CT BASED MODELS FOR MONITORING BONE CHANGES IN PARAPLEDIC PATIENTS UNDERGOING FUNCTIONAL ELECTRICAL STIMULATION

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ABSTRACT
Spinal Cord Injured (SCI) paraplegics suffer from pathological changes in the lower extremities such as muscle degeneration, hormonal alterations and bone resorption. The aim of the present study was, with the help of finite element and image analysis, to evaluate the osteogenic response of the patella of paraplegic patients undergoing Functional Electrical Stimulation (FES). For this purpose, a patient that began a daily home based FES treatment 5 years after paralysation was monitored. Bone mechanical parameters were compared at the beginning of FES and after 3 years of treatment.

According to our results, it is possible to conclude that application of long term FES treatment on denervated, degenerated muscles can be beneficial for bone growth in bones attached to the stimulated muscles.

Keywords: Finite Element Modelling, Functional Electrical Stimulation, Flaccid Paraplegia, Bone Strains, Patella.

1. INTRODUCTION
Spinal Cord Injured (SCI) paraplegics suffer from pathological changes in the lower extremities, such as muscle degeneration, hormonal alterations and bone resorption (Maïmoun et al 2006). Loss of bone mineral density (BMD), which is one of the symptoms of osteoporosis (Marcus et al 2008), results in bones becoming more fragile, with an increased risk of fracture in the paraplegic’s extremities as a consequence (Maïmoun et al 2005; Lazo et al 2001; Jiang et al 2006). In order to decrease this acceleration of tissue deterioration, electrotherapy such as Functional Electrical Stimulation (FES) has been proposed (Gargiulo, 2008; Gargiulo et al 2009, 2011; Kern 2002, 2005; Gallasch & Rafolt et al 2005; Mandl et al 2008). However, recent studies claim that the lack of osteogenic response in paralyzed extremities to electrically evoked exercise during sub-acute and rehabilitation/recovery phases, could not be fully explained, and may warrant further evaluation (Clark et al 2007).

CT data can be used to monitor bone changes in paraplegic patients by quantification of morphological parameters. Additionally CT based finite element models can provide useful information on the structural changes that result from the changes in bone morphology when direct mechanical testing is not possible. The absence of mechanical stimulation in the lower extremities of paraplegic patients makes the patella bone, ideal for monitoring such changes resulting directly from external stimulation.

The aim of the present study was thus to perform a CT based evaluation of the osteogenic response of the patella of paraplegic patients undergoing FES.

2. MATHERIAL AND METHODS
A pre-treatment CT dataset of the lower extremities for a paraplegic patient (a 32 year old male suffering
complete flaccid ThXI syndrome with paralysis and areflexia in the legs and medium atrophy) was used to create a FE model of the patient’s right patella. A QUASAR phosphate phantom (Modus Medical Devices Inc., London, Ontario, Canada) was used to calibrate the images. The construction of the FE model was carried out in several steps briefly explained as follows:

I) Creation of a 3D triangular surface mesh (STL) through semi-automatic segmentation in MIMICS (Materialize Interactive Medical Image Control System, Leuven, Belgium) using a Hounsfield (HU) threshold of 200 to determine the boundary between bone and soft tissue. II) Creation of a solid model (IGES) in SOLIDworks (Dassault Systèmes SolidWorks Corp., Concord, Massachusetts, USA). III) Creation of a 10-node tetrahedral FE mesh in ANSYS Workbench (ANSYS, Canonsburg, Pennsylvania, USA). IV) FE model imported into ANSYS (ANSYS, Canonsburg, Pennsylvania, USA), where FE equations are solved.

Rigid boundary conditions were applied at the patella ligament and the patella tendon attachments points. Force ($F_r$) was applied on the model were the distal femur contacts the patella. For determining this force a biomechanical model of the knee joint (Ward 2004; Ward 2005) was used. The joint moments were measured during stimulation at the beginning and three years into the FES treatment, with a non invasive pendulum test (Gallasch & Rafolt et al 2005). Moment arms and force directions in the sagittal plane were derived from the CT data.

Isotropic, linear elastic, heterogeneous material properties were assigned to each node in the model with an in-house MATLAB script (The Mathworks, Natick, MA) based on the NI material mapping method introduced by Helgason et al. (2008b). The relationship (1) between Young’s modulus ($E$) and apparent bone density ($\rho$) was taken from Morgan et al. (2003):

\[ E = 6850\rho^{1.49} \text{(MPa)} \]  

Poisson’s ratio was set to 0.3.

A CT dataset acquired after 3 years of daily home based FES treatment was also available for the same patient. Using the procedure described above, this CT dataset was used to create another FE model for comparison to the pre-treatment situation. After FE simulations, the equivalent Von Mises element strains were derived from the FE solutions and compared as shown in Fig. 1. Additionally, Young’s modulus distribution, patella bone total volume, weight and average Young’s modulus were derived directly from the CT data as shown in Fig. 3 and Tab. 1. A third CT dataset of a healthy, 37 year old male was available for comparison to the patient results but FE simulation was not carried out for this individual.

3. RESULTS

The maximum load on the patella during FES, derived from the biomechanical knee model, was found to be $F_r = 60\pm2$ N at the start of FES treatment and $F_r = 123\pm3$ N after 3 year of FES treatment. The volumetric strain histograms derived from the FE simulations are illustrated in Fig. 1, with a Frost interval of [200, 2000] micro strains (Frost HM, 1987) and, Rubin and Lanyon threshold of 1000 micro strains, (Rubin & Lanyon, 1987) indicated but these authors reported these thresholds being relevant for maintaining bone mass. 71% of the total bone volume was found to be strained beyond 200 micro strains and 5% beyond 1000 micro strains at the start of FES treatment. The corresponding results after three years of FES were 71% and 19%. The calculated patella weight (mg), bone volume (mm$^3$) and average Young's modulus (MPa) per element are presented in Tab. 1. Fig. 2 and 3 illustrate a comparison between the Young’s modulus distribution for the healthy subject and the patient before and after FES treatment.

![Figure 1](image1.png)
1. Patella of a healthy subject. 2. Paraplegic patient after 5 years of paralysis. 3. Same Paraplegic patient after 5 years of paralysis and 3 years of FES treatment.

<table>
<thead>
<tr>
<th>Sets</th>
<th>Weight (mg)</th>
<th>Average Young’s Modulus (MPa)</th>
<th>Volume (mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy Subject</td>
<td>7210</td>
<td>2490</td>
<td>14100</td>
</tr>
<tr>
<td>5.y of paralysis</td>
<td>4820</td>
<td>790</td>
<td>13100</td>
</tr>
<tr>
<td>5.y of paralysis and 3 y of FES</td>
<td>5340</td>
<td>960</td>
<td>13600</td>
</tr>
</tbody>
</table>

Table 1. Trabecular bone quantities (HU range 200-1000 HU); Total weight (mg), average Young’s (MPa) and total volume.

4. CONCLUSION
The aim of the present study was to evaluate the osteogenic response of the patella of a paraplegic patient undergoing FES using the finite element method and image analysis. The results, as shown in Fig. 2, indicate that bone strain stimulus at the start of treatment was sufficient for bone formation according to published thresholds for bone maintenance (Rubin & Lanyon 1984 and Frost 1987). The results also indicate, that even after 3 years of FES treatment, strain stimulus was larger than was found at the beginning of treatment. This suggests that there is potential for further bone formation.

Comparing the stiffness for the pre- and post-treatment situation as shown in Fig. 3, indicates that during FES the bone is adapting to the loads being applied, especially at the patella ligament and
quadriceps femoris insertion points. The trabecular bone appears to adapt to the load increase by increasing both mass and volume which results in increased average Young's modulus. However, the influence of long term disuse on the cortical shell can clearly be seen in Fig. 3, where Young's modulus distribution in the patella for the healthy and paralysed subjects is compared.

According to our results it is possible to conclude that application of long term FES treatment on denervated degenerated muscles can be beneficial for bone growth in bones attached to the stimulated muscles.

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