and structural analyses can be imported from classic engineering fields. In recent years, the application of reverse engineering methods has allowed us to realize the three-dimensional reconstruction of the joint from computed tomography (CT) images whenever they are available, or from radiographs in all other cases (3–6). Structural analyses can be performed on the whole biomechanical system, and a virtual surgery can be performed in silico (4, 7–9). The engineering methodology considered in this work is multibody analysis coupled to finite element analysis. The multibody analysis allows performing kinematic studies on complex geometries: joint range of motion can be precisely assessed as well as joint stability (9). On the other side, finite element models are required whenever a body cannot be simulated as a rigid body because its deformation plays a crucial role (such as the ischio-pubic symphysis in DPO) and its stress distribution must be analysed in order to avoid failures.

The aim of the current work is to evaluate whether these methodologies can be used to optimize preoperative planning of DPO.

Materials and methods
Three-dimensional geometric model

The bone geometry was derived from CT images of the pelvis of a seven-month-old male Labrador dog with a moderate hip dysplasia, requiring a surgical correction. The following was visible in the CT images:
- 30° reduction angle and a 12° subluxation angle as measured with an electronic goniometer (2).
- 14° DAR, 39.8% acetabular coverage, and 79.7° Norberg angle as assessed from a radiograph of the dog with extended legs (2, 10).
- Distraction index 0.7 as measured from a radiograph with hip distraction, using the Badertscher method (11).

Bone contours were identified by a commercial software, through ‘DICOM’ images segmentation, which was based on grey levels. These contours were then exported to a CAD software program as ‘iges’ files, and three-dimensional bone models were created.

Double pelvic osteotomy and TPO osteotomies were realized by cutting the virtual bone model with plans realized by the CAD software (Figure 1 a).

Partially deformable multibody element model

The obtained geometries were imported into the Multibody software program.

Dealing with boundary conditions, the body of the ilium was connected to the sacrum through the sacroiliac joint and the pubic bone was joined to the opposite hemipelvis by the ischio-pubic symphysis. Both joints are actually amphiarthroses, since they allow a limited range of motion;
in DPO. The femur was left free to translate along all three orthogonal directions, and it could rotate around its own longitudinal axis (internal/external rotation). The two remaining rotations (flexion/extension and abduction/adduction) were not allowed, thus simulating the action performed by the surgeon.

Soft tissues were simulated by springs, the mechanical behaviour of which being described by a piecewise function. This function is called piecewise because it has a different analytic formulation, according to strain levels, as reported in the following formula (15):

\[
f(\varepsilon) = \begin{cases} 
\frac{1}{4}k\varepsilon^2 & 0 \leq \varepsilon \leq 2\varepsilon_l \\
K(\varepsilon - \varepsilon_l) & \varepsilon > 2\varepsilon_l \\
0 & \varepsilon < 0
\end{cases}
\]

Where \( f \) was the force in the ligament, \( \varepsilon \) is its elongation, \( 2\varepsilon_l \) was the elongation value at which the ligament moved from the 'toe' region to the linear region of the stress-strain curve (\( \varepsilon_l = 0.03 \) was assumed from Comerford and colleagues), and finally, \( k \) was the elastic constant of the ligament, obtained by the following formula (16):

\[ K = E \cdot A \]

Where \( E \) was the ligament Young's modulus, set equal to 248 MPa, as estimated by Rice and Amis for human ligaments, and \( A \) was the ligament cross-sectional area (17).

Contact constraints were simulated through a function able to model a unilateral constraint, where a non-null force was generated only when two bodies interfered (18). Contact constraints were placed between the femoral head and the acetabular cavity as well as between the cranial part of the plate and the surface of the iliac wing. The simulation ended when the cranial side of the plate lay on the pelvic bone.

In contrast to TPO, the simulation of DPO required taking into account the deformability of the ischiatic table; therefore this bone was to be modelled as a flexible body. Adams multibody software allows the study of flexible bodies using an integrated finite element solver ('Adams Flex' module), based on a modal decomposition technique; this approach remains valid as long as the deformation behaviour is linear.
Finite element modelling requires the knowledge of material properties: bone Young's modulus was set equal to 1.6 GPa, having considered an immature bone that was still terminating its chondral development; Young's modulus of the steel plate was set equal to 190 GPa; the Poisson ratio was set equal to 0.3 for both materials.

The DPO simulations were performed, considering a multivariate analysis with the following parameters:

- The angle of rotation of the acetabulum in reference to a neutral (pre-ostectomy) position, for plate angles $\alpha$ (Figure 2a), ranging from 15° to 35° in five degree increments;
- The iliac osteotomy angle $\beta$ (Figure 2b): this angle was varied from $-10^\circ$ to $+10^\circ$, in five steps;
- $0^\circ$ is the orientation of the perpendicular ('s', Figure 2b) to the line joining the lower one-third of the iliac wing to the ischiatic tuberosity, being approximately tangent to the acetabulum in the point where the femur head would subluxate (3, 24);
- The distance between the acetabular centre of rotation and the axis of rotation of the plate ($\Delta y$, Figure 1b): this distance was changed by moving the plate on the ilium from a position aligned to the dorsal profile of the acetabular iliac segment to 5 mm in the ventral direction (Figure 2c), in six steps, with increments of 1 mm.

Additionally, five TPO simulations have been performed, considering a 20° plate, $\beta$ ranging between $-10^\circ$ and $10^\circ$, and a null plate offset ($\Delta y = 0$ mm), which is considered in literature as a reference (24).

The total number of performed numerical experiments was equal to 155.

At the end of each simulation, the following indices, which are commonly used in the clinical practice to assess hip stability, were calculated:

- The percentage of acetabular coverage (PC): PC was evaluated on a ventrodorsal view with the femoral head congruent to the acetabulum. On such a view, the dorsal edge of the acetabulum divides the femoral head in two parts. PC was defined as the ratio of the area of the femoral head covered by the acetabulum versus the acetabular ventroversion; grey areas represent 'unsafe' conditions (percentage of acetabular coverage $>66\%$ or Norberg angle $>105^\circ$, in relation to this specific patient).
abulum to the area of the entire femoral head represented by a best fit circle. In a congruent hip, femoral head coverage increases with acetabular ventroversion provided by the DPO (10).

- The Norberg angle (NA): this was measured on a simulated ventro-dorsal view, as described in literature (2).
- The acetabular ventral rotation, measured in the centre of the dorsal margin (VV, ▶Figure 3).
- The lateralization of the acetabular segment of the ilium (L, ▶Figure 3).
- The DAR (dorsal acetabular rim) angle (2).
- The moments required to deform the pelvis.
- The maximum strain and the strain distribution at the ischio-pubic symphysis and at the ischiatic table.

Results

In the following, the model outputs for a given patient geometry were reported.

The acetabular coverage and the Norberg angle increased as the acetabular ventroversion grew according to two curves (▶Figure 4). ▶Figure 4a reports the amount of coverage of normal hips as an upper limit curve (PC = 66% for the given patient’s breed) since an excessive femoral head coverage can produce an impingement between the acetabular lateral margin and the femoral neck, causing internal limb rotation during walking and subluxation with abduction (10, 22). Similarly, ▶Figure 4b reports a lower limit value for Norberg equal to 105° since this angle should always be equal to or larger than 105° for joint stability (10). Curves reported in ▶Figure 4 allowed the assessment of the acetabular ventroversion range which may be acceptable in order to identify surgical parameters through the curves reported in ▶Figure 5 to ▶Figure 7. Referring to ▶Figure 4, the ventroversion should range between 14° and 17° because this range leads to a PC less than 66% and an NA more than 105° for the examined case.

The increment of acetabular ventroversion obtained by different plate angles was reported in ▶Figure 5. According to the model, results obtained by 25° DPO plate were the most similar to 20° TPO. However, it should be stressed that also the distance between the acetabular centre of rotation and the axis of rotation of the plate played a role: in the examined case, the 25° plate needed to be displaced 1 mm ventrally in order to produce results close to 20° TPO.

The acetabular lateralization was reported in ▶Figure 6. It should be emphasized here that the lateralization is a multivariate function as it depends not only on parameters through the curves reported in ▶Figure 5 to ▶Figure 7. Referring to ▶Figure 4, the ventroversion should range between 14° and 17° because this range leads to a PC less than 66% and an NA more than 105° for the examined case.

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The acetabular lateralization was reported in ▶Figure 6. It should be emphasized here that the lateralization is a multivariate function as it depends not only on
the plate inclination, but also on the iliac osteotomy angle as well as the plate offset. The DAR angle (Figure 7) should always be kept negative. The 20° DPO plate allowed us to respect this condition, unless its position was aligned to the dorsal profile of the acetabular ilium segment, and a positive iliac osteotomy angle was chosen (25). The 15° DPO plate could be very critical for what concerned the DAR angle.

As said above, according to Figure 4, the acetabular ventroversion should range between 14° and 17° in order to accomplish both the Norberg angle limit (>105°) and to best approximate the physiological acetabular coverage (approximately 67% for the examined patient). In the following step, configurations leading to the highest lateralization and to the lowest DAR could be selected: the 25° plate with the +10° osteotomy line inclination and null offset from the dorsal edge. The last indication was strongly related to the preoperative condition since the ventral offset ‘modulated’ the ventroversion which could be obtained by a given fixation plate (Figure 5).

The model allowed the attainment of an estimate of the moments which the surgeon needed to apply. A 20° plate DPO surgery required a 6.98 Nm torque moment, while a 25° DPO and 30° DPO required an 8.60 Nm and 8.85 Nm torque moment, respectively. Stress analysis through the finite element method allowed assessing the stress and strain distribution. The largest part of ventroversion took place at the pubic symphysis; peak stresses were reached at the ischiatic table and got smaller moving towards the ilium. Stresses became higher for larger plate inclinations, especially considering the largest ventroversion possible (38.55° with 35° DPO plate, −10° iliac osteotomy angle and 5 mm ventral displacement of the plate).

Discussion

This report illustrates the results obtained on one specific canine hip joint and pelvis as its main objective was to assess the potential of a structural model for the preoperative planning of pelvic osteotomies. Therefore, specific numerical outputs reported here have a limited value, while general trends should be observed as well as the relevance and the amount of information which can be derived from the structural model outputs.

Model prediction concerning the similarity of behaviours between the 20° TPO and the 25° DPO agrees with findings of Punke and colleagues who performed procedures on canine cadaveric pelves, and with in vitro radiographic observations by Haudiquet and colleagues (25, 26). The model allowed the more precise establishment of the influence of two more parameters: the angle of the iliac osteotomy and the distance between the acetabular centre of rotation and the axis of rotation of the plate created by the position of the plate on the ilium (Figure 8).
lapse due to ischiatic instability (27). The lateralization of the acetabulum after DPO is related to the iliac osteotomy angle: this aspect has been emphasized by Graehler and colleagues on the basis of experimental tests on cadaveric canine pelves where they considered the reference position (that is perpendicular to the long axis of the pelvis) or positive inclinations of the osteotomy line in TPO, and concluded the reference position was the one producing the least pelvic canal narrowing (21, 22).

Norberg angle has been used as a model output because this measurement has been commonly used in literature, and limit values for the prediction of hip dysplasia can be found. However it should be emphasized that this measurement is being questioned in recent times because it is influenced by joint laxity, sedation, and positioning (28).

Data concerning the estimate of the moments which the surgeon needs to apply can be used to design surgical tools, and select bone plate and screws.

The stress analysis using the finite element method has confirmed evidence re-

Figure 7  Patterns of the dorsal acetabular rim (DAR) angle versus the iliac osteotomy angle for different plate angles and plate offset. The grey area represents ‘unsafe’ conditions. Dy in legend is $\Delta y$.

Figure 8 Von Mises stress distribution (35° DPO plate, –10° iliac osteotomy angle and 5 mm ventral displacement of the plate). A von Mises stress value above 100 MPa would lead to cortical bone failure.
ported by Punke and colleagues who demonstrated the largest part of ventroversion takes place at the pubic symphysis (26). Localised stress peaks are not a concern since local plasticization would redistribute stress, and pubic symphysis results are biased by simplified constraint conditions. Therefore, the most critical region is located at the ischiatic table and arch: here the bone may fracture in extreme conditions (very large ventroversion), as confirmed sporadically by the clinical practice (2). Another critical aspect is given by the risk of screw pull-out; a more specific stress analysis should be performed to check that the ultimate bone stress is not reached with a reasonable safety factor (2).

It should be emphasized that calculated stresses and moments are strictly related to material properties, therefore their values need to be carefully discussed and possibly validated through full-field experimental stress analysis (30). Referring to stretched ligaments, one critical assumption is that the Young’s modulus for canine hip ligaments is equal to the human PCL (posterior cruciate ligament) one; however the adopted value has resulting values of ligament stiffness that are in agreement with values experimentally measured on the dog (17, 31).

A model like the one developed here could be semi-automatically built, both from CT images and by deforming a standard three-dimensional model on the basis of geometric features as taken from radiographs, since CT scans are actually confined to research purposes as they are not commonly available in the clinical practice (5, 6). The realization of the numerical model from CT scans requires 10–15 hours since the three-dimensional bone geometry can be obtained automatically, but an operator is still required for optimization of the finite element mesh, and to individuate reference planes and axes on the bone as well as ligament insertion points. Once the model has been realized, it can run on a personal computer, and the output of a given combination of surgical parameters can be foreseen in a few seconds by the surgeon without the intervention of specifically trained personnel. The routine use of this model is not currently foreseeable though it can certainly be of support when studying very complex cases and for research purposes.

The model could benefit from specific mechanical tests performed on hip joint ligaments in order to allow a more precise determination of these properties along with their variability among breeds.

Conclusions

This research work has demonstrated how a structural model of the hip and pelvis can be implemented as a guideline for the surgical execution of DPO for the correction of hip dysplasia and to foresee the respective outputs in the immediate postoperative time period; among these, the acetabular ventroversion and lateralization, the NA and DAR angles as well as the bone peak stress. This work focused on canine hip dysplasia, however the methodology introduced here can be transferred to other joints and species once the geometrical data and material properties have been updated.

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Author contributions

CB, PC, ALA and AV were responsible for study conception and design as well as data analysis and interpretation. EMZ and MT were responsible for study design, and together with LM, they were also involved with the acquisition, analysis and interpretation of the data. All authors were involved in the drafting or revising of the manuscript and approved of the submitted version.

Conflict of Interest

There are no conflicts of interest to declare.

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