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Virtual Prototyping and Hardware-in-the-Loop Testing for Musculoskeletal System Analysis

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Abstract:

In this paper, we present some ongoing research in the development of tools for biological hypothesis testing, leveraging research methodologies that have revolutionized the mechatronics domain. In particular, this work emphasizes: (a) development of suitable low-resolution computational models (b) simulation, testing and iterative what-if studies performed using virtual prototyping; and (c) development of a test-bed suitable for hardware-in-the-loop testing. We anticipate that such a coupling of computational analysis with development of hardware-in-the-loop simulations will play a significant role in rapid and systematic validation of biological hypotheses. Specifically in the context of musculoskeletal system analysis, we focus on presenting two aspects in greater detail: (i) development of a low-resolution screw-theoretic computational model; and (ii) development of an Integrated Framework for rapid virtual prototyping and hardware-in-the-loop testing. A case study of Bite Force Estimation in members of the felid (cat) family helps unify the presentation of many of these aspects.

Index Terms – Virtual Prototyping, Hardware-in-the-Loop, Musculoskeletal system, screw-theoretic modeling

I. INTRODUCTION

In recent years, every scientific arena has benefited from the ubiquitous availability of computational power and advances in creation of computational tools. While engineering related fields have witnessed the greatest benefits, these advances have percolated down far slower into other arenas. In particular, in traditional biological sciences such as anatomy, the lack of significant and useful computational tools hinders the ability of scientists to effectively and rapidly test various hypotheses in a rigorous and quantitative manner.

At this point we would like to note that in recent years, virtual prototyping and hardware-in-the-loop testing methodologies have revolutionized the process of design, analysis, and validation of various electromechanical and mechatronic systems. By virtual prototyping, we refer to the functional simulation and iterative refinement of suitable models of a product in software. Computer simulation can now be used to compute/calculate the kinematic, dynamic and FEA-based responses of a prototype (within a computer), and the results visualized in a 3D interactive graphical virtual environment. By permitting designers to realistically, accurately and quantitatively prototype and test multiple intermediate models within a virtual environment, Virtual Prototyping (VP), also known as Simulation-Based Design (SBD), has rapidly gained popularity and become a crucial part of most engineering design processes [1].

The usefulness of such a virtual prototyping exercise is limited only by the fidelity of the model and the accuracy of the results. Some of the factors affecting this accuracy include: (a) the modelling skills of the designer; (b) the selection of suitable effects to model; (c) the coupling between various physics phenomena; and most often (d) the availability of computational power. For example, oftentimes, there are many effects such as friction, contact etc. that are very simplistically modelled (for computational efficiency or for the lack of more accurate models) and can only be accurately determined by physical testing. For such situations, hardware-in-the-loop (HIL) frameworks permit a quick replacement of the virtual model by the actual physical prototype to permit experimental testing. Furthermore such VP and HIL frameworks permit the designer to select easily between physical testing and simulation-based testing, at both the component and system level, in order to most effectively perform the iterative design.

Hence, the purpose of this paper is to explore the transfer and translation of this paradigm to support the process of biological hypothesis testing in one of the candidate arenas – musculoskeletal analysis. Virtual and physical models of various animals can be (re-)created from CT scans of fossils/ living animals and through the use of computational simulation tools the various actions/ behaviours can be analyzed. In particular, hypotheses about specific behaviours can now be analyzed for compatibility with the underlying physical system (and thus provide a powerful physics-based tool for systematic elimination of poor hypotheses).

However, unlike traditional engineering systems, musculoskeletal systems inherently possess considerable irregularities and redundancies – characteristics which cannot be readily handled by current computational tools and requires the development of suitable alternatives. This provides the motivation for development of a low-order computationally tractable model based on screw-theoretic methods in this paper. Many of these aspects will be illustrated in the case study of bite force estimation in the members of the felid (cat) family.

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Case Study: Bite Force Estimation in the Cat Family

The goal of this case study is to accurately estimate the bite forces and requisite muscle forces within in the skull/ mandible structure of members of the cat family, ranging from extinct sabertooth cats to modern day large cats. Accurate information pertaining to skeletal geometry and the underlying articulated structure may be obtained from the various anatomical databases/ fossil records. Anatomical studies of modern-day large cats [2] also enable us to approximately locate the origin and insertion points of various associated jaw muscles. Our goal is to use this information to estimate the muscle forces associated with an applied/ desired bite force, and ultimately estimate the maximal bite force of the animal.

To this end, the underlying articulated structure and superimposed musculature can be modeled as a redundantly actuated parallel mechanism allowing us to bring the considerable literature in the domain of parallel manipulators [3, 4] to bear on this problem. In particular, such musculoskeletal systems share a number of features with a subclass of parallel manipulators – cable-actuated robotic systems [5, 6]. Such systems require careful handling principally due to the unidirectional nature of application of actuation forces through the attached cables. The analysis is undertaken using screw-theoretic methods – which retain explicit geometric meaning in terms of lines of action, velocities, forces, and moments while providing a simplified analysis framework suitable for force analysis/optimization and muscle location studies.


Figure 1: Fossilized Skull/ Mandible of an Extinct Sabertooth Cat

The rest of the paper is organized as follows: Section II provides a brief overview of literature related to musculoskeletal and redundant system modeling. Section III discusses some of the issues encountered during preliminary simulation of the musculoskeletal system with conventional computational tools. Sections IV and V present the modeling and implementation of our proposed framework, and we conclude the paper with a brief discussion in Section VI.

II. LITERATURE

There have been several attempts at using computer-based tools for analyzing biomechanical systems [7, 8]. The Fauna Group [9, 10], consider detailed musculoskeletal models, replete with skin, joint motions and tissue deformation, purely from a viewpoint of realistic animation. Others such as the Primate Evolution and Morphology Group of Liverpool [11, 12] 'retroengineer' gait and masticatory behavior of early hominids and other primates and gauge comparative energetic costs of different behaviors. The musculoskeletal analyses, includes the use of EMG to determine muscle firing patterns together with solid skeletal models but do not consider soft tissue. Yet others such as Thow-Hing and Fiume [13], consider very detailed muscle models including fiber orientation, but with limited consideration of their impact on the overall system. Terzopoulos *et al.* [14] adopt a simplifed yet physics-based approach to creating a virtual marine world inhabited by realistic artificial fishes. While their algorithms are not based on formal biomechanical principles, they emulate the appearance, movement, and behavior of individual animals and groups very realistically.

Musculoskeletal systems offer significant redundancy and require careful modelling of muscles. The total number of muscles included in the model and the muscle modelling fidelity is dependent on the desired complexity of the model. Multiple muscle systems (MMS) [15] while better representing the actual animal, are by nature redundant and create statically and dynamically indeterminate problems, with the system model having more actuators than degrees of freedom (DOF). Solution methodologies to these indeterminate problems have been examined by many authors [16-19].

A host of these systematization approaches reported in the biomechanics literature have leveraged the structure provided by the underlying articulated-rigid-body model to progressively develop constraints. The emphasis on *recursive computational implementation* seen in the traditional multi-body dynamics formulations of the kinematic/dynamic equations can potentially mask the underlying geometry inherent in the articulated structure. Hence, in contrast, we examine the applicability and utility of screw-theoretic modelling methods, developed traditionally in the context of parallel robotic systems [3, 4], to develop the requisite equations for quasi-static musculoskeletal analysis rapidly while retaining the explicit geometric meaning in terms of lines of action, velocities, forces, and moments.

III. PRELIMINARY SIMULATION APPROACHES

Virtual prototypes of the animal's jaw structure can be generated using a wide variety of commercial simulation packages such as ADAMS or VisualNastran. Computer simulation may now be used to compute/calculate the

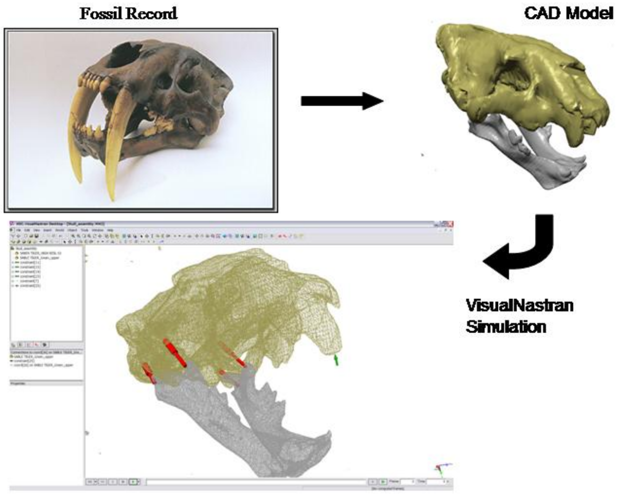


Figure 2: Illustration of the initially adopted virtual prototyping process.

kinematic, dynamic and FEA-based responses of the prototype to a control algorithm (within the computer), and the results visualized in a 3D interactive graphical virtual environment.

The creation of such a virtual prototype was our first course of action, as shown in Figure 2. We used CT scans of an extinct sabertooth cat skull to create a CAD (solid model) of the skull/ mandible structure. This solid geometry was then imported into dynamic simulation software package (VisualNastran). Constraints were then placed on the system to represent muscles (linear actuators), and the skull/ mandible interaction (revolute joint). An external force (or alternately a prescribed motion) was applied to the skull as user-specified input to the system. However, 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 – and provided the motivation for proposing the modelling and analysis framework described below.

IV. MODELLING FRAMEWORK

Mathematical Modeling:

We will model the skull/ mandible musculoskeletal system using screw-theoretic methods to serve as a low-resolution computational model. We assume a planar model (2-Dimensional) where the skull (upper jaw) and mandible (lower jaw) are considered to be rigid bodies. The mandible is assumed to be grounded in space. In the felid family, the motion of the jaws can be very closely approximated as a pure rotation [2]. Thus we assume the skull to be attached to the mandible via a revolute joint (with axis normal to the display plane). All muscle are simplified and considered to act along the line of action joining the origin and insertion points.

A simple nomenclature was developed to represent the muscle, joint, and force characteristics of the model. The three main coordinate systems are shown in Figure 3. The *Inertial (Fixed) Frame, (X_O, Y_O)* is fixed in space and is the principal calculation frame of the model. An *Upper Jaw Frame, (X_U, Y_U)* is attached to the skull (upper jaw) and is related to the inertial frame through the *jaw gape angle, θ.* An *Inertial End Effector Frame, (X_E, Y_E)* is created with the application point of the external/ desired or bite force.

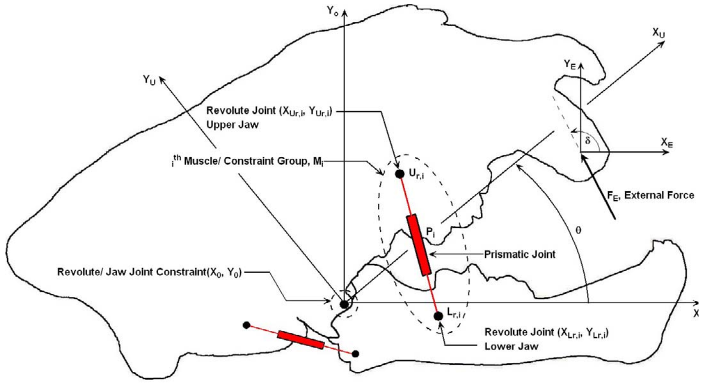


Figure 3: Schematic illustrating model nomenclature.

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, as seen in Figure 3. A total of n_m such muscles are assumed to couple the upper and lower jaws. ${}^{O}\boldsymbol{R}_U$ is a rotation matrix that relates coordinates of the upper jaw frame to coordinates of the inertial frame.

$$ {}^{U}\mathbf{R}_O = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 \\ \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1} $$

$$ {}^{O}\mathbf{R}_U = \left[{}^{U}\mathbf{R}_O \right]^{-1} \tag{2} $$

The external bite force, F_E is assumed to be applied at the origin of the end effector frame (${}^{U}X_F$, ${}^{U}Y_F$) at an angle δ and can be represented in component form as:

$$ \vec{F}_E = \begin{bmatrix} F_E \cos(\delta) \\ F_E \sin(\delta) \end{bmatrix} \tag{3} $$

Using (1) and (2) all the joint locations and forces can be transformed and expressed in the inertial frame.

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. e.g. The displacement of a rigid body can be defined as a *screw displacement*, such that its motion can be broken down into a rotation about a unique axis and a translation about the same unique axis called the *screw axis*.

Given a unit vector pointing along the direction of the screw axis, $\hat{\mathbf{u}}$, the location of a point on this axis $\vec{\mathbf{r}}$, and the pitch λ, defined as the ratio of translation to rotation, we can define a unit screw, $\hat{\$} = [S_1 \quad S_2 \quad S_3 \quad S_4 \quad S_5 \quad S_6]^T$ as:

$$ \hat{\$} = \begin{bmatrix} \hat{\mathbf{u}} \\ \hat{\mathbf{u}}_0 \end{bmatrix} = \begin{bmatrix} \hat{\mathbf{u}} \\ \vec{\mathbf{r}} \times \hat{\mathbf{u}} + \lambda \hat{\mathbf{u}} \end{bmatrix} \tag{4} $$

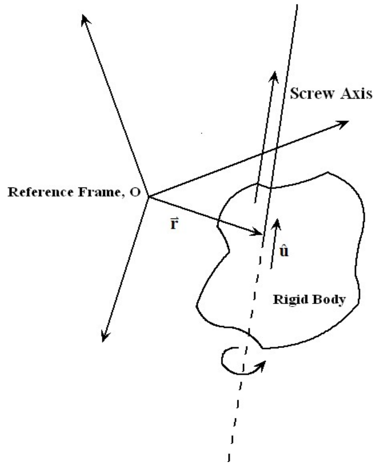


Figure 4: Schematic of a general unit screw

where $\hat{\mathbf{u}}_0 = \vec{\mathbf{r}} \times \hat{\mathbf{u}} + \lambda\hat{\mathbf{u}}$ is the moment of the screw axis about the origin of a reference frame. Such screws have been used to define both motions (twists) and forces (wrenches). In two dimensions equation (4) reduces to:

$$\hat{\$} = \begin{bmatrix} \hat{\mathbf{u}} \\ \vec{\mathbf{r}} \times \hat{\mathbf{u}} + \lambda\hat{\mathbf{u}} \end{bmatrix} = \begin{bmatrix} S_3 \\ S_4 \\ S_5 \end{bmatrix} \tag{5}$$

Considering each muscle as an RPR serial chain manipulator we see that the end-effector twist due to the screws generated by each joint can be written as:

$$\$_{T,E} = [\mathbf{J}_i]\dot{\Theta}_i \tag{6}$$

Where $\mathbf{J}_i = \begin{bmatrix} \hat{\$}_{Ur,i} & \hat{\$}_{P,i} & \hat{\$}_{Lr,i} \end{bmatrix}$ is a 3×3 Jacobian matrix whose column vectors represent the unit screws associated with each joint, and $\dot{\Theta}_i = \begin{bmatrix} \dot{\theta}_{Ur,i} & \dot{d}_{P,i} & \dot{\theta}_{Lr,i} \end{bmatrix}^T$ is the column vector of the joint velocities.

Reciprocal Wrench Formulation:

Following Firmani and Podhorodeski [3] we then find the selectively non-reciprocal screws (SNRS) associated with each active-joint for the given muscle. A selectively non-reciprocal screw, $W_{k,i}$, in the given RPR serial chain will be reciprocal all other screws except the given screw, and may be defined as:

$$W_{k,i} \otimes \$_{j,i} = 0 \ , \forall k, j = \{U_r \quad P \quad L_r\}, k \neq j \tag{7}$$

For example, $W_{P,i}$ is the selectively non-reciprocal screw to the unit screw corresponding to the P joint that satisfies:

$$W_{P,i} \otimes \$_{Ur,i} = 0$$

$$W_{P,i} \otimes \$_{Lr,i} = 0$$

$$W_{P,i} \otimes \$_{P,i} \neq 0$$

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

$$\begin{aligned} \begin{bmatrix} | & | & | & | & | \\ W_0 & W_{p,1} & W_{p,2} & \cdots & W_{p,n_m} \\ | & | & | & | & | \end{bmatrix} \begin{bmatrix} f_0 \\ f_1 \\ \vdots \\ f_{n_m} \end{bmatrix} &= \$_w \\ = \quad [\mathbf{W}]_{m \times (n_m+1)} \{\mathbf{f}\}_{(n_m+1) \times 1} &= \$_w \end{aligned} \tag{8}$$

where $\$_w = [M_z \quad F_x \quad F_y]^T$ is the external wrench created by the application of the external bite force (F_E), and **f** represents the wrench intensities to the corresponding selectively non-reciprocal wrenches, which in this case correspond to the magnitudes of the muscle forces $\left(f_1 \ldots f_{n_m}\right)$ and the reaction forces at the jaw joint $\left(f_0\right)$. A pseudo-inverse based solution to this linear system can be found by:

$$\begin{aligned} \vec{\mathbf{f}} &= \mathbf{W}^{\#}\$_W + \left[I - \mathbf{W}^{\#}\mathbf{W}\right]\vec{\mathbf{z}} \\ &= \quad \mathbf{f}_P + \mathbf{f}_H \end{aligned} \tag{9}$$

where $\mathbf{W}^{\#}$ is the pseudo-inverse of the **W.** Since the system under consideration is almost always redundantly actuated, i.e. $m < n$, the $\mathbf{W}^{\#}$ can be computed as:

$$\mathbf{W}^{\#} = \mathbf{W}^T\left(\mathbf{W}\mathbf{W}^T\right)^{-1} \tag{10}$$

The first term of Equation (9) corresponds to the particular solution ($\mathbf{f_P}$) and the second term corresponds to the homogeneous solution ($\mathbf{f_H}$). As shown by Kumar [20], these terms can be interpreted as the equilibrating force field and interaction force field respectively The equilibrating force field gives the least squares solution to the problem, and we can now add multiples of the interaction force field without changing the output. This becomes important because we will require the wrench intensities corresponding to the muscle forces $\left(f_1 \ldots f_{n_m}\right)$ to be positive, and the interaction force field can now be used to ensure the satisfaction of this condition.

V. IMPLEMENTATION FRAMEWORK

Our overall desire is to perform iterative and repeated what-if studies for Bite and Muscle Force Estimation using both virtual prototypes and a Hardware-In-the-Loop (HIL) test-bed. To this end, we are developing an Integrated Framework to support these efforts. The overall development and implementation of the Integrated Framework involves the merger of various software and hardware elements along with the development of low-resolution mathematical models, as shown in Figure 5.

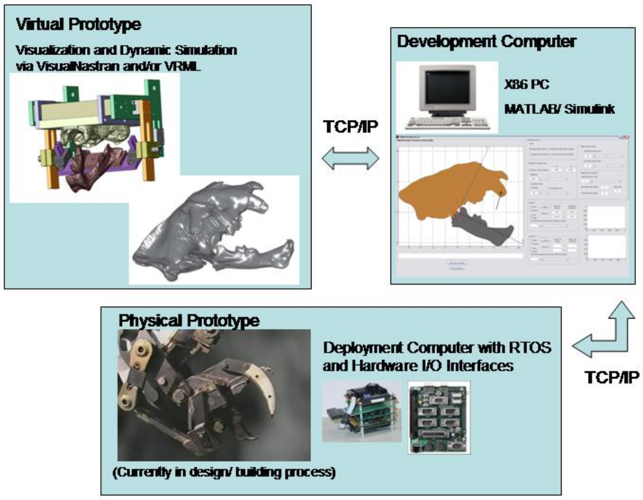


Figure 5: Proposed paradigm for the virtual prototyping and hardware-in-the loop testing of musculoskeletal model

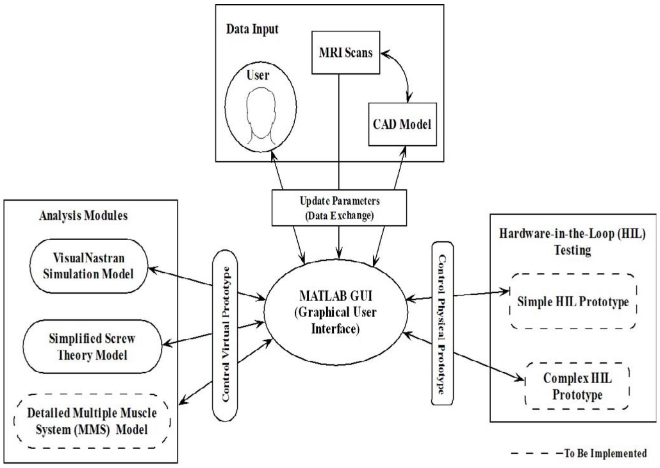
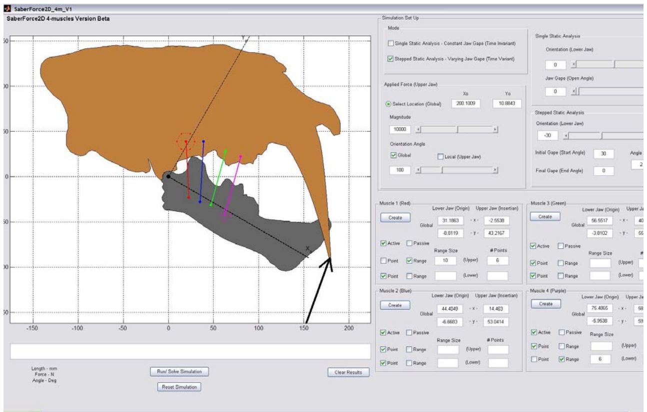


Figure 6: Functional interaction of the GUI, VP and HIL components for the rapid testing, analysis and verification of the various biological hypothesis



Simulation Set Up

Mode

☐ Single Static Analysis - Constant Jaw Gape (Time Invariant)

☑ Stepped Static Analysis - Varying Jaw Gape (Time Variant)

Applied Force (Upper Jaw)

● Select Location (Global) Xo 200.1009 Yo 10.8843

Magnitude 10000

Orientation Angle ☑ Global ☐ Local (Upper Jaw) 100

Single Static Analysis

Orientation (Lower Jaw) 0

Jaw Gape (Open Angle) 0

Stepped Static Analysis

Orientation (Lower Jaw) -30

Initial Gape (Start Angle) 30

Final Gape (End Angle) 0

Muscle 1 (Red): Lower Jaw (Origin) Global 31.1863 -x- Upper Jaw (Insertion) -2.5538; -8.8119 -y- 43.2167; ☑ Active ☐ Passive; ☐ Point ☑ Range Range Size 10 (Upper) # Points 6; ☑ Point ☐ Range (Lower)

Muscle 2 (Blue): Lower Jaw (Origin) Global 44.4049 -x- Upper Jaw (Insertion) 14.463; -6.6683 -y- 53.0414; ☑ Active ☐ Passive; ☑ Point ☐ Range (Upper); ☑ Point ☐ Range (Lower)

Muscle 3 (Green): Lower Jaw (Origin) Global 56.5517 -x-; -3.8102 -y-; ☑ Active ☐ Passive; ☑ Point ☐ Range (Upper); ☑ Point ☐ Range (Lower)

Muscle 4 (Purple): Lower Jaw (Origin) Global 75.4865 -x-; -5.9538 -y-; ☑ Active ☐ Passive; ☑ Point ☐ Range (Upper); ☐ Point ☑ Range 6 (Lower)

Figure 7: GUI for facilitating interactions with users (biologists)

Specifically, it consists of a deployment computer and three major components – the Graphical User Interface (GUI), the Virtual Prototype (VP) and the HIL test bed. The entire framework was developed modularly with bidirectional I/O in order to facilitate ease of adding, removing and modifying the modules. Figure 6 depicts the functional interaction between these different components.

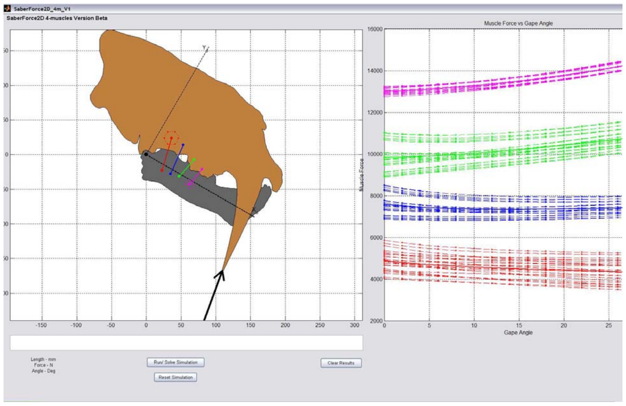


Figure 8: Magnitudes of Muscle Forces using the Screw Theoretic Formulation – GUI output.

Figure 7 shows the GUI developed in MATLAB that interacts with underlying implementation of twist/wrench based analysis. It allows the biologist to select/change the number of muscles and muscle locations, location and direction of external forces, etc. and outputs preliminary results in terms of internal forces developed in the muscles and the torques required at the joints. Figure 8 shows the ranges of muscle forces developed as the location of the origin and insertion in four different muscles are parametrically varied.

The HIL test-bed, shown in Figure 9, is currently in development. Geometric data from the CT scans is being used to develop castings of the dentition (upper and lower jaws). The developed test-bed is capable of being adjusted to allow bite-testing of a wide variety of specimens. Muscles will be approximated by tensioned cables and actuator forces in these cables are determined from the simulation of the virtual model. The deployment computer is a barebones x86 computer with a RTOS used to control the physical prototype. The MATLAB/ Simulink/ Real-Time-Workshop [21] framework is intended to facilitate the rapid conversion into a real-time executable for execution on the deployment computer.

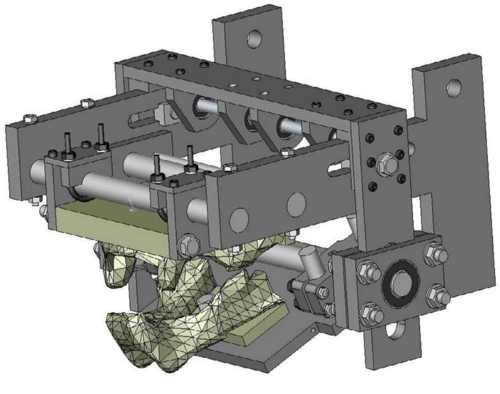


Figure 9: Virtual model of HIL test-bed to be used in bite – testing using castings of dentitions of various specimens.

VI. DISCUSSION:

We presented a brief overview of a framework for rapid virtual prototyping of musculoskeletal models as well as for performing hardware-in-the-loop simulations in order to assist with biological hypotheses testing. This is an ongoing research effort with the framework and its supporting modules being continually validated, tested and modified. This modular framework allows for ease of addition, modification and removal of modules. Further, one of these modules, the low-resolution screw-theoretical model developed for modelling and simulation was discussed in greater detail. The screw-theoretic framework, as explored in the context of a case study of bite force estimation in members of the felid family, provides a convenient computational model that quickly resolves redundancy and evaluates muscle forces for a given quasi-static bite force problem. Some preliminary results of application of this method for redundancy resolution are presented. The case study specifically addresses the estimation of the bite force and the subsequent muscle forces in a sabertooth cat. In the ongoing work we a pursuing creation of the physical test-bed. The proposed framework shows significant promise for speeding up the overall analysis process.

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