Integrated Physiologically Motivated Controller for the Open-Source Extended Hill-type Muscle Model in LS-DYNA

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I. INTRODUCTION

Present-day vehicle safety is based on a complex interplay of different safety systems, which are developed with the help of virtual modelling and testing tools. Corresponding processes include application of Human Body Models (HBMs) to represent occupants inside the vehicle. The growing number of Partially and Highly Automated Vehicles (HAV) requires advanced pre-crash safety systems that take into account active behaviour of occupants. Thus, HBMs should be appropriate to rising demands and enhanced with the required features. The conventional method of enhancement is the integration of beam finite elements with the distinctive material, representing active muscles, and the addition of a specifically designed high-level muscle controller, representing central nervous system, responsible for the generation of voluntary and reflexive motions or bracing [1]. Recent studies show that additional low-level layer of the controller, based on the biology-specific physical laws existing in the musculoskeletal system [2], benefits to the high-level controller movement generation stability and computation speed. The aim of the study is the implementation of a physiologically and biologically motivated low-level muscle internal controller for the open-source Extended Hill-type muscle model in LS-DYNA software package [3-4].

II. METHODS

LS-DYNA provides a special material model for active muscle modelling named *MAT_MUSCLE (*MAT_156), which is based on the macroscopic Hill-type muscle model consisting of three simple mechanical elements in parallel. There are drawbacks to its use, however, such as inaccurate approximation of the physical muscle structure, complicated definition of material parameters from the anatomical literature and absence of encapsulated activation dynamics. For these reasons, the authors opted to use an Extended open-source Hill-type muscle material as user-defined material in LS-DYNA [3-4], with integrated activation dynamics dependent on neural activation level or muscle length sensitivity and clear separation between muscle and tendon structures.

Nonetheless, any existing or newly implemented muscle material model needs a supplemental controller for simulations of active or reactive HBM behaviour. Existing controller realisations in LS-DYNA [5-6] rely on scripting commands of the *KEYWORD modelling language, e.g. *DEFINE_CURVE_FUNCTION, and use additional "flying nodes" for the transfer of history variables over time steps by specifying their motion with the *BOUNDARY_PRESCRIBED_MOTION command for LS-DYNA releases 9.2 and below. Such an approach is tedious, error-prone and leads to sluggish code execution, e.g. the same lines of code are repeated for each muscle. Therefore, the authors chose to include the controller code into the compiled LS-DYNA binary, executable by adding the control scheme directly to the FORTRAN code of the open-source Extended Hill-type muscle model. In contrast to technical control approaches in [5-6], this suggested control method is based on the physiologically inspired Equilibrium point control (EPC) proposed in [7]. It states that the human brain controls movement and body position in space by sending an activation signal to the muscle through α- and γ-motoneurons to set its individual lengths learned by producing voluntary movements during a lifetime. Activation signals are stopped when the controlled actual muscle length reaches a certain threshold, which is detected by the brain via interpreting signals received from muscle spindles for the active muscle fibre (senses muscle fibres stretch) and the Golgi tendon organ for the tendon (senses changes in muscle tension). Each combination of constant muscles activation is called equilibrium point (EP) and represents a steady state position in space. Control signals could be feedforward (α-control) or feedback (λ-control) [8] only, or combined (hybrid-control) [9].

The EPC does not need a priori any dynamical model of the controlled system. The assumption of learned

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movements is remodelled by a data-driven optimisation. Due to the possibility of multiple muscle activation level combinations referring to the same equilibrium position, this mapping procedure is not bijective. LS-OPT software is used to find combinations leading to a desired steady elbow angle $\phi_{elb,i}$ in arm models. Stimulation levels of the muscles are used as optimisation parameters, with specified final angle $\phi_{elb,i} \pm \epsilon_{\phi}$ and angular velocity $\pm\epsilon_{\dot{\phi}}$ values as defined constraints. Minimisation of total stimulation in combination with compliancy against an external force is used as cost functions to rate the valid solutions. Arbitrary movements can be performed by switching from one optimised set of values to another.

III. INITIAL FINDINGS

To demonstrate the functionality of the EPC method, modified upper extremities of female ViVA OpenHBM [10] and male THUMS V3 HBM [11] are used. Nine muscle elements with implemented material and parameters based on the data from [12] (scaled for the female model), and an ideal one-DoF hinge joint at the elbow were added. Achieved EPs at angles $\phi_{beg} = 45°$ and $\phi_{end} = 95°$ for the movement are shown in Fig. 1. Due to the highly redundant activation, the optimisation is performed using six independent values of stimulation levels for the muscles (Fig. 2), and respective elbow angle vs time curves are given in Fig. 3.

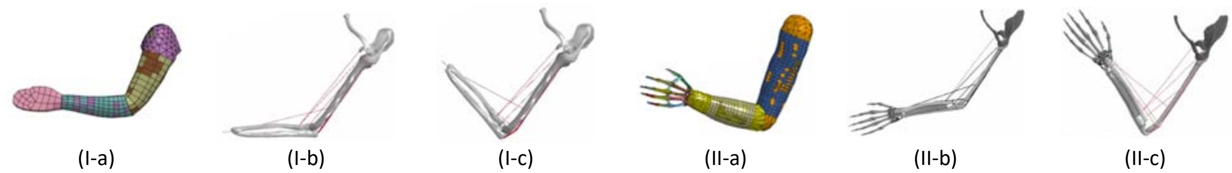

Fig. 1. Upper extremity of ViVA OpenHBM (I) and THUMS AM50 occupant Academic V3.0 models (II). Full finite element models (a), multibody models with shown implemented muscles in starting (b) before movement and ending (c) after movement positions.

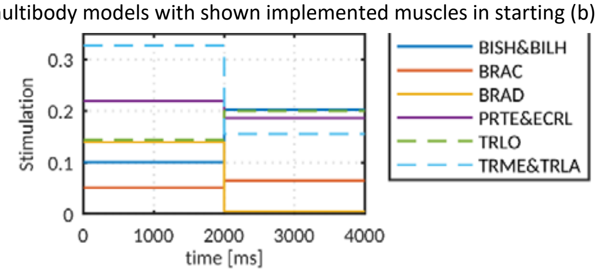

Fig. 2. Stimulation values for the flexors biceps short/long head (BISH&BILH), brachialis (BRAC), brachioradialis (BRAD) and pronator teres/extensor carpi radialis longus (PRTE&ECRL) and the extensors [dashed lines] triceps long head (TRLO), triceps medial/lateral head (TRME&TRLA). Found for ViVA OpenHBM with proposed optimisation strategy in LS-OPT software for movement from $\phi_{beg} = 45°$ to $\phi_{end} = 95°$ with minimised elbow compliancy.

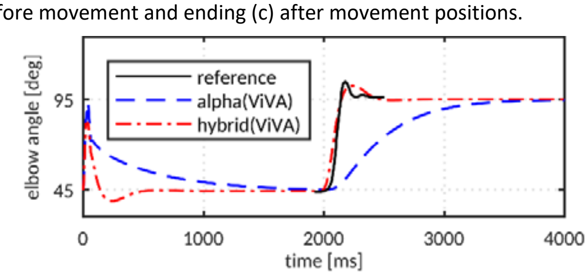

Fig. 3. Comparison of the resulting elbow angle vs time for the ViVA OpenHBM. α-control (dashed) and hybrid control with standard parameterisation (dash-dotted) compared to [11] (black solid line). After the initialisation phase, the transition from 45° to 95° equilibrium is depicted. The superposition of additional stimulation based on the feedback control shows improved performance.

IV. DISCUSSION

A physiologically motivated controller for the open-source Extended Hill-type muscle model was successfully implemented as a material model in LS-DYNA within the user-defined subroutine umat41. As this is a low-level muscle internal controller by design, it could be used for simulation of any model movements (voluntary or reflexive) and bracing (muscle co-contraction). Type of the movement is dependent on the input control signals, which could be predefined before the simulations from the experimental EMG measurements or by the means of the optimisation algorithm, or computed in the simulations by an additional high-level controller, which is not covered by the current study. As an initial finding, a method for determination of a predefined muscle stimulation values for voluntary model movements within the optimisation package LS-OPT is proposed. This method is universally applicable to any finite element human body model, which was validated by applying it to arm parts taken from ViVA OpenHBM and THUMS V3.0.

V. ACKNOWLEDGEMENT

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VI. References

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