Modelling and Validation of the 3D Muscle-Tendon Unit with Solid Finite Elements in LS-DYNA for Active Human Body Model Applications

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I. INTRODUCTION

Human Body Models (HBMs) have become an essential tool for Finite Element Analysis studies involving humans. Current HBMs have a significant drawback in the modelling of the muscle-tendon unit (MTU) because they usually use material models, which incorrectly characterise the passive muscle tissue [1]. At the same time, there are many studies in the literature providing accurate material formulations for the MTU, however, having it divided into multiple parts each with a distinct and custom material formulation [2-3]. This limits applications of such findings in HBMs, where typically the entire MTU is meshed with solid-type finite elements (FE) with only one material type assigned per MTU. As such, the primary objective of this study is to find an easily implementable material already existing in the LS-DYNA default material library that can represent the whole scope of MTU's properties realistically and accurately enough to be used in the Active Human Body Model (AHBM) environment.

II. METHODS

Experimental Data

To validate the developed MTU model, experimental results from [4] were used. In the given study, the tendon of the New Zealand rabbit's *tibialis anterior* muscle was elongated with three different strain rates until failure. For active experiments, elongation would only occur 0.5 s after tetanic stimulation of the fully activated muscle. Independent of the strain rate, material failure would occur at 25 % stretch.

Computational Modelling

The FE model was created according to the description provided in [4] and using the reference images shown in [2]. The geometrical model was conceptualised in Autodesk AutoCAD and meshed consequently in LS-DYNA with eight-node solid elements. After a mesh convergence study was done for the elements size from 1.80 mm to 0.45 mm, the average size of 0.90 mm was used. The MTU was conceived as a single volume entity with MAT_TISSUE_DISPERSED material, which is included in the default LS-DYNA library. Material parameters were obtained from different literature sources [5-7], additionally adjusted to the experimental data and optimised to more accurately describe the expected performance of the muscle. A viscous form for the hourglass element stabilization was applied. All nodes are constrained for every degree of freedom on the one side of the model, while the other side has only one degree of freedom that allows elongation in the desired direction. The resulting stress was measured in the muscle mid-belly cross-sectional area (Fig. 1).

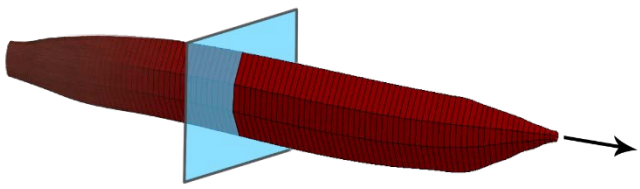

Fig. 1 – MTU model representation

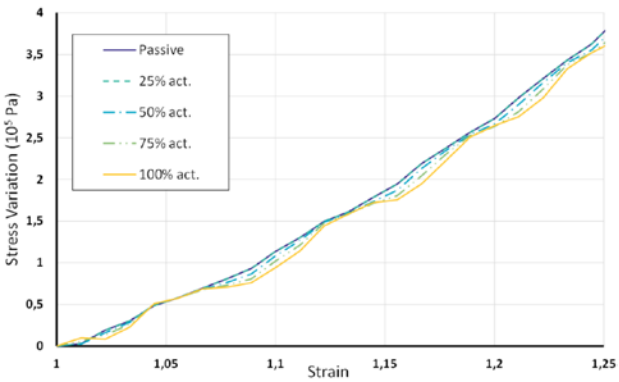

Fig. 2 – Stress variation with different activation levels.

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III. INITIAL FINDINGS

Initial findings show that the proposed material has a distinct behaviour for different muscle fibre activation levels (Fig. 2), which is changed by specifying one input parameter for the material. Furthermore, the model can predict reliably both passive (Fig. 3 (a)) and active (Fig. 3 (b)) MTU stress-strain relationship.

When comparing results for the passive MTU performance (Fig. 3 (a)), the model from [2] matches the muscle's behaviour, while the model from [3] underestimates its performance during passive elongation. All implementations exhibit a curve slope like the experiment [4]. However, calculated Normalised Root Mean Square Error (NRMSE) values (Table 1) show that the modelling approach with the separation of MTU into several parts with different materials could be considered more accurate compared to only one material proposed by the authors, when it comes to the passive response. The MAT_VISCUOUS_FOAM material used for 3D MTU modelling in THUMS v5 HBM [8] severely underestimates the passive tissue behaviour and the curve obtained does not resemble the expected stress-strain relation at all.

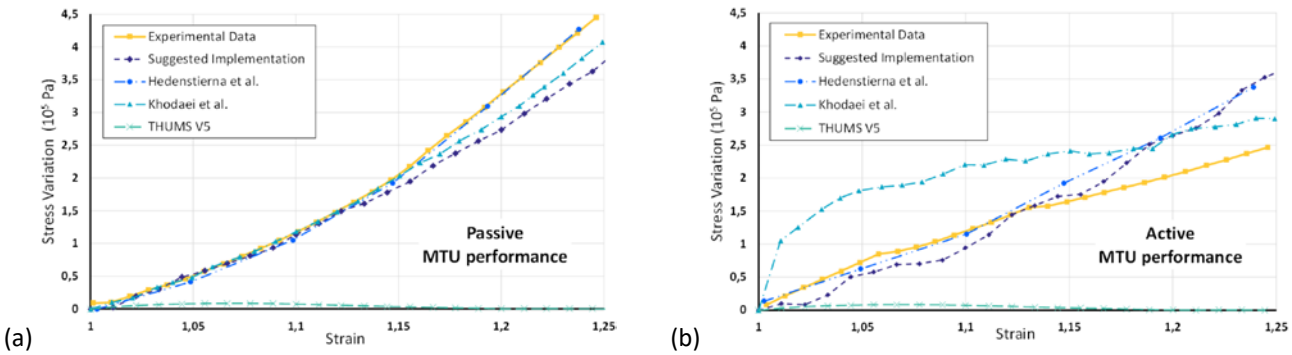

Fig. 3 – Stress variations for passive (a) and active (b) states of the MTU.

Results for the active MTU performance (Fig. 3 (b)) show that both [2] and [3] implementations overestimate while material from THUMS v5 severely underestimates the experimental values. Although the material model proposed in this current contribution has the best conformity with the active experiment [4] according to the NRMSE method (Table 1), none of the materials analysed were able to achieve a curve shape similar to results measured. It is important to note here that the MTU models in [2-3] are subdivided into nine different parts with distinct materials enabling the user to characterise the muscle better.

TABLE I

NORMALIZED ROOT MEAN SQUARE ERROR OF EACH IMPLEMENTATION COMPARED TO THE EXPERIMENT [4]

	Current contribution	Hedenstierna et al.	Khodaei et al.	THUMS V5
Passive Trials	8%	2%	4%	48%
Active Trials	17%	20%	33%	61%

IV. DISCUSSION

It is evident from the results obtained that the proposed approach allows a considerably accurate way for 3D solid element modelling of the active MTU in LS-DYNA with only one material. MAT_TISSUE_DISPERSED material has an option to input muscle activation level that changes the material stiffness (Fig. 2). This function gives clear benefit for application in HBMs comparing to the method proposed in [1], where rubber-like 3D elements coupled with 1D Hill-type elements that control stiffness is suggested for adequate muscle modelling. The error obtained could be attributed to the fact that the implemented model has a small discrepancy in dimensions compared to the real rabbit's muscle due to the absence of such data in the publication [4]. Thus, geometrical properties were extracted from the figures given in [2].

The next stages of the study will include material application into an arm model in different environments, coupling with a 1D Hill-type elements including a controller for direct transfer of the muscle activation into the material, studying the behaviour of the muscle tissues during contraction and a future publication with a detailed description of the final material properties and settings.

V. Acknowledgements

This work was supported by the EU Horizon 2020 Research and Innovation Programme under Grant Agreement No768947 *OSCCAR* and ERASMUS Placement Programme, and by the German Research Foundation (DFG) within the Cluster of Excellence *Data-Integrated Simulation Science* (EXC 2075), University of Stuttgart, Germany.

VI. References

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