A TIME-EFFICIENT METHOD FOR ANALYZING BONE STRAIN WITH LARGE SUBJECT POOLS

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INTRODUCTION

Bone strain is a useful measurement when investigating overuse injuries such as stress fracture [1]. In-vivo data for bone strain is difficult to obtain due to the invasiveness of surgical procedures and even when such studies can be conducted, interpretation of data from implanted strain staples and gauges is non-trivial [2].

Due to the difficulties in measuring in-vivo strain there has been some momentum in utilizing numerical modeling methods to investigate strain. Finite element modeling (FEM) has been used in past investigations in conjunction with mechanical testing of cadaver specimens to investigate certain aspects of bone stress and strain. This methodology is quite time consuming computationally, however, and can be difficult to use in conjunction with subject-specific kinematic and kinetic data, thus limiting its application in investigations requiring large subject pools.

Recent work has been done to overcome the computational time and de-coupling of FEM inputs by Al Nazer and Klodowski using a flexible body in conjunction with a subject-specific musculoskeletal model [3]. The data and methods presented in these papers still suffer from limitations of small sample size and using simulation-generated ground reaction forces, however, and do not present methods to manage large sets of data.

It is the purpose of this paper to present a time-efficient methodology of calculating bone strain utilizing subject-specific tibial geometry and material properties derived from computed tomography (CT) scans and musculoskeletal models driven by experimental kinematic and kinetic inputs. Data and computational times from a single subject and gait trial will be presented as an example of how this methodology can be used with implications for automation across large cohorts.

METHODS

A representative subject from a larger study on tibial stress fracture was used to describe this process. All experimental procedures were approved by the University’s Institutional Review Board and the subject signed an informed consent form. The subject was a 21 year old male.

CT scans were collected for the entire length of the tibia using a GE Light Speed VCT (General Electric, USA). Images were segmented in Mimics 12.1 (Materialise, Belgium), a surface mesh automatically generated, and a 3mm³ solid hexahedral mesh generated from that surface mesh using MD MARC 2008 (MSC.Software, Santa Ana, CA). An automated custom MATLAB routine was used to assign material density and elastic modulus to each individual element of the mesh based on the average Hounsfield unit value of the pixels contained within each element; this process was automated across the full cohort for the larger study as well. Six hundred material properties were used in this assignment with 300 each being considered cortical bone [4] and 300 cancellous [5].

Motion capture data were collected using a cluster-based marker set at 120Hz while the subject walked at 1.67m/s on an in-line AMTI force instrumented treadmill collecting analog data at 2400Hz.

A scaled lower-body model was built using LifeMOD 2008.2805 (Lifemodeler, San Clamente, CA) based on the subject characteristics [6]. Twenty three muscles were then added to the right leg [7]. The tibia constructed in MARC was then exported
and manually aligned in the musculoskeletal model using digitized landmarks. Relative locations of relevant attachment sites were then exported and applied to the FEM tibia in MARC using an automated Python script and a Craig-Bampton modal analysis performed with 6 degrees of freedom applied to each “joint” node. This process was automated using the MD ADAMS command language and references to text files containing subject characteristics and tibia node numbers.

An inverse-kinematic (IK) trial was performed using experimental trajectory data to set kinematic goals for muscle and joint controllers and then the modal neutral file imported to align with three known points in the musculoskeletal model. The rationale for using an MNF is described more fully in [8]. A forward dynamic simulation was then performed using inverse-kinematic results as targets and experimental ground reaction forces applied. Strains were then calculated using the Durability plug-in for MD ADAMS/View (MSC.Software, Santa Ana, CA). This IK through strain calculation process was automated using the MD ADAMS command language and automated across the larger cohort using MATLAB and the Windows command line.

RESULTS AND DISCUSSION

Strain and strain rate data generated by the model fall well within expected values for gait. An example stride of strain data is shown in Figure 1 and results summarized in Table 1.

<table>
<thead>
<tr>
<th>Strain Magnitude (Microstrain)</th>
<th>Strain Rate (Microstrain/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max P ( \rightarrow ) Min P</td>
<td>Max ( \rightarrow ) Min P</td>
</tr>
<tr>
<td>395 ( \rightarrow ) -434</td>
<td>829 ( \rightarrow ) Not reported</td>
</tr>
<tr>
<td>Burr et al</td>
<td>-4000 ( \rightarrow ) Not reported</td>
</tr>
<tr>
<td>437 ( \rightarrow ) -544</td>
<td>871 ( \rightarrow ) 11006</td>
</tr>
<tr>
<td>Milgrom et al</td>
<td>-7183</td>
</tr>
<tr>
<td>840 ( \rightarrow ) -454</td>
<td>1183 ( \rightarrow ) 3955</td>
</tr>
<tr>
<td>3955 ( \rightarrow ) -3306</td>
<td>10303</td>
</tr>
<tr>
<td>Al Nazer et al</td>
<td>4000 ( \rightarrow ) -7000</td>
</tr>
<tr>
<td>Present Simulation</td>
<td>490 ( \rightarrow ) -515</td>
</tr>
</tbody>
</table>

Table 1: Summary of strain results compared to previous studies

The methods utilized in this study are time efficient and highly automatable. User interaction is required through software only to segment CT images (though this is largely automated), select nodes for which to compute strain data, and to orient the tibia model within the musculoskeletal model. These tasks collectively take less than one hour per subject for an experienced operator. Simulation times for this method were easily manageable for large groups, taking only 5.5 minutes per 5 seconds of gait. Calculation of strains in Durability took only 0.5 seconds per node for a 5 second gait trial. With well-planned software automation utilizing scripting capabilities of MARC, LifeMOD, and MATLAB, large volumes of data can be handled reasonably for strain studies requiring large sample sizes.

REFERENCES


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