Lower Limb Design for a Child Test Dummy, based on Osteogenesis Imperfecta characteristics

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Abstract. Active and passive safety have played an essential role in solidifying ground transportation. However, safety-focused on children with some rare diseases is little attacked. This article shows the design of a diseased leg prototype into a crash test dummy Q3, the novelty of this work is based on the morphology and biocompatibility of the lower limbs, which principal characteristics of this prototype replicate the shape of a child with bone-degenerative diseases. In this work, it shows the essential features that a child dummy of this type must contain in order to generate a homologation and approval under the strictest passive safety standards used in the automotive industry. Results show the important kinematics parameters and CAD bones development necessary to conform a new numerical crash test dummy prototype.

1. Introduction

The development of researches on the impact kinematics in traffic accidents starts from the general, showing the behaviour of the human body protected by passive safety that a vehicle has (restraint systems), in this way, the crash test dummies have been developed anthropomorphically to simulate the behaviour of the human body during a collision. Unfortunately, exceptional cases where people with disabilities are involved in a vehicular incident are left aside, especially children. In medical diseases theory, rare illnesses on bones affect to a specific percentage of people around the world; some of this quantity is related to children who have a bone disease at birth. The most severe bone disease is osteogenesis imperfecta OI, rickets, scoliosis, rheumatoid arthritis, among others where morphology is abnormal. For example, some children have column, vertebrae, thorax, skull, or long limbs deformities depend on the chronic level disease. Most children with this type of illness do not exceed 90 centimetres in height [1]. Due to these ailments, parents should use custom homemade child carrier systems to transport their patients. Nevertheless, these homemade systems have not a good design to protect children integrity efficiently. Some researchers have tried to adapt different sizes of child dummies limbs taking from different age dummies [2]. However, those studies cannot represent good bio-fidelity. It is relevant to mention that the mechanical properties of bones affected with Osteogenesis Imperfecta OI are critical to adapt at lower limbs in a child dummy prototype. Thus, compression tests are useful to evaluate fractures in traffic accidents [3]. For this reason, it is crucial to develop researches on the best way to transport children with bone deformities, low bone density and significant bone fragility [4]. Child dummy with bone diseases morphology is quite necessary to reach that population that until today
have not been considering in the crash tests [5]. The main objective of this study is to fit a lower limb bone with the geometry of a Q3 dummy pelvis, to carry out tests of a frontal or a lateral collision considering population with OI.

2. Virtual bone geometry development

Crash test dummies of different age have been developed to define a better way to approach a more reliable bio-fidelity to the human body behaviour in a collision scenario [6]. Q series has the main characteristics of measure speed, acceleration and loads on head, thorax, and hips. Notwithstanding, children with bone diseases have the particularity characteristics of having acute frailty, which implies that the long limbs are areas of high risk to present injuries due to fractures in the long bones. This new dummy prototype considers measuring long limb, unlike Q series dummies. However, not only it is enough to add load and speed sensors to the extremities, but long legs with the geometry of the bones like what a child with OI would be developed. Computational Tomographic CT of a three years old child who has osteogenesis imperfect level II was used [5]. Software to process CT images (Scan IP) was used to create stereolithography (STL) bones file (see Figure 1). This STL file offers a mesh that can be refined to get a better STL image (Scan FE). STL file was exported to CAD software to create accurate surfaces that generate a solid model with excellent quality in its geometry that will later be reflected in bone mesh suitable for numerical analysis.

![Figure 1](image1.png)

**Figure 1.** a) Q3 dummy virtual model (4). b) Stl skeleton with osteogenesis imperfecta [7].

An adequate development of the bones from mesh STL image is essential to customize the real geometry of the bones by surfaces making with CAD software. Figure 2 shows the applied process in the femur. This process was replicated in the entire leg that includes the femur, tibia, and fibula bones.

![Figure 2](image2.png)

**Figure 2.** Femur bone CAD process, a) STL model from Scan IP software, b) Mesh model from Scan FE software, c) Surface model from CATIA software, d) Solid model from CATIA software and e) CAD adaptation model to join femur with hip part.
Deviation analysis was carried out to validate the bones geometry with the STL geometry, respectively as it is shown in Figure 3, where one can observe that bones shape has a minimal deviation respecting with STL geometry. The creation of solid models of long bones will have excellent quality in future finite element analysis.

![Figure 3](image)

**Figure 3.** Deviation analysis of the bones, a) Femur, b) Tibia and c) Fibula.

Keeping good surface quality on each bone will help later when a mesh on a CAE software would have be defined with better control, and consequently with a correct delimited numerical analysis.

### 3. The mathematical formulation of Scale Model

The original femur conforms by a structural bar has a measurement of 230 mm while the length femur STL is just 130 mm. Therefore, it is necessary to get a scale to find a housing parameter and knee join dimension. Hence, taking both aspects (Q3 Femur and STL femur), it is possible to make a scale definition between both measurements. Table 1 shows the scale factor estimated to build all mechanical components, to ensure contacts and assembly with a real bone with OI for Q3 dummy.

| SCALE | Dimension | Element         | Femur with OI | Q3 Dummy Femur |
|-------|-----------|-----------------|---------------|----------------|
| 01:01 | 230 mm    | Dummy (PDF)     |               |                |
| X     | 130 mm    | Bones (STL)     |               |                |
| DIV   | 0.565     |                 | 130 mm        |                |
| X     | 0.57      |                |               |                |

According to the previous table and taking into account the length values of the Q3 Dummy femur and femur with OI, a scaling factor of 0.57 was established, so that, hip and knee join dimensions will change to adapt the new bones to the mechanical parts of the Q3 dummy. This scale factor helps to adjust any mechanical part corresponding to the low limb’s union. In this way, the proportion among, bones, joining and dummy hip will look as good as possible.

### 4. Q3 dummy hip adaptation

Q series characteristics were used to perform lower limb at child dummy assembly (See Figure 4). To design a hybrid prototype (Q3 project and OI bones geometry) was necessary to scale joins among the bones. Unlike the original model, where the joints are unaffected due to the simple geometry of the structural elements, the linkage of bones through a joint must be adapted to generate mobility that should be most biomechanically compatible with the natural movement of a human lower limb.
Due to several different bone shape, unlike $Q^3$ leg structure, joint adaptation must be according to knee medical prosthesis. In this way, this option provides a contact among mechanical components and bones, which will help to future numerical analysis. Based on the *Tibial Modular Replacement System medical* manual [7], the optimal coupling of the mechanical components of the knee joint was carried out by sculpting the base of the femur, depending on the shape of the femoral component and the rotational tibial component. In this way, it was possible to control mobile restrictions of the knee joint.

Knee femoral coupling was designed base on a commercial knee prosthesis. However, The Tibial Modular Replacement medical manual does not specify the position, angle and cuts applying to people who suffer bones diseases. In order to fix this problem, computational tomography was used, because, by this way, it is possible to use *STL* file as a 3d map to position all leg bones in the same child leg position. Once established the correct position, section cuts are generated on the femur base to adapt the femoral component. This process is performed with boolean operations to remove material from the bone, respecting the symmetrical geometry of the femoral component (see Figure 5b and 5c)). In the same way, Femur head and Tibia were modified to adapt simple geometries. This process will provide better control over constraints during the assembly process.

5. Results

All the process to perform each bone into a 3d model from CT is complicated and time-consuming, but this allows high-quality customization that will later facilitate mesh generation and numerical analysis without significant complications. Measurements such as the height or the length of the long limbs of a child with OI compared to a child without deformities are sizeable. For this reason, the scaling of the joints in both connections (knee and pelvis) were crucial. Medical techniques used in joint replacement have been taken as the basis for the generation of appropriate joints in OI lower limb dummy prototype. Cuts section made in the bones could affect the structural rigidity of these extremities, but thanks to this change in the geometry of the bone joints, the constrains of movement and position of the entire
assembly could be controlled. Figure 6 shows the CAD results done in the joints bones to adapt real OI bones geometry to the Q3 dummy mechanical components (in this case to the Hip).

Figure 6. Bones adaptation with dummy Q3 hip a) Q3 dummy Hip, b) Femur head adaptation with hip housing and c) Knee adaptation.

In Figure 6, it is possible to see hip characteristics and femoral head adaptation done to join bone shape to hip coupling and knee coupling adapted to Femur and Tibia. This result demonstrates a methodology for generating organic geometries and adapting them to a functional product such as the Q3 dummy.

6. Conclusion
Feasibility analysis for coupling the geometry of a real femur with a spherical mechanical assembly has a high difficulty degree in trying to fit irregular geometries into a universal joint. However, the intuitive use of 3d processing software makes it possible to model and assemble organic geometries with mechanical geometries. This process offers a practical and straightforward solution for the development of biomechanical models closer to the kinematics movements of the joints. In relation with numerical analysis, the intricate process to develop high quality bones geometries allow performing dynamics analysis with high precision to understand the kinematic parameters that govern the physics phenomena during the crash tests. In addition, 3d printing offers a low-cost process and several possibilities to create complex products with a great variety of composite materials with adequate mechanical resistance which allows withstanding large amounts of energy. All this new experience in dummies development could transform the way of how passive and active safety in the automotive industry is researching. Finally, it can be concluded that the development of this kind of numerical models can offer validations of new child restraint systems [8], new prototypes child seat with shocks absorbers or evaluate different passive safety tests under various crash scenarios [9] and [10].

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