The Effects of Active Muscle Contraction into Pedestrian Kinematics and Injury during Vehicle-Pedestrian Collision

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Abstract

The objective of this study is to develop a finite element model of active human skeletal muscle, which can mimic the contraction behavior of the skeletal muscle and also to analyze the effects of active muscle contraction into pedestrian kinematics and pedestrian injuries during vehicle-pedestrian collision. The skeletal muscles are modeled by combination of solid tetrahedral elements and line beam elements. In order to mimic the passive properties of the skeletal muscle, an Ogden material model is implemented for solid tetrahedral elements. To simulate the active behavior of the these muscles, a Hill-type muscle model for the line beam elements is implemented. The only important muscles were inserted into the THUMS Pedestrian Model. The simulation of pedestrian–vehicle collisions is also conducted in order to analyze the effects of skeletal muscle contraction to the pedestrian kinematics and injury.

Keywords: Active Muscle Contraction; Skeletal Muscle; Finite Element Modeling; Pedestrian Safety

1 Introduction

Pedestrians are most at risk in urban areas due in part to the large amount of pedestrian and vehicle activity in urban areas. No matter if the primary mode of transportation is the automobile, bicycle, or public transit, people must walk as a part of the trip, such as from their home to the store or place of employment, and/or to the transit stop. [1]

Collisions between pedestrians and road vehicles present a major challenge for public health, trauma medicine and traffic safety professionals. More than one third of 1.2 million people killed and 10 million injured annually in road traffic crashed worldwide are pedestrians [2].

In the European Union roads, 12–35% of seriously injured or killed people account for pedestrians [3]. The National Highway Traffic Safety Administration (NHTSA 2004) announced that the numbers of pedestrians killed and injured in the United States in 2003 were 4700 and 70,000 respectively [4]. Moreover, In Japan, recent traffic accident data shows that the number of pedestrian fatalities are larger than occupant fatalities. In year 2011, the proportions of Japanese traffic accident fatalities were reported as 37% in pedestrians, 32% in cyclists and 31% in occupants. Therefore, how to reduce pedestrian accidents is also one of the most significant issue in Japan. [5].

Based on the data mentioned above, many efforts have been conducted by researchers and automotive industries around the world in order to reduce the number of car-pedestrian collision. Although, the number of collision between vehicle and pedestrian can be reduced, this kind of accident cannot be eliminated. Therefore, the research in this field has been focused on reducing the injuries severity of pedestrian. For this purpose, car manufacturers have begun efforts such as modify the front bonnet and bumper of the vehicle to be more pedestrian-friendly.

In order to successfully modify or redesign the part of vehicle to be pedestrian friendly, the understanding of pedestrian kinematics while colliding with vehicle is the most important thing. This can be done by conducting experiments or simulations of vehicle-pedestrian collision. The most difficult part for conducting experiments and simulations of pedestrian-vehicle collision is to get the pedestrian model acting as same as possible like living human body or in another word, the model of pedestrian should have good biofidelic properties. It is really important because incorrect modeling of human body affects to incorrect results of injuries mechanism and kinematics.

To understand how specific vehicle designs affects injury type, injury mechanism, source and severity of the pedestrian, three paths of analysis are possible: experimental tests with post mortem human surrogates (PMHS) or crash dummies, computational simulations with mathematical models of the vehicles and pedestrians, or retrospective examinations of crash, vehicle and pedestrian parameters from crash database.[6]

Some researchers have been published their works in order to analyze the mechanisms and kinematics of pedestrian while hit by the vehicle. They have done their research with PHMS or cadaver as pedestrian model, and another have done by using simulation methods whether using multibody dynamics or finite element (FE) method. But, almost all of them were excluded the effects of active muscular forces as one of variables that may affects the result of pedestrian mechanisms and kinematics of injury.

There are some importance reasons to included the muscular response into the analysis : Firstly, human natural response while in dangerous situation. When human in dangerous situation, in this case, when pedestrians notice they will hit by the car, as natural response of body muscle will tighten for preparation of the impact. This natural response is caused by our adrenaline hormone. Adrenaline has long been known to cause an increase in the contractions of fast-contracting skeletal muscles, stimulated directly or through their motor nerves.[7]

Secondly, in order to get more realistic result of pedestrian-car collision. As mentioned before, more realistic results can be achieved if the biofidelic quality of human model is also high. The muscle responses is one of the aspects to get high biofidelic quality.

The third reason is the capability of finite element simulations to performs this analysis. As the outstanding development of computers technology nowadays, it is really possible to do the computer simulations in this field. As comparison to experimental research, computational simulations are often more efficient in term of cost and time and also the the influence of varying conditions can be easily investigated.

The present study will explain the process to develop 3D muscles model with active and passive properties of skeletal muscle as a finite element model. This active 3D muscle model will be combined together with THUMS model from Toyota in order to develop a pedestrian finite element model with 3D active and passive muscles properties. The simulations of pedestrian–vehicle collisions are also conducted in order to analyze the effects of skeletal muscle contraction to the pedestrian kinematics and injuries.

2 Theoretical Fundamentals

2.1 Hill's Three Element Models

The Hill's three element model of muscle is originated from the Hill's work [8]. Hill's model is the basis for most of currently used muscle models and his model is composed of three elements, as depicted in Figure 1.

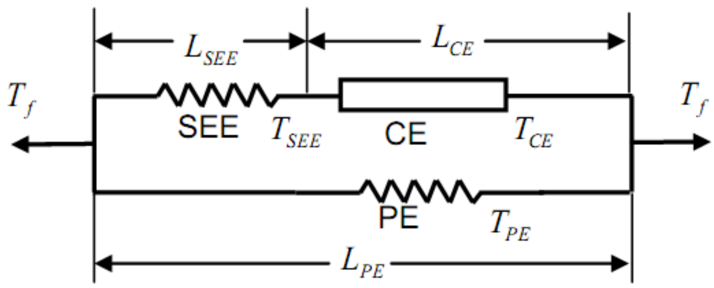


Fig.1: Hill's three-element muscle model

The contractile element (CE): This is used to model the active part of the muscle.It can freely extend when the muscle is non-activated and it is responsible for force generation within the muscle when activated.[9]

The series elastic element (SEE): This is a non-linear spring arranged in series with the contractile element. It allows a rapid change of the muscle states from inactive to active and provides an energy storing mechanism. [9]

The parallel element (PE): This is a non-linear spring in parallel with CE and SEE. It is responsible for the passive behaviour of the muscle when stretched. It is related to the elasticity of the connective tissues. [9]

2.1.1 Force-Length Relation

From experiments [10] the active force generated by the muscle has a dependency on the length of the muscle, and has its maximum value at the optimal muscle length L_{opt}, which can be assumed to be the resting length of the muscle [11], but in reality L_{opt} often varies a little bit from the resting length. The force-length relation can be expressed as [10] :

$$fL(L) = e^{-\left(\frac{\left(\frac{L}{Lopt}-1\right)}{csh}\right)^2} \tag{1}$$

Where L is the total muscle length and csh is a shape factor

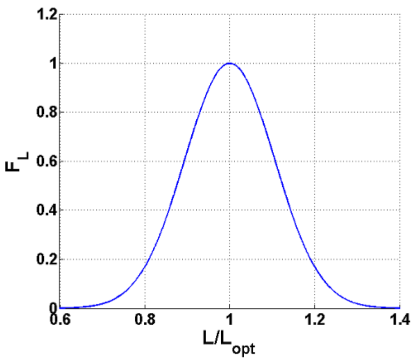


Fig.2: Force-Length relationship graph

2.1.2 Force-Velocity Relation

It has also been observed in experiments that the active force generated by the muscle depends on the shortening and lengthening velocity. With increasing shortening velocity the generated force will be reduced. Also, with increase of lengthening velocity the muscle force will respond in an asymptotic manner as shown in Figure 2.3. This relation is presented as the following equation [10] where is the normalized shortening velocity with respect to the maximum shortening velocity of the muscle V_0. For shortening velocities larger than V_0 the muscle is unable to produce any forces.

$$fv(V) = 0 \qquad \mathrm{v} \leq -1 \tag{2}$$

$$fv(V) = \frac{1+\mathrm{v}}{1-\frac{\mathrm{v}}{\mathrm{Cshort}}} \qquad -1\mathrm{v} < v \leq 0,\ v = \frac{\mathrm{V}}{\mathrm{Vo}} \tag{3}$$

$$fv(V) = x = \frac{1+\mathrm{v}\frac{\mathrm{Cmvl}}{\mathrm{Clength}}}{1+\frac{\mathrm{v}}{\mathrm{Clength}}} \qquad \mathrm{v} > 0 \tag{4}$$

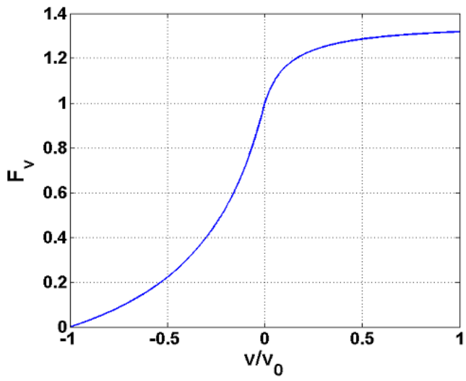


Fig.3: Force-Velocity relationship graph

2.1.3 Total Muscle Force

The total active force generated in a Hill-based contractile element (CE) can be expressed as :

$$FCE(L,V) = \mathrm{a(t)\sigma 0\ FL(L)\ FV(V)} \tag{5}$$

where a(t) is a function of time, representing the state of activation, which takes a value between 0 and 1, and 0 is the maximum isometric stress of the muscle [12].

Since the force in the contractile element FCE will be the same as the force in the series element (SEE), FSEE can be ignored; consequently, the total muscle force in a muscle can be expressed as the sum of the forces in the contractile element and the passive element (PE).

$$F = FPE + FCE \tag{6}$$

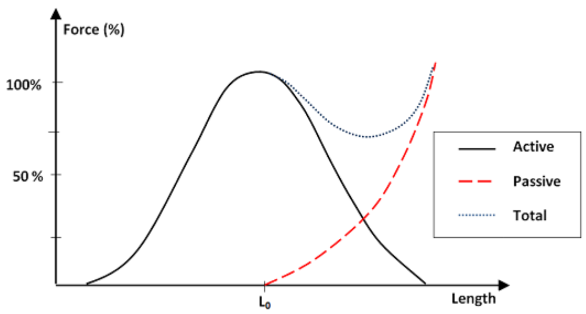


Fig.4: Schematic force-length relation of the muscle for active, passive and total muscle force

2.2 Architectural Properties of Muscle

Skeletal muscle architecture is defined as the arrangement of muscle fibers in a muscle and predicts muscle functional capacity [13-15]. The physiological and mechanical functions of muscle are characterized by associated architectural parameters, such as thickness, fascicle length, pennation angle and physiological cross-sectional area [16].

2.2.1 Physiological cross-sectional area (PCSA)

Physiological cross-sectional area (PCSA) is the area of the cross section of a muscle perpendicular to its fibers, generally at its largest point. It is typically used to describe the contraction properties of pennate muscles [17].

2.2.2 Pennation Angle

Pennation Angle is defined as the angle between the orientation of a fascicle and the attached tendon axis (i.e., the line of action) [18]

2.2.3 Optimal Muscle Length

Optimal muscle length is defined as the length of the overall muscle which can generating maximum forces.

2.2.4 Optimal Fiber Length

The optimal fiber length refers to the mean length of muscle fiber when the sarcomeres are at a length capable of producing maximal contractile force.

2.2.5 Peak Isometric Force

Peak isometric force is defined as a maximum force that can be produced by the muscle at its optimal length.

3 Methodology

3.1 FE Model Development Process of Skeletal Muscle

In order to develop the finite element model of skeletal muscle with its active and passive properties, there were three process that have been conducted. The first step was to find the correct geometrical data of muscles. Then, the next process was the development a finite element model. The meshing process was conducted by using Hypermesh preprocessor. In the preprocessing, the constitutive material model were assigned to active and passive muscle properties. The last step was the insertion of FE model of the skeletal muscle into THUMS version 4.0 model.

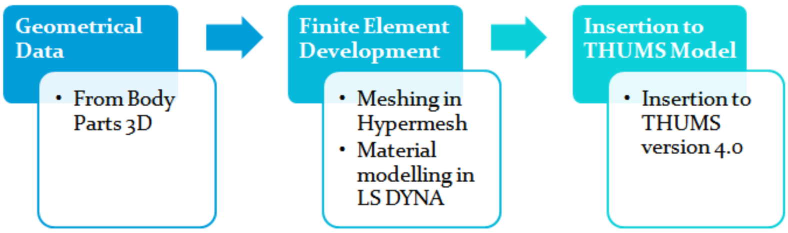


Fig.5: The process of developing FE model of skeletal muscle

3.1.1 Geometrical Data of Skeletal Muscle

The geometrical data of muscles which used in this research was downloaded from Body Parts3D projects [19]. The BodyParts3D is a dictionary-type database for anatomy in which anatomical concepts are represented by 3D structure data that specify corresponding segments of a 3D whole-body model for an adult human male. It encompasses morphological and geometrical knowledge in anatomy and complements ontological representation. Moreover, BodyParts3D introduces a universal coordinate system in human anatomy, which may facilitate management of samples and data in biomedical research and clinical practice. As of today, 382 anatomical concepts, sufficient for mapping materials in most molecular medicine experiments, have been specified. Expansion of the dictionary by adding further segments and details to the whole-body model will continue in collaboration with clinical researchers until sufficient resolution and accuracy for most clinical application are achieved. These geometrical data were developed by the use of magnetic resonance imaging (MRI). The developed models consist of cubic voxels of 2 mm on each side. These models were segmented into 51 anatomic regions. The model was based on size of average japan adult male which has size equal to 172.8 cm height tall and weight 65.0 kg.[20]. The geometrical data of skeletal muscles from this project have been modified in order to match the THUMS size.

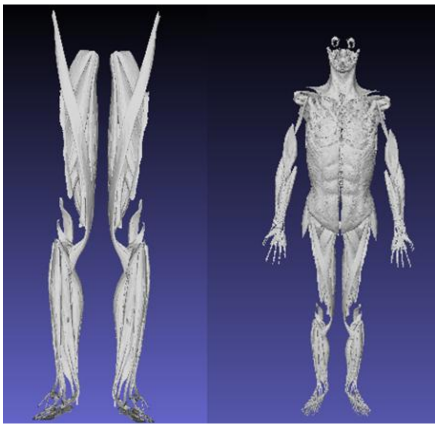


Fig.6: The geometrical from Body Parts3D projects

3.1.2 Finite Element Modeling

Architectural Properties of Skeletal Muscle from Literature

The architectural properties of skeletal muscle which have been used in this research were based some measurenment on the cadavers [21-27]. Table below shown some values of the architectural properties of skeletal muscle.

Table 1: Example of Architectural Properties value of Skeletal Muscle

No	Muscle Name	Mass (g)	Density (g/cm^3)^c	Optimal Muscle Length (cm)	Optimal Fiber Length (cm)	PCSA (cm^2)	Pennation Angle (^{0})	Peak Isometric Forces (N)	Fiber Length / Muscle Length
1	Biceps Femoris Long Head	113.4	1.056	34.73	9.776	11.3	11.6	705.2	0.28
2	Biceps Femoris Short Head	59.8	1.056	22.39	11.03	5.1	12.3	315.8	0.49
3	Gastroc-nemius Medial Head	113.5	1.056	26.94	5.10	21.1	9.9	1308.0	0.19
4	Gastroc-nemius Lateral Head	62.2	1.056	22.35	5.88	9.7	12.0	606.4	0.27
5	Plantaris	12.0	1.056	-	4.8	2.4	0	146.4	-
6	Semimem-branosus	134.3	1.056	29.34	6.90	18.4	15.1	1162.7	0.24
7	Semiten-dinosus	99.7	1.056	29.67	19.30	4.8	12.9	301.9	0.65
8	Soleus	275.8	1.056	40.54	4.40	51.8	28.3	3585.9	0.11

Meshing Procedure in Hypermesh

The geometrical data of the skeletal muscle was meshed using the Hypermesh software. Firstly, the model was meshed by automatic feature for 2D shell mesh with triangle element. The size of this triangle element was set equal to 5.0 following the criteria by Burkhart et al [28] . After successfully meshing with this feature, the shell 2D element then was converted into 3D solid tetrahedral element. After this process, the 1D element was made manually in the surface of the model. After finish this process, the next process was deleting shell element.The final model have 2 element types, the solid tetrahedral elements and the beam 1D elements. The orientation of 1D elements that will act as the fibers of the muscle was set as same as possible with the fibers orientation of the real muscles. Some example of this fibers orientation can be seen in the Fig. 8

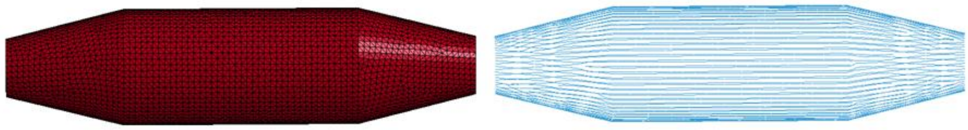


Fig.7: Solid 3D tetrahedral element and line 1D element

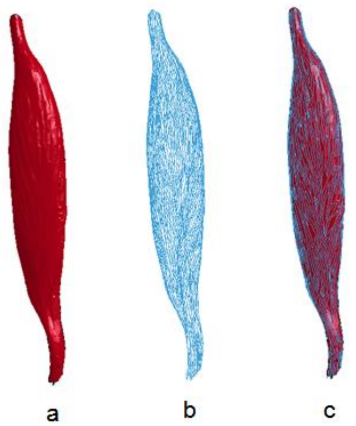


Fig.8: Fibers orientation of Long Head Biceps Femoris. a: Solid 3D element of Long Head Biceps Femoris,b : 1D Beam element, c : Combination of 3D and 1D element

Material Modelling in LS DYNA

The muscle model was developed by combination of 1D element and 3D solid tetahedral element. In order to simulate the passive behaviour of the muscle, the solid tetrahedral elements were modeled by using Ogden material model (LS-Dyna Material model number MAT_181-SIMPLIFIED_RUBBER/FOAM) and the 1D elements were used to simulate the active behaviour of the muscle. Material number 156 based on Hill's Muscle (MAT_156_MUSCLE) model was applied in this 1D truss element. Modeling the muscle by the combination of 3D element and 1D element have been published also by Iwamoto et al [5] and Hedenstierna et al [12].

In order to successfully modeling this active material of muscle, several active functions graphs are needed. Below is given the graph of normalized force versus length function and the graph of normalized force versus velocity function.

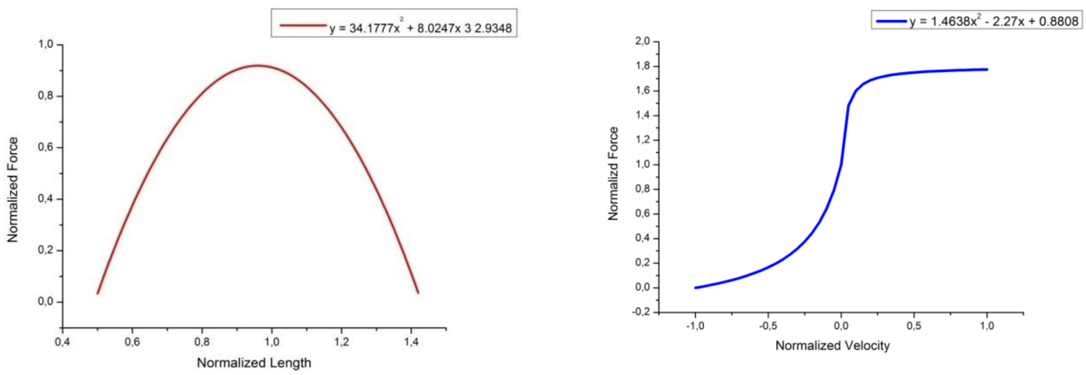


Fig.9: Normalized length vs normalized force graph and normalized velocity vs normalized force graph

3.2 Crash Simulation Set Up

3.2.1 Vehicle Finite Element Model

Vehicle Finite element model that was used in this research is come from National Crash Analysis Center (NCAC) of The George Washington University [29]. This model is available online and can be downloaded for free. In this research Pick Up Truck Chevrolet C2500 1994 was choosed as the vehicle model. In order to reduce time calculation, the reduced version (10500 elements) was used in the simulations.

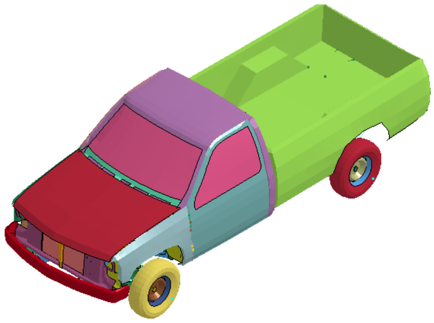


Fig.10: Pick up truck Chevrolet C2500 10.500 Elements

3.2.2 Total Human Body for Safety (THUMS) Academic Version 4.0

A Finite Element Model of Pedestrian that was used in this research is called Total Human For Safety (THUMS). The THUMS is a human FE model jointly developed by Toyota Motor Corporation and Toyota Central R&D Labs., Inc. The model aims to simulate human body kinematics and injury responses in car crashes. The geometries of the human body parts are represented by FE meshes and their material properties are defined assuming constitutive laws. There are versions and variations in THUMS. The basis is an average size adult male (AM50%ile) model which has a height of 175 cm and a weight of 77 kg. A small size female (AF05%ile) model and a large size male (AM95%ile) models have been developed. Each model has two postures; one is a sitting posture representing a car occupant, and the other is a standing posture representing a pedestrian.[30]

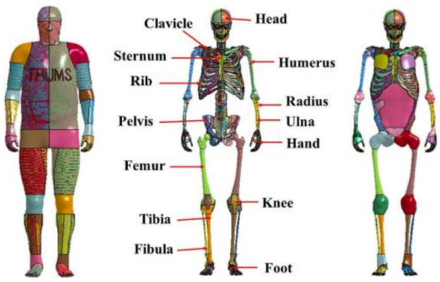
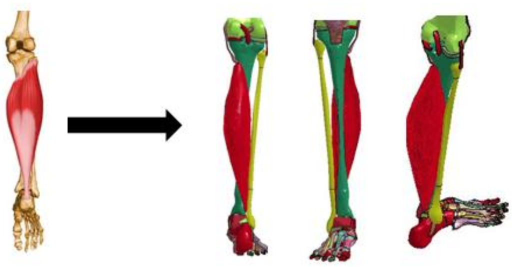


Fig.11: Total Human Model for Safety (THUMS) version 4.0

3.2.3 Inserting the muscles model into THUMS Model



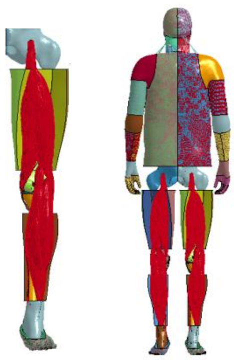


Fig.12: Inserting muscle model into THUMS Model (example : Soleus muscle)

The muscles that have been succesfully developed than were inserted into the THUMS Pedestrian model. The insertion was made by sharing nodes and elements between the muscle model and the bone. As preliminary study, there were 8 important muscles in the leg were inserted such as Long Head Biceps Femoris, Short Head Biceps Femoris, Medial Head of Gastrocnemius, Lateral Head of Gastrocnemius, Soleus, Plantaris, Semimembranosus and Semitendinosus.

3.2.4 Simple Biceps Brachii simulation set up

In order to know the characteristics of the active muscle model which have been developed, the simple biceps simulation were conducted. The simple biceps was fixed in the both of its end (isometric contractions). Then, this model was put in the top of the rigid plate. This muscle then was impacted by the rigid ball impactor which has mass equal to 100 gram with impact velocity equal to 10 Km/h.

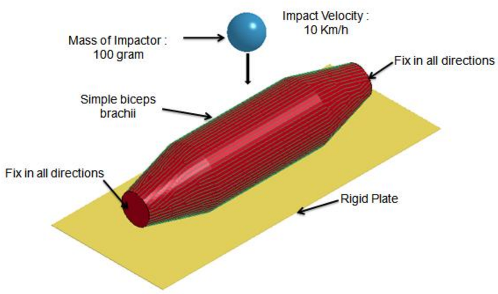


Fig.13: Simple Biceps Brachii Simulation set up

3.2.5 Vehicle-Pedestrian simulation set up

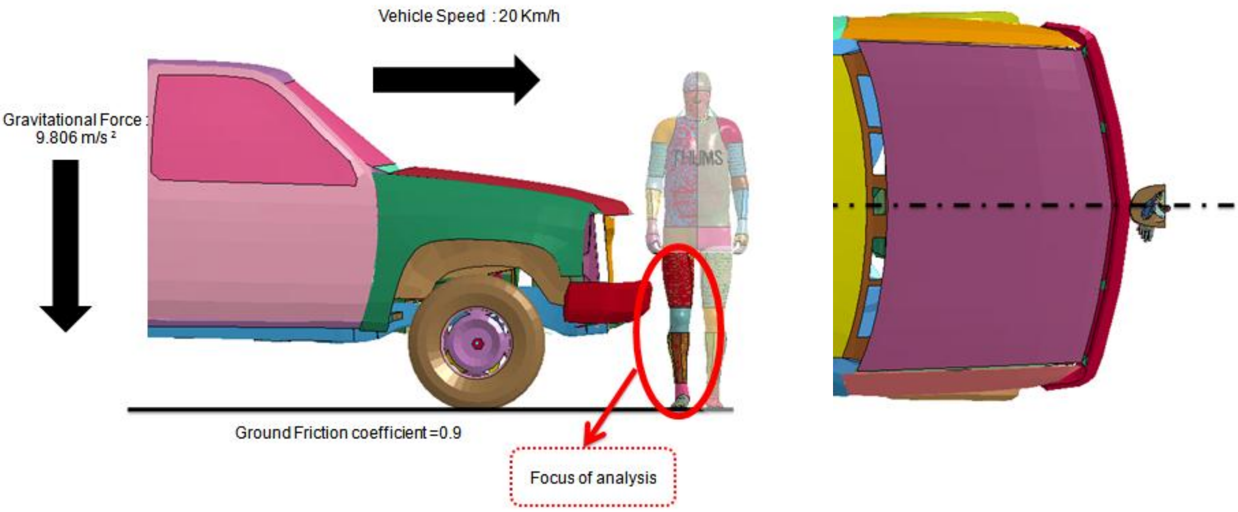


Fig.14: Vehicle-Pedestrian Leg simulation set up

The vehicle-pedestrian crash simulation was also conducted in order to know the response of active muscles contraction. In order to reduce calculation time, the analysis was focusing on the right leg of the THUMS model. The leg of THUMS with active muscle was initially positioned in front of the car centerline. The vehicle was set to impact the leg of the THUMS model at the velocity of 20 Km/h. The contact friction coefficient between the THUMS Leg and the vehicle was set equal to 0.3 and the ground friction was set equal to 0.9. The gravity acceleration was set equal to 9.806 m/s^2 . The THUMS leg was hit by the vehicle immediately after the start of the calculations.

4 Results and Discussion

4.1 Simple Biceps simulations

4.1.1 Shortening and lengthening simulation

Firstly, the simple biceps was analysize based on shortening (concentric contractions) and lengthening (eccentric contractions) characteristics. The muscle was fix in the right side of its end.

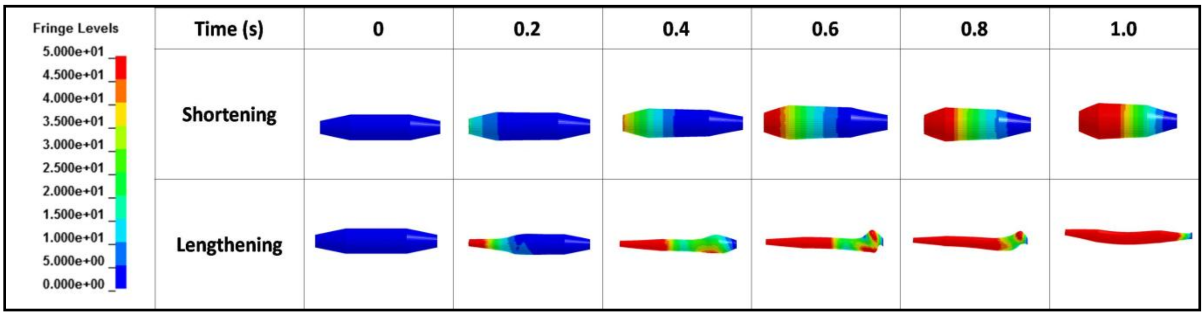


Fig.15: Total displacement contours in concentric contractions and eccentric contractions of simple Biceps Brachii muscles at activation equal to 10%

Fig.15 shows the muscles model can mimic the contraction behaviours of the muscles. In order to get shortening behaviours, the Peak Isometric Force properties were set in positive value. For the lengthening behaviour, the Peak Isometric Force properties should be set in negative value.

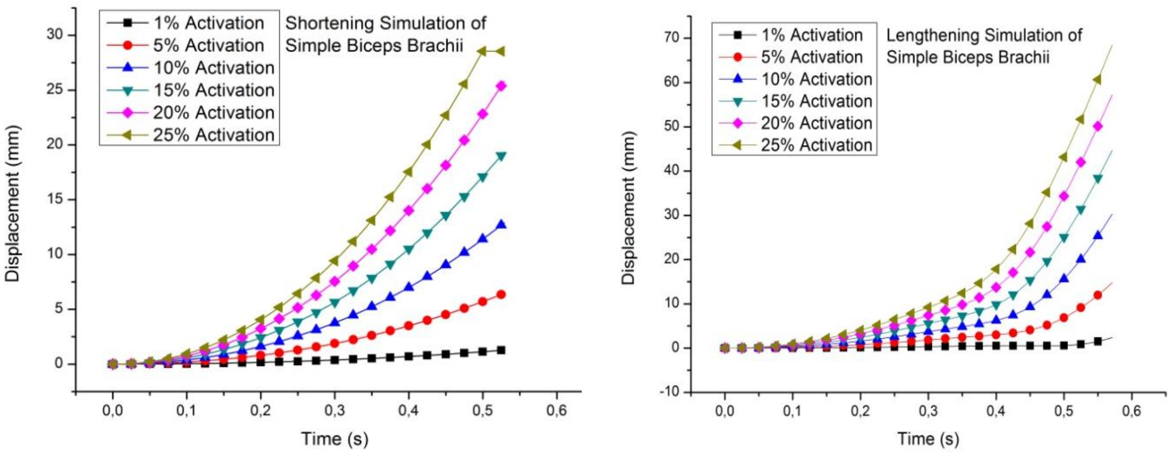


Fig.16: Displacement vs time graph of the Shortening and Lengthening behaviours of Biceps Brachii in different values of activation

The effects of different activation into the displacement of the muscles can be seen in t Fig.16. The displacements of the active muscles increased when the activation level of the active muscle were also increased. The displacement behaviour of shortening and lengthening muscles had same trend and characteristics but the displacement values were different. The lengthening muscles got higher displacement values than shortening muscles, this was caused by the starting point of the contractions. When the muscles was shortening, It was started in the left end then it contracted from left end to the right end, and it was againts its passive properties. But in case of lengthening, the muscles itself was started from the left end and then contracted to the left direction. Therefore, it was not againts its passive properties. Thus, the displacement value of shortening muscle was lower than lengthening muscles contraction.

4.1.2 Simple Biceps Isometric Simulation and Kinematics

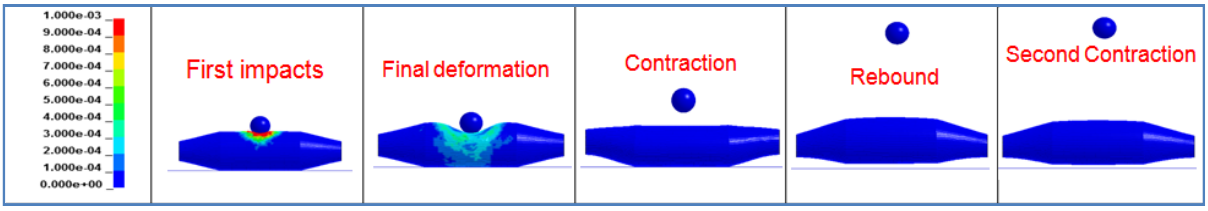


Fig.17: Simple biceps isometric simulation (contour : von Mises stress)

In order to know regarding stiffness characteristic of the active muscles, the simulation of isometric contraction behaviours of the simple muscles were also conducted. The both end of the muscle were fixed and the muscles was impacted by a rigid ball. The kinematics behaviours of that muscle can be seen in the Fig 17.

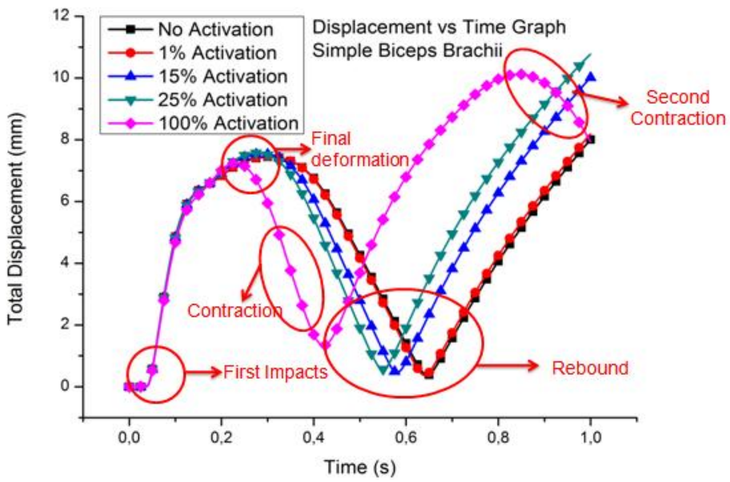


Fig.18: Displacement vs time graph of simple Biceps Brachii in isometric contraction condition with different activation level.

When the muscles impacted by the rigid ball, it was deforming in order to absorb the kinetic energy of the impactor. After all the kinetic energy of the impactor was absorbed, it started to contract until reached its maximum contraction value. Because the passive properties of the muscles was modeled as rubber like-materials, it was started to rebound. Again, because it has active properties, the simple muscles was starting to contract, and it contracted until it came back into its normal position. The displacement characteristic of this isometric contraction can be seen in Fig. 18.

The most important properties while modeling the active muscle is the stiffness change properties. When the muscle contracts it should has higher stiffness than when it is just in normal situation. Fig 19 shows stiffness variation of simple muscle model in isometric contraction based on different activation. This stiffness value was calculated when the muscle got its maximum displacement. It is found that the stiffness of the muscle increased when the activation level also increased.

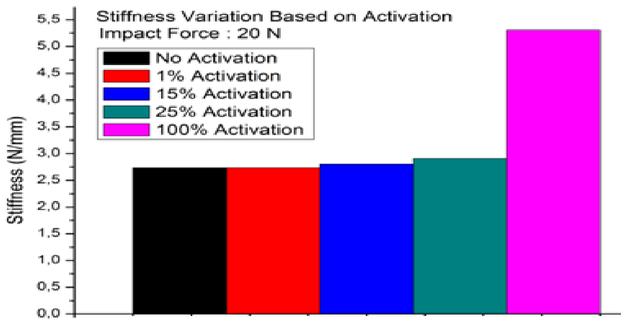


Fig.19: Displacement vs time graph of simple Biceps Brachii in isometric contraction condition with different activation level.

4.2 Vehicle-Pedestrian leg simulation result

After conducted the simulations in order to characterize the active behaviours by using a simple muscle model, the vehicle-pedestrian crash simulation were also conducted. For reducing computational time, in the present study, the simulation was focusing on the Right Leg of the pedestrian. As explained previously, there were 8 3D muscles model inserted into the Leg of the THUMS model. These muscles were choosed because these muscles are important for standing position of the human. The activation level of those muscles were set equal 0 and 10%. Because , as long as authors found, there were no literatures regarding activation value of pedestrian muscles.

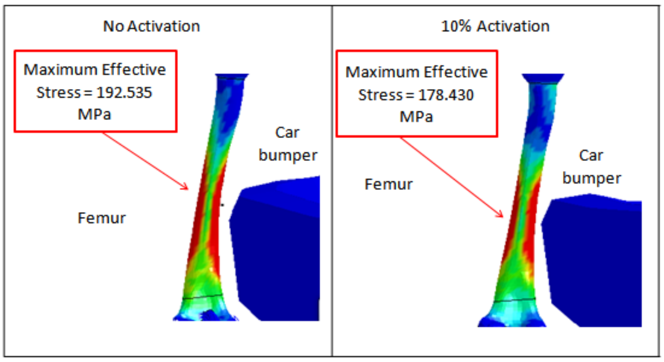


Fig.20: Comparison of Effective stress in Femur

The results of the simulations can be seen in the figure 20. In that figure, the effective stress distribution of the Femur is given. When the femur hit by vehicle without active muscles, the maximum stress of the Femur were equal to 192535 MPa. But, when all of the muscles in Femur and Tibia were activated with 10 percent activation, the maximum effective stress were equal to 17843 MPa. From the results above, can be concluded that the active muscles contraction has effects to the pedestrian injury in this case the effective stress in the Femur were decreasing when the muscles contracted.

5 Summary

It has successfully developed a 3D Finite Element Model of Active muscles with real 3D geometries. These muscles were developed by the combination of solid 3D tetrahedral elements with line 1D beam elements. In order to mimic the passive properties of the skeletal muscle, an Ogden material model was implemented for solid tetrahedral elements. To simulate the active behavior of the these muscles, a Hill-type muscle model for the line beam elements was implemented. Based on the simulation that were conducted, these muscles model can mimic the contraction behaviour of the human muscles. It has also proven that these muscles can has different stiffness value by changing its activation level. These muscles were also successfully inserted into THUMS Pedestrian Model. Then, from the vehicle- pedestrian leg simulation can be concluded that the active muscles contraction can reduce the injury of the pedestrian, in this case, the effective stress in the femur were decreasing when the muscles contracted. This present study is still in the beginning study regarding active muscle contraction effects in the pedestrian during the pedestrian-vehicle crash. For the next study, there must be an experiment and measurenment regarding the activation level of the pedestrian when its in standing and walking position and also when its in danger situation (when the vehicle seems will hit the pedestrian) . This can be done probably by the combination of EMG measurenment and 3D virtual-reality video simulation.

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