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The effect of boundary constraints on finite element modelling of the human pelvis

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ABSTRACT

The use of finite element analysis (FEA) to investigate the biomechanics of anatomical systems critically relies on the specification of physiologically representative boundary conditions. The biomechanics of the pelvis has been the specific focus of a number of FEA studies previously, but it is also a key aspect in other investigations of, for example, the hip joint or new design of hip prostheses. In those studies, the pelvis has been modelled in a number of ways with a variety of boundary conditions, ranging from a model of the whole pelvic girdle including soft tissue attachments to a model of an isolated hemi-pelvis. The current study constructed a series of FEA models of the same human pelvis to investigate the sensitivity of the predicted stress distributions to the type of boundary conditions applied, in particular to represent the sacro-iliac joint and pubic symphysis. Varying the method of modelling the sacro-iliac joint did not produce significant variations in the stress distribution, however changes to the modelling of the pubic symphysis were observed to have a greater effect on the results. Over-constraint of the symphysis prevented the bending of the pelvis about the greater sciatic notch, and underestimated high stresses within the ilium. However, permitting medio-lateral translation to mimic widening of the pelvis addressed this problem. These findings underline the importance of applying the appropriate boundary conditions to FEA models, and provide guidance on suitable methods of constraining the pelvis when, for example, scan data has not captured the full pelvic girdle. The results also suggest a valid method for performing hemi-pelvic modelling of cadaveric or archaeological remains which are either damaged or incomplete.

1. Introduction

Total hip arthroplasty is considered one of the most successful orthopaedic interventions [1], and its importance is only set to increase with an increasingly aging population. This success has been aided by the continuous development of hip joint replacement designs [2], in terms of strength to support loads while limiting stress shielding to the surrounding bone [3], material choice [4] and method of fixation [5]. Evaluation of these design factors often utilises computational methods such as multi-body dynamics and musculoskeletal (MS) modelling to predict loading in the normal joint [6–8], and after prosthetic implantation [9]. This has been used in conjunction with finite element analysis (FEA) to estimate stress distributions in the femoral stem [10,11] and acetabular cup [12], wear rates [13] and to assess bone remodelling after implantation [14]. However, to evaluate such factors it is important to understand the force transfer through the hip joint during normal loading conditions.

Modelling of the hip joint must consider the physiology of the pelvis and its associated joints. The pelvis articulates with the femur through the hip joint, and the sacrum via the sacro-iliac joint (SIJ), while the pubic symphysis connects the two hemi-pelves. The hip joint is reported to be a generalised ball-and-socket articulation joint [15] and studies have investigated the biomechanics of the pubic symphysis [16], but less is known about the interaction of the SIJ. The SIJ permits movement in both rotation and translation [17], although there is a ligamentous structure that limits this motion and stabilises the joint [18]. The SIJ is an important link that facilitates the transfer of upper body weight through to the lower limbs. Therefore it is important to model these joints accurately in multi-body dynamic and FEA modelling, in order to accurately predict load transfers and the associated stress distributions.

Previous FEA models of the pelvis vary in complexity and the approaches used to capture the movement at the joints frequently differ between studies. Some studies have taken advantage of the symmetrical nature of the structure and only model the hemi-pelvis, with the SIJ and pubic symphysis constrained in all

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Table 1.
Description of the boundary conditions applied to the FEA models.

Model	Boundary condition
1	Pelvic girdle with constraint applied at the sacrum
2	Pelvic girdle (minus sacrum) with nodes around the circumference of the exterior surface of the SIJ constrained in all DOF
3	Pelvic girdle (minus sacrum and SIJ cartilage) with exterior nodes of the pelvic bone within the SIJ articulation area constrained in all DOF
4	Left hemi-pelvis with the SIJ constrained in all DOF, and the pubic symphysis allowed to translate in a medio-lateral direction
5	Left hemi-pelvis with the SIJ and pubic symphysis constrained in all DOF

Increasing constraint ↓

degrees of freedom (DOF) [19–21]. Coultrup et al. [22] also modelled the pelvis in a similar manner but with symmetric conditions defined at the pubic symphysis. Attempts to simplify modelling of the pelvic girdle have been made by eliminating the sacrum and constraining both SIJs in all DOF [23,24]. In contrast, all of the bones within the pelvic girdle have also been modelled, enabling the pelvis to freely rotate about the sacrum, while connecting the two hemi-pelves through the inter-pubic disc [25,26].

The sensitivity of material properties [27,28] and boundary conditions [25,29–31] considered in FEA of the pelvis has been previously investigated. Phillips et al. [25] and Hao et al. [29] both reported a variation in stress distributions between modelling a constrained SIJ and inclusion of a ligamentous structure. In contrast, Ghosh et al. [30] examined the effect of enabling varying degrees of movement at the pubic symphysis, and found no difference within the stresses of the lateral cortex, but variations were observed medially. However, none of these previous studies examined the sensitivity of simultaneously varying the boundary conditions of both joints. Clarke et al [31] did model the pelvic girdle with ligaments spanning the SIJ and a hemi-pelvis with fixed constraints at the SIJ and pubic symphysis, reporting no significant difference in peak stresses and strains. However, this study was limited in its analysis, considering only the stresses and strains at the acetabulum, and therefore did not investigate the effect on other areas of the pelvis.

This study initially considered an FEA model of the pelvic girdle to predict the stress and strain distributions associated with MS loading. The complexity of this model was subsequently reduced via the application of constraints at the SIJ and pubic symphysis, and the resulting variation in the stress and strain distributions were analysed. This aimed to assess the level to which the pelvic anatomy can be simplified in FEA modelling before the predicted stresses and strains within the pelvis become incomparable.

2. Material and methods

2.1. Musculoskeletal modelling

The forces experienced by the pelvis during walking were predicted using an existing MS model which is freely available from the AnyBody Managed Model Repository v.1.3.1 (AnyBody Technology, Aalborg, Denmark). The model has a detailed representation of the lower extremity, incorporating full muscle wrapping and containing numerous strands for large pennate muscles (e.g. the glutei and iliacus), in order to capture numerous lines of action. The model is driven by three-dimensional (3D) motion capture data, which includes accompanying ground force reactions, of two successive gait cycles (heel strike–heel strike). Simulations were performed in the AnyBody Modelling System v.5.0, which utilises inverse dynamics to compute muscle and joint forces associated with the motion capture data.

A single gait cycle was then analysed which consisted of a left-legged stance phase, and the forces of 22 muscles spanning the hip joint were recorded for the left side. The accompanying resultants of the hip joint reaction force were also recorded. Two load regimes were subsequently created which corresponded to phases of the gait cycle containing the largest hip joint reactions, in this case: at initial heel strike (~15% of the gait cycle); and, just before toe-off (~48% of the gait cycle). Hereafter these load regimes are referred to as the 15% loading regime and 48% loading regime.

2.2. Finite element modelling

The CT dataset of the male visible human [32] was digitised in AVIZO image visualization software v.6.3 (Visualization Sciences Group, Burlington, MA, USA) and segmented to create a solid 3D volumetric model which comprised of the two hemi-pelvic bones, sacrum, SIJ cartilage and inter-pubic disc. This volumetric model was meshed within AVIZO with 10-node tetrahedral elements. The mesh was subsequently imported to ANSYS v.14.5 (ANSYS Inc., Canonsburg, PA, USA), where 6-node triangular shell elements were clad around the pelvic bones to represent the cortical bone. In total, the model of the pelvic girdle consisted of 389,795 elements (385,924 representing bone and 3871 representing cartilaginous material).

Five separate FEA models were constructed to investigate the effects of different boundary conditions, and the validity of modelling only the hemi-pelvis in comparison to the full pelvic girdle (see Table 1). The models were a gradual simplification of the most complex scenario (Model 1) which contained the pelvic girdle and constrained nodes located on the superior surface of the sacrum in all DOF (see Fig. 1(a)). This was simplified by eliminating the sacrum to create: Model 2 where 10 nodes around the circumference of the exterior surface of the SIJ were constrained in all DOF; and Model 3 where the cartilage was eliminated and the exterior nodes of the pelvic bone within the SIJ articulation area were constrained in all DOF (see Fig. 1(b)). This allowed the influence of pelvic rotation about the SIJ to be examined. The pelvis was then further simplified by eliminating the right hemi-pelvis and connecting cartilaginous material, and creating two left hemi-pelvic models: one with the exterior nodes of the pelvic bone in the SIJ articulation region constrained in all DOF and the exterior nodes at the pubic symphysis permitted to move in medio-lateral translation only (in order to simulate the natural widening of the pelvis) (Model 4); and another, with the exterior nodes of the pelvic bone in the SIJ articulation region and pubic symphysis constrained in all DOF (Model 5) (see Fig. 1(c)).

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