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Robotics and Virtual Prototyping Applied to Musculoskeletal System Analysis

Abstract

- Increases in computational power and advances in the development of computational tools have led to significant advances in the engineering fields.
  - Benefits can been seen in other professional arenas, specifically the biological sciences field, by making use of these developments.
- Introduction of the development of a *Musculoskeletal Analysis Toolkit*.
  - Encompassing the use Robotics and Virtual Prototyping to develop a low-resolution computational model.
  - Such a toolkit would give scientists a physics-based tool with which they can systematically develop and test hypotheses.
- Application to a specific case study.
  - Bite force estimation in members of the feline (large cat) family.
  - Using fossil/ living records (CT scans) the geometry of the skull/ mandible structure of the animal can be analyzed and virtually (re-)created
  - Screw-theoretic modeling methods typically seen in the context of parallel (robotic) manipulators are used to develop a mathematical model of the system.
  - This model serves as the basis of a graphical-user-interface (GUI), which is used as a low-order virtual representation or virtual prototype of the skull/ mandible musculoskeletal system, providing a useful tool under which the forces of the system can be analyzed.

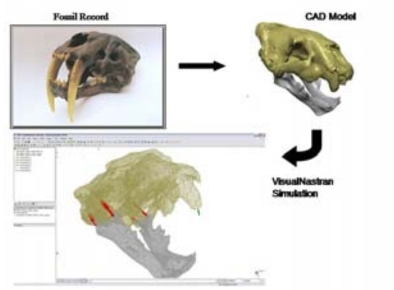
Case Study - Development and Challenges

- The creation and application of such a toolkit are addressed in the development of the case study.
  - Case Study – Bite force estimation in members of the feline family.
  - This study will encompass modeling the skull/ mandible structure and the associated jaw muscles of the feline.
  - Using this model the muscle forces generated by the application of external/ desired bite force are estimated. This information allows an estimate the maximal bite force of the animal.
  - The particular feline that will be the focus of the case study is the extinct Sabertooth Cat.
- Why the Sabertooth Cat?
  - Considerable fossil records exist giving accurate skeletal (geometric) information.
  - Topic of interest among many research groups (science and engineering).
  - Similarities (anatomical) to modern day cats, giving us an approximation of various muscle locations.

- Challenges
  - Virtual (re-)creation – Converting the CT scans of the cats fossil records to an appropriate virtual representation, CAD model, GUI Model.
  - Redundancy resolution – Biological problems inherently exhibit irregularities and redundancies both of which have to be handled by the model.
  - Muscle simplification – Due to the high number of muscles an appropriate muscle representation/ simplification must be developed.
  - Implementation and programming – The model must be implemented in a program to produce a satisfactory user interface, allowing for systematic testing of the model.

Preliminary Simulation

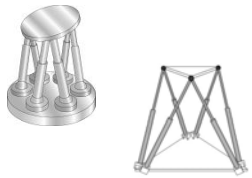
- As a preliminary course of action a virtual prototype and simulation were created using existing computational tools.
  - A virtual model was generated in by converting CT scans of the skull/ mandible structure to CAD model.
  - This CAD model was then exported to a dynamic simulation software (VisualNastran).
  - Constraints were placed on the system in the form of linear actuators (muscles) and a revolute joint (jaw joint).
  - An external force representing the bite force was applied to the system and forward and inverse dynamic simulations were attempted



  - The simulation and analysis of the system met with limitations due the software's inability to handle redundancy – both in terms of resolving redundancy in inverse-dynamics settings as well as in application of redundant forces for forward dynamics simulations
  - As a result of the limitations of the current computational tools the mathematical model and virtual simulation tool were developed.

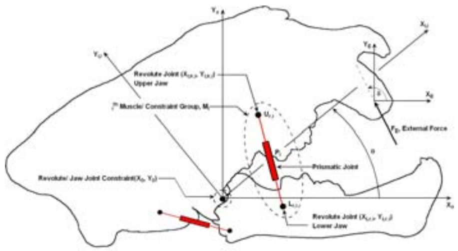
Mathematical Modeling – Set Up

- The skull/ mandible structure of the cat will be modeled using screw-theoretic methods, serving as a low-resolution computational model.
  - This modeling method is typically seen in the context of parallel (robotic manipulators)



- Assumptions - In deriving the mathematical model several assumptions were made.
  - A planar (2 – Dimensional) model is assumed where the skull and mandible are considered to be rigid bodies.
  - The mandible is considered to be grounded in space, and the skull is attached to the mandible via a revolute joint (with axis normal to the display play). Thus, allowing the skull to rotate (purely) with respect to the mandible via the revolute joint (jaw joint).
  - All muscles are simplified and are considered to act along the line of action joining the muscle origin and insertion points.

Mathematical Model



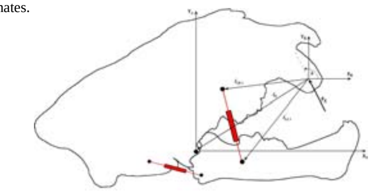
- Model Nomenclature - Developed to represent the muscle, joint, and force characteristics of the model.
- Coordinate Systems
  - *Inertial (Fixed)Frame,* (X_O, Y_O) - Fixed in space and is the principal calculation frame of the model.
  - *Upper Jaw Frame,* (X_U, Y_U) - Attached to the skull (upper jaw) and is related to the inertial frame through the *jaw gape angle,* θ.

$$
{}^{U}\mathbf{R}_{O} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad {}^{O}\mathbf{R}_{U} = \left[{}^{U}\mathbf{R}_{O}\right]^{-1}
$$

  - An *Inertial End Effector Frame,* (X_E, Y_E) - Created with the application point of the external/ desired or bite force, F_E - Applied at the origin of the end effector frame $({}^{U}X_F, {}^{U}Y_F)$ at an angle δ

$$
\vec{F}_E = \begin{bmatrix} F_E \cos(\delta) \\ F_E \sin(\delta) \end{bmatrix}
$$

- Muscle Modeling - Each muscle consists of a revolute joint on the upper jaw ($U_{r,i}$), a revolute joint on the lower jaw ($L_{r,i}$), and a prismatic joint (P_i).
  - Hence each muscle is modelled as a *Revolute-Prismatic-Revolute* (RPR) serial chain manipulator.
  - A total of n_m such muscles are assumed to couple the upper and lower jaws.
- Screw Coordinates/ Representation - The various motions of the system as well as the external bite force may also be expressed in terms of screw coordinates.



  - Finding the total end-effector twist created by each RPR chain the screw coordinates of each muscle (RPR) can be calculated.

$$
\$_{T,E} = [\mathbf{J}_i]\dot{\Theta}_i
$$

End-Effector Twist Matrix

$$
\mathbf{J}_i = \begin{bmatrix} \hat{\$}_{Ur,i} & \hat{\$}_{P,i} & \hat{\$}_{Lr,i} \end{bmatrix}
$$

3x3Jacobian matrix whose column vectors represent the unit screws associated with each joint

$$
\hat{\$}_{Ur,i} = \begin{bmatrix} \hat{z}_{Ur,i} \\ \vec{\ell}_{Ur,i} \times \hat{z}_{Ur,i} \end{bmatrix} \quad \hat{\$}_{P,i} = \begin{bmatrix} \vec{0} \\ \hat{z}_{P,i} \end{bmatrix} \quad \hat{\$}_{Lr,i} = \begin{bmatrix} \hat{z}_{Lr,i} \\ \vec{\ell}_{Lr,i} \times \hat{z}_{Lr,i} \end{bmatrix}
$$

- Reciprocal Wrench Formulation:
  - The selectively non-reciprocal screws (SNRS) associated with each active-joint for the given muscle are calculated

$$
W_{k,i} \otimes \$_{j,i} = 0, \forall k, j = \{U_r \quad P \quad L_r\}, k \neq j
$$

  - Collecting the SNRS for the prismatic joints of all serial chains and the SNRS for the single revolute jaw joint (W_0) we get.

$$
\begin{bmatrix} | & | & | & | & | \\ W_0 & W_{p,1} & W_{p,2} & \cdots & W_{p,n_m} \\ | & | & | & | & | \end{bmatrix} \begin{bmatrix} f_0 \\ f_1 \\ \vdots \\ f_{n_m} \end{bmatrix} = \begin{bmatrix} M_z \\ F_x \\ F_y \end{bmatrix}
$$

$$
= [\mathbf{W}]_{m\times(n_m+1)} \{\mathbf{f}\}_{(n_m+1)\times 1} = \$_w
$$

  - Solving the above equation for {**f** }, the forces associated with each prismatic joint and the reaction forces at the jaw joint are found.

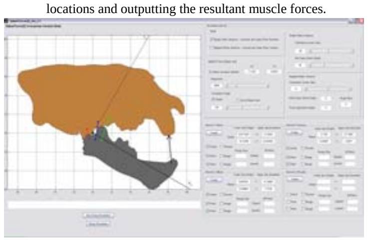
$$
\vec{\mathbf{f}} = \mathbf{W}^{\#}\$_w + \left[I - \mathbf{W}^{\#}\mathbf{W}\right]\vec{\mathbf{z}}
$$

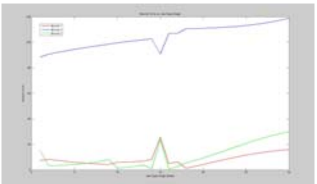
$$
= \mathbf{f}_p + \mathbf{f}_H
$$

  - $\mathbf{f}_p$ and $\mathbf{f}_h$ can be interpreted as equilibrating and interaction force fields respectively and by adding multiple of the interaction force field (i.e. modifying **z**) it can be ensured that the muscle forces are all positive.

GUI Implementation

- Implementing the mathematical model in as the basis of the GUI a low-resolution computation tool is developed
  - Enabling the user to easily choose the muscle and external force locations and outputting the resultant muscle forces.





Future Work

- Future work will involve expansion of model to encompass 3-D and the creation of a mechanical prototype for Hardware-in-the-Loop testing.

Related publications: Del Signore, M., Krovi, V., "Virtual Prototyping and Hardware-in-the-Loop Testing for Musculoskeletal Systems Analysis" – Submitted to the Proceedings of the 2005 IEEE International Conference on Mechatronics and Automation, Niagara Falls, Ontario, Canada, July 2005.

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