Comparison of Controller Strategies for Active Human Body Models with Different Muscle Materials

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I. INTRODUCTION

Active Human Body Models (AHBMs) are used for vehicle occupants' motion prediction in pre-crash scenarios. To ensure that their response is biofidelic, both existing muscle materials and control strategies must be compared and evaluated. State-of-the-art approach is to model muscles for AHBMs in LS-DYNA with a material named *MAT_MUSCLE (*MAT_156). Recently, a new muscle material with a more realistic serial damping and eccentric force-velocity relation was implemented in LS-DYNA as a user-defined material for truss elements [1]. Such elements are mostly controlled by open- and closed-loop strategies based on sensory information, for instance, angle deviations [2]. However, there are also alternative control approaches, such as using muscle spindle feedback to regulate muscle activity, which are inspired by the physical attributes of the central nervous system [3].

This study aims to show the differences between two muscle materials' responses using various muscle controllers that are already available in the literature. Due to the complexity of the simulation set-up with full AHBM, the results will be shown for a simple arm model with four lumped muscles and compared to validation experiments in which participants performed fast point-to-point movements with an elbow flexion of 100° [4].

II. METHODS

Experimental Data

Experimental data from Kistemaker *et al.* [4] were used to validate the computational approach. In that study, participants were asked to perform several fast point-to-point movements. The shoulder angle was kept constant, and the elbow was flexed up to an angle difference of 100°. Desired time for the movement is 0.20 s, according to the data given in the source.

Computational Modelling

The upper right extremity of the THUMS v5 [5] was transformed into a rigid body model with four lumped muscles. The humerus bone was fixed to make it comparable to the experimental set-up. Four lumped muscles are composed of beam elements representing two flexors and two extensors (biarticular and monoarticular). Each of the muscles consists of four nodes and the modelling takes into account physiological routing over the joint: origin node, two deflection nodes, and an insertion node.

Two different muscle materials, based on a macroscopic Hill-type formulation, are compared in this work: the *MAT_156 muscle model; and the user-defined extended Hill-type material (EHTM) [1][6]. The first model has three elements in parallel, namely a contractile element (CE), a parallel elastic element (PEE) and a parallel damping element (PDE). The second muscle material consists of four elements: a CE and a PEE in series with a serial elastic element (SEE) and a serial damping element (SDE). Hatze's activation dynamics function [7], which models the non-linear free calcium ion concentration and is dependent on the muscle length, was used to activate both materials.

Four different control strategies are investigated in this study: (1) an open-loop (alpha) controller; (2) a closed-loop controller based on the muscle length (lambda); (3) an angle closed-loop controller; and (4) a hybrid controller, which is a combination of (1) and (2). Controller's gains were optimised using Bayesian optimisation with the objective that the end position is close to the desired position and has zero velocity. For the alpha and angle controllers, the gains had to be optimised for each group of muscles (flexors and extensors), whereas for the muscle length controller it was sufficient to optimise one gain and scale it by the optimal fibre length.

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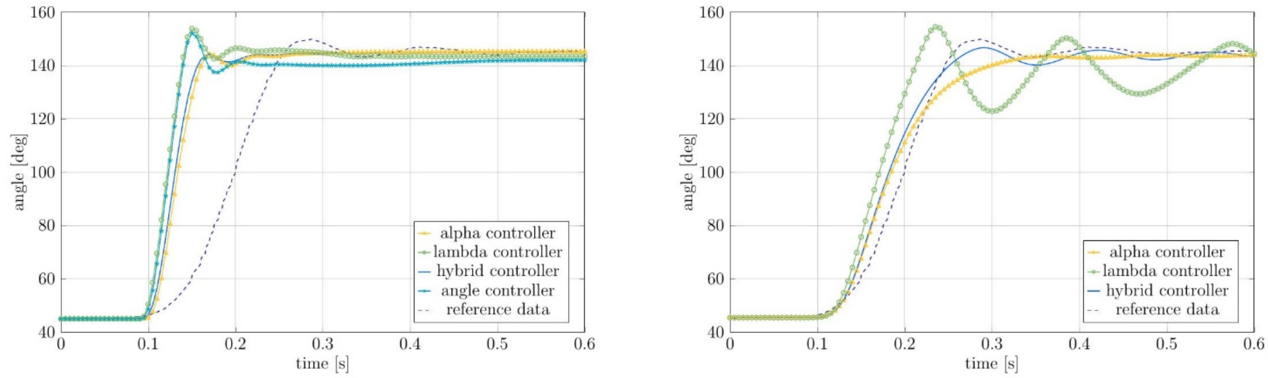
III. INITIAL FINDINGS

Comparison of the angle response for different controllers with the reference data from [4] for the standard muscle material *MAT_156 (a) and the EHTM (b) plotted over time is shown in Fig. 1. Furthermore, a comparison of CPU times of the two muscle materials is given in Table I for 4.5 s simulation time of the elbow flexion.



(a) *MAT_156 (b) EHTM

Fig. 1. Comparison of different controllers with reference data

TABLE I.

CPU TIME IN SECONDS FOR SIMULATIONS WITH DIFFERENT MODELS

	α, EHTM	α, *MAT_156	λ, EHTM	λ, *MAT_156	Hybrid, EHTM	Hybrid, *MAT_156	Angle, *MAT_156
Element processing	0,719	6,386	0,724	6,751	0,748	6,729	6,808
Rigid Bodies	1,137	13,771	1,141	14,196	1,151	14,361	14,262
Time step size	2,010	23,521	2,004	23,638	2,006	24,061	23,709
Misc. 1	0,976	10,547	0,961	11,057	0,972	11,137	10,989
Misc. 4	2,797	33,255	2,781	33,965	2,786	34,478	33,886
Problem cycle	45001	517624	45001	549290	45001	548631	549303
Total CPU	9,021	97,897	8,987	100,650	9,074	101,730	100,490

IV. DISCUSSION

As can be seen, the standard *MAT_156 has a much faster angle response reaction for all considered controllers compared to the reference data (Fig. 1 (a)), in contrast to the EHTM material which better approximates the motion of the volunteers (Fig. 1 (b)). A slope of the resulting curve for the EHTM tends to be closer to the experimental data and movement time approaches 0.2 s. This could be explained by the fact that the eccentric force-velocity curve and the serial damping represented in the EHTM is modelled more physiologically compared to *MAT_156. Another noteworthy point is that the difference between the four compared controllers seems to be not significant for this movement. It should be mentioned that the open-loop controller tends to have smaller oscillations in comparison to the lambda and angle controllers. However, the open-loop controller is not resistant to perturbations by design which makes other types of controller, such as the hybrid one, more favourable because of its additional advantages. First, physiological design, because by using the muscle length as a control signal it is analogical to a biological muscle spindle sensor. Secondly, fewer controller gains need to be fitted for the AHBM compared to the angle control. It is sufficient to optimise one gain and then divide it by the optimal fibre length to make it scalable for many muscles, which enables easier control of muscle groups.

Furthermore, the EHTM material with the integrated controller [8] has the potential to speed up AHBM simulations significantly. This is explained by the fact that it is implemented using FORTRAN code and fitted into LS-DYNA software, thus runs much faster than the standard Keywords interpretation. A comparison of CPU times with the load distribution over solution steps for different test cases performed on one CPU of the AMD Ryzen Threadripper 1950X processor is given in Table I. The main discrepancy could be found in Misc. 4 step (muscle controller keywords processing), which shows the benefit of EHTM. For such simple models, simulation speed can increase up to 10 times comparing to *MAT_156.

V. ACKNOWLEDGEMENTS

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