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REVIEW ARTICLE

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REVIEW OF METHODS USED TO INVESTIGATE MECHANICAL PROPERTIES OF SKELETAL MUSCLE

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ABSTRACT

Skeletal muscle generates force within the body which results in motion and provides stability to the body. Physiological and mechanical study of muscle is crucial to the enhancement of clinical applications and therapies to improve its performance as well as in tissue engineering. To understand the mechanical behavior of the skeletal muscle, need to understand the structure, architecture and geometry of muscle; with relationship between force-length-velocity of its contraction as physiological aspect. The skeletal muscle material behavior is often not described properly. Skeletal muscle exhibits material non linearity in stress and strain relation. It is simulated using viscoelastic, hyperelastic, transversely isotropic and anisotropic material to identify its characteristics. Hence this paper reviews several experimental methods and numerical model that have been used to depict the stress-strain relation to study the material behavior of the skeletal muscle.

Since the skeletal muscle has poisoned ratio 0.499; therefore, it exhibits incompressible material behavior. The skeletal muscle has shown fibrous structure, then it also consider for transverse isotropy and anisotropic material behavior. Therefore, several studies based on numerical models and experimentation [Tension - Compression test of skeletal muscle] were done to identify its response in terms of stress, strain and deformation with respect to its material behavior. Therefore, this paper summarizes and discusses all the methods and models of focusing on the material behavior of the skeletal muscle.

Keywords: viscoelastic, hyperelastic, transversely isotropic, anisotropic, incompressible

1. INTRODUCTION

Modeling and simulation of skeletal muscle has been an important domain for the researchers in the field of biomechanics, tissue engineering, ergonomics, and crash analysis of the vehicle. The numerical and graphics based modeling and simulation of human response to perform the required function helps to improve the design of medical devices. It is very challenging to model human skeletal muscle to study its behavior computationally due to the immense complexity of the human body and muscle structure itself. Computational modeling of human skeletal muscle must have an accuracy in the construction of its anatomical structure, physiological function and mathematical models. This review focuses on mechanical behavior of skeletal muscle using numerical and experimental methods. The material behavior of skeletal muscle is crucial to improve the accuracy in the field of biomechanics and physiology of its clinical applications. It helps to understand the material aspect of skeletal muscle and its stiffness. The skeletal muscles have a non linear relation of stress and strain and are incompressible because its poisson's ratio of the order of 0.499. With the keen perception to identify material behavior of skeletal muscle this review collectively surveys several research and studies on the different behavior with the use of numerical models and experimentation.

Initially the research which represents physiological, biomechanical and human models based on rigid skeletons (Hanson, J & Huxley HE, 1953; Huxley AF, 1969; Huxley AF and Simmons 1971; Paul et al., 1959; Badler & Smoliar, 1979 and Magnenat, 1985) is studied. Later, the physically unrealistic muscle model to present elastic deformation of soft tissues (Chandwick et al., 1989) is reviewed. Several researchers have put in efforts to model realistic muscle to represent the muscle shape and deformable behavior. At the end, anatomical studies by constructing muscle geometry has been reviewed (Wilhelms, J., 1997; Scheepers et al., 1997; Nedel & Thalmann, 1998 and Aubel & Thalmann, 2001). The use of medical imaging technique has improved the visual quality and realism of muscle geometry (Ng-Thow-Hing & Fiume, 1999). The realistic muscle geometry has developed a need to describe the muscle deformable characteristics during its contraction. With this perception, several methods and approaches have been proposed to identify the mechanical properties of skeletal muscle like Mathematical formulation and experimentation under tension-compression test. Most of the research work was done in the direction of understanding mechanical properties and physiological function of skeletal muscle.

Mechanical properties and function of skeletal muscle was studied numerically with two different models. One is a continuum based model in which active and passive behavior of skeletal muscle was studied during the contraction considering hyperelasticity. Cauchy or true stress induced in skeletal muscle in the eccentric and concentric contraction was determined assuming its hyperelasticity and viscoelasticity. At the end, with the rigorous numerical formulation for the mechanical behavior of skeletal muscle, constitutive model was formulated (Martins et al., 1998; Van Loocke et al., 2006; Van Loocke et al., 2008; Van Loocke et al., 2009; Tang et al., 2009; Lu et al., 2011; Ito et al., 2010; Choudhry et al., 2008 and Meyer et al., 2011). Another numerical method used is finite element method to simulate the hyperelasticity of skeletal muscle coupled with fatigue as well as different strain rates (Martins et al., 1998; Tang et al., 2007; 2009 and Lu et al., 2011). Finite element models of the human body were developed to study the deformations for static and transient loading (Raul et al., 2008)

Experimentation was performed on different animal skeletal muscle tissues to examine the hyperelasticity and anisotropy with different strain rates. Transversely isotropic material properties of skeletal muscle have been determined experimentally under tension, studies concluded that muscle is stiffer in fiber direction as compared to transverse direction (Van Ee et al., 2000; Mathur et al., 2001; Linder-Ganz & Gefen, 2004 ; Blemker et al., 2005 ; Morrow et al., 2008 and Morrow et al., 2010), muscle under compression infers that it is much stiffer in the transverse direction than in the fiber direction (Van loocke et al., 2006; Bol et al., 2008 and Bol et al., 2012). Furthermore, several researchers examined the muscles experimentally under tensile loading and stated that muscle is stiffer in transverse direction than in the fiber direction (Van Loocke et al., 2006; Nie et al., 2011 and Machael Takaza et al., 2013).The mechanical behavior of skeletal muscle is dependent on fiber direction in tension – compression.

Thus the aim of this article is to 1] review the anatomical and physiological properties of skeletal muscle contraction 2] review the mathematical formulation of basic active and passive characteristics of skeletal muscle with hyperelasticity 3] survey the deformable characteristics of skeletal muscle using Finite Element Method 4] review the researches on experiments on animal skeletal muscle under tension and compression to depict its hyperelasticity and anisotropy 5] Discuss the results, limitations and clinical applications of studies. The information may better contribute to the understanding of mechanical behavior of skeletal muscle and the review will influence the direction of future research.

2. Background

Muscles contribute 50% of body weight and are responsible for the motion of the body by generating forces. Muscles are of three type's cardiac, skeletal and smooth muscle depending on their physiological functions. The walls of the heart are of cardiac muscles and smooth muscles makes up the walls of blood vessels or other organs. The contractions of both these muscles are involuntary type of contraction and it is controlled by nervous system, where as skeletal muscle shows voluntary contraction. The movement of the human body is due to the force generated by voluntary contraction of skeletal muscle. Several researchers have focused on physiological structure and functions of skeletal muscle in the fields of biomechanics, sports medicine, medical rehabilitation and robotics (Lee et al. 2010). In this section, brief review of structural, architectural details and contraction of skeletal muscle is described.

2.1 Structure

Each skeletal muscle fiber is a single cylindrical muscle cell. An individual skeletal muscle may be made up of hundreds, or even thousands, of muscle fibers bundled together and wrapped in a connective tissue covering. Each muscle is surrounded by a connective tissue sheath called the epimysium. The fascia, the connective tissue outside the epimysium, surrounds and separates the muscles. Portions of the epimysium project inward to divide the muscle into compartments. Each compartment contains a bundle of muscle fibers, see figure 1. Each bundle of muscle fiber is called a fasciculus and is surrounded by a layer of connective tissue called the perimysium. Within the fasciculus, each individual muscle cell, called a muscle fiber, is surrounded by connective tissue called the endomysium (Martini & Nath, 1997). It shows that muscle is composed of oriented fibers to perform its basic function of force generation. One of the important components in the structure is the tendon, which transmits forces generated by muscles to the bone. Aponeurosis is the area where the tendon connects to the muscle. The end of the muscle attached to the stationary bone is known as the origin or proximal end and the opposite end to movable bone known as insertion or distal end. Tendons are mechanically much stiffer as compared to muscle when pulled because it has a parallel arrangement of collagen fibers closely bundled together (Lee et.al, 2010).

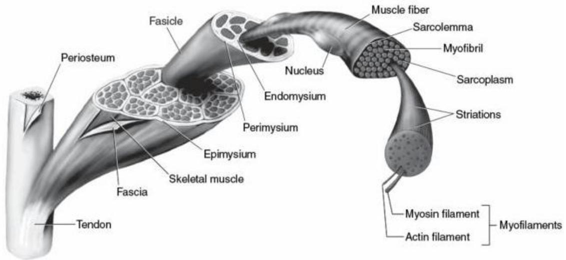


Figure 1: Structure of skeletal muscle
(From Whiting & Rugg, Dynatomy, 2005)

2.2 Architecture

Skeletal muscle architecture is defined as the arrangement of muscle fibers relative to the axis of force generation. The internal arrangement of the fascicles within a skeletal muscle refers to the angular orientation of fascicles along the length known as pennation angle. It has arrangements as numerous as themselves, but majorly it is categorized into four types as parallel or fusiform, unipennate, bipennate and multipennate. Parallel muscles are larger muscles with fascicles arranged parallel to one another along the length. Muscles with the angular orientation called pennation angle between the tendinous attachment and the length of the muscle falls in the category of pinnate muscle. The Unipennate muscle group has only angular orientation while bipennate muscles have symmetry of orientation about tendinous attachment and multipennate muscles have more angular orientation than the bipennate, as illustrated in figure 2. The functional effect of muscle architecture can be simply stated as: muscle force is proportional to the physiologic cross-sectional area (PCSA), and muscle velocity is proportional to muscle fiber length (Zajac FE, 1989).

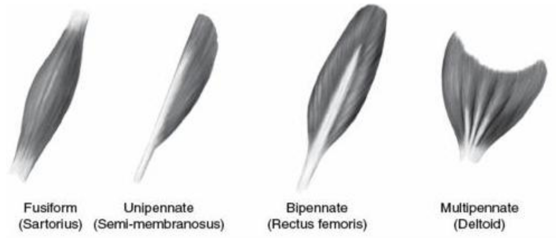


Figure 2: Muscle fiber arrangement
(From Whiting & Rugg, Dynatomy, 2005)

2.3 Types of muscle contraction

The central nervous system controls the voluntary muscle contraction. The central nervous system releases the impulse in the form of action potentials to the motor neuron that innervates several muscle fibers which stimulates the flow of calcium resulting into sliding action of filaments (Jones et al. 2004). Thick filament (myosin) and thin filaments (actin) slide over one another to shorten the muscle during contraction. Cross bridge theory and sliding filament theory describe a process used by muscle to contract (Hanson, J. & Huxley, H.E., 1953; Huxley, A.F., 1969; Huxley & Simmons 1971 and Rayment et al., 1993). Sliding filament theory is also known as walk along theory or Ratchet theory. In muscle shortening the thick and thin filaments do not shorten. Contraction is accomplished by the thin filaments from opposite sides of each sarcomere sliding closer together or overlapping the thick filaments further. Skeletal muscle contraction can be classified on the basis of change in its length during the contraction and force level as illustrate in figure 3. In spite of the fact that the muscle actually shortens only in concentric contractions, all are typically referred to as "contractions". In isotonic contraction the tension in the muscle remains constant despite a change in muscle length. This can occur only when a muscle's maximal force of contraction exceeds the total load on the muscle. In concentric contraction the force generated is sufficient to overcome the resistance, and the muscle shortens as it contracts. This is what most people think of as a muscle contraction. In eccentric contraction the force generated is insufficient to overcome the external load on the muscle and the muscle fibers lengthen as they contract. An eccentric contraction is used as a means of decelerating a body part or object, or lowering a load gently rather than letting it drop. In isometric contraction the muscle remains the same length. An example would be holding an object up without moving it; the muscular force precisely matches the load, and no movement results. In isovelocity contraction (sometimes called "Isokinetic") the muscle contraction velocity remains constant, while force is allowed to vary. True isovelocity contractions are rare in the body, and are primarily an analysis method used in experiments on isolated muscles that have been dissected out of the organism.

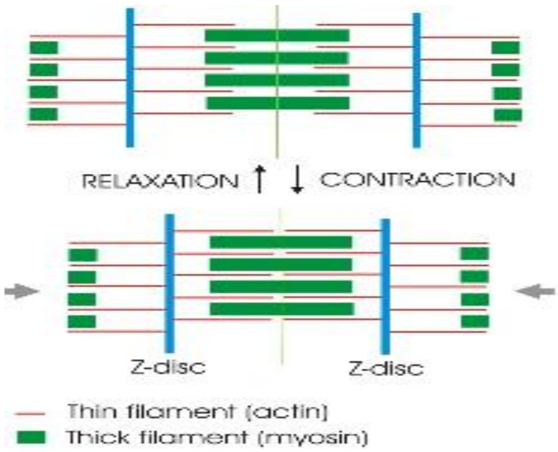
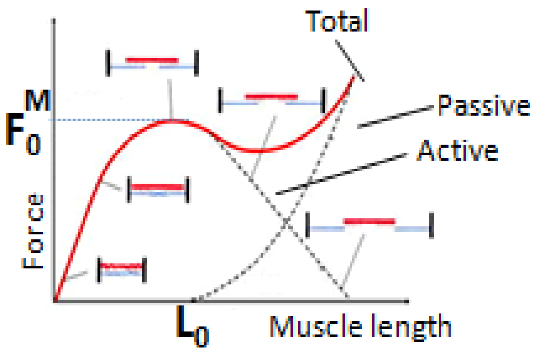


Figure 3: Actin-myosin filaments sliding action during contraction of skeletal muscle
(From Gardel et al., 2006)

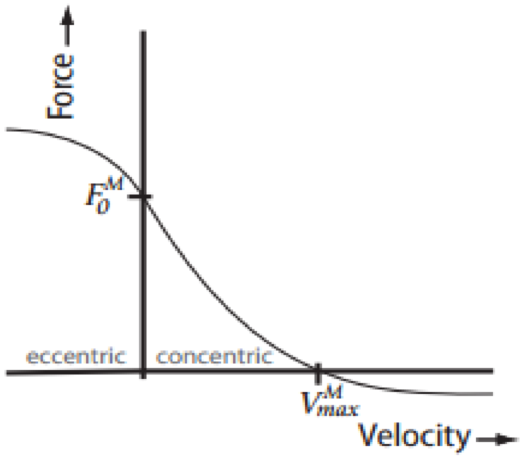
3. Mechanical properties

Research initiated in the direction of mechanical properties of skeletal muscle was in terms of muscle length during the contraction and force generated as well as the velocity of contraction. A total force generated by the muscle is the sum of active and passive force and influenced by the muscle length. Passive force is the restorative force generated by the skeletal muscle against the stretch without activation. On the other hand, active force is force generated due to the interaction of actin myosin contractile proteins with skeletal muscle activation. The relationship of the force - length is non linear in consistent with the muscle contraction (Lee et al., 2010). Basically, active force is obtained by subtracting the passive force from the total force. As muscle stretches to its maximal length, passive force increases exponentially. Active force is maximal at the resting length of the skeletal muscle. It shows parabolic relationship between force and length of muscle for the active force as they are not measured directly as illustrated in figure 4 (Brodie TG, 1895; Haycraft JB, 1904; Evans & Hills, 1914; Banus & Zetlin, 1938; Ramsey & street, 1940; Gordon et al., 1966; Stolov & Weilepp, 1966; Tabary et al., 1972; Tabary et al., 1976; Williams & Goldspink, 1978; Astrand & Rodauhl, 1986 and Gajdosik et al., 2001).

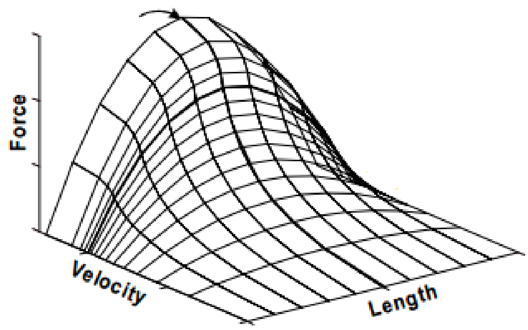
Force-Velocity relationship for concentric and eccentric contraction is illustrated in figure 4 (b). It shows the maximum velocity of shortening of skeletal muscle when no external force is applied to the muscle. In concentric contraction as the external load comes into action, the force generated by muscle increases and velocity of shortening decreases because of the time taken for participating cross bridges to generate the force. When a maximum isometric force (F_0^M) is generated, more time is taken in the recruitment of more number of cross bridges and velocity of shortening is minimal. Therefore, it is necessary to study the mechanical properties of skeletal muscle contraction to identify the small variation from its expected behavior during the muscle drive in movement of the human body.



(a)



(b)



(c)

Figure 4: Mechanical properties of skeletal muscle in terms of Force- length (from Zajac FE, 1989; Gajdosik et al., 2001 and Odegard et al., 2008,]. (a) Force-Length plot, where F_0^M is the maximum isometric force generated by muscle and L_0 is the optimal length or resting length. (b) Plot of force-velocity shows the changes in force generation in muscle contraction with respect to change in velocity of contraction.(c) 3D plot of force-velocity-length shows interdependent relationship.

3.1 Numerical Formulation

It is necessary to understand the mechanical properties and physiological function of skeletal muscle at the microscopic and macroscopic level. Historically, many bio mathematical models of skeletal muscle have been developed. Past models were focused on narrow (and at times, isolated) aspects of the excitation–contraction coupling process. Examples include: (1) phenomenological energy-conversion models, which may consider only one or two steps in the biochemical sequence of events (Bornhost & Minardi, 1970). (2) Generalized Voigt, Maxwell, and Kelvin viscoelastic models, which applies to any one of many biological materials (Fung, YC, 1993). (3) Models that are applicable under certain conditions, such as Hill's model that applies to tetanised whole muscle; and (4) microscopic models, such as the H.E. Huxley cross-bridge model. First order differential system based model was used to predict the effect of calcium turnover during contraction. The first mathematical model proposed by V. Comincioli et al, composed of Series elastic elements in series with the contractile element to describe the cross bridge mechanics of active muscle. It also described the dynamics of muscle contraction at the macromolecular level (Comincioli et al., 1984; Comincioli & Naldi, 1990 and Hill, TL et al., 1975). The classic cross bridge model was refined with two simple adaptations, first was steady state force depression described by single scalar variable and the second was dynamic, history dependent cross bridge described by fading memory (Wu & Herzog, 1999). Electrical simulation based mathematical models were also used to predict a variety of nonlinear properties of skeletal muscle, which found the use in physiological based design of control strategies of Neuro-prosthesis (Frey & Shields, 2005; Frey & Shields, 2006 and Stephen, 1997). Several mathematical models were focused on the active and passive behavior of skeletal muscle for force-length, the force – velocity relation of muscle contraction. These models were based on a differential equation with static and dynamic condition with fiber recruitment rate and fiber type within the muscle (Wexler et al., 1997; Rasmussen et al., 2001; Neidhand-Doll et al., 2004; Zakotnik j., 2006 and Chin et al., 2006). More numbers of numerical models were formulated to simulate the mechanical properties of skeletal muscle with the assumption of isotropic and homogeneous material behavior of the muscle (Colli & Math, 1986; Colli et al., 1988; Colli P., 1989; Comincioli & Torelli, 1983; Comincioli et al., 1984; Comincioli & Torelli, 1988; Gastaldi & Tomovelli, 1984; Gastaldi & Tomovelli, 1987 and Allain & Colli, 1988). Later on mathematical models were refined further and formulated based on strain energy density function with the consideration of hyperelastic, viscoelastic and anisotropic skeletal muscle (Martins et al., 1998; Odegard et al., 2008; Tang et al., 2009; Calvo et al., 2010 and Grasa et al., 2011). These models were well examined for the active and passive response of the skeletal muscle with the fiber orientation within the muscle mass. Skeletal muscles drive the movement of the human body so with this keen perception, various researchers have formulated the numerical tool to predict the functioning and mechanical properties of skeletal muscle. The muscle tissue shows the non linear hyperelastic or viscoelastic and anisotropic behavior. To this end, mathematical formulation and constitutive relation were well defined by C. Y. Tang to describe the hyperelastic properties of skeletal muscle and it is given in detail in following section

3.1.1 An improved 1D numerical algorithm for concentric and eccentric contraction:

C. Y. Tang et al. refined and proposed basic Hill-type three components, muscle model consisting of a contractile element (CE) in series with a series elastic element (SEE) and in parallel with a parallel elastic element (PEE) as illustrated in figure 5 (a). The model was formulated to simulate the active and passive behavior of skeletal muscle considering the fiber recruitment in the muscle as activation function of the muscle see figure 5 (b).

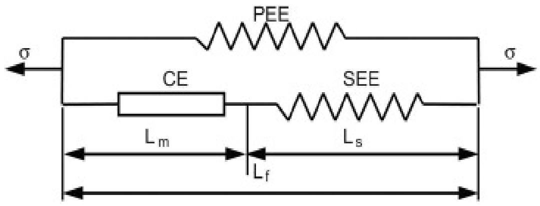


Figure 5(a): Basic Hill Type Three element

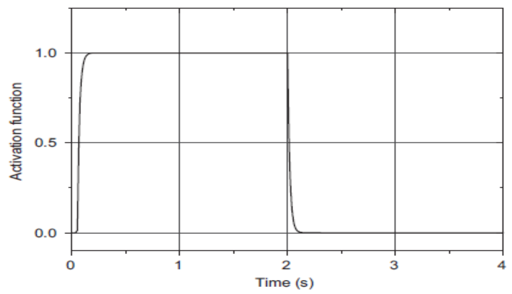


Figure 5(b): Activation function Skeletal muscle model (From Tang et al., 2009)

Stress Produced in Contractile element (CE): The stress $\sigma_m^{t+\Delta t}$ produced by the contractile element in the case of the concentric contraction of the muscle at time $t+\Delta t$ is given by (Eqn.1).

$$\sigma_m^{t+\Delta t} = \sigma_0^t * \alpha_a^{t+\Delta t} * \left[\frac{1+\Delta\lambda_m/\Delta\lambda_{m0}}{1-k_c\Delta\lambda_m/\Delta\lambda_{m0}}\right] \quad (1)$$

Where σ_0^t is the stress corresponding to the fibre stretch t_{λ_f}, $\alpha_a^{t+\Delta t}$ is the muscle activation function see figure 5 (b), and $\Delta\lambda_{m0}$ is given by (Eqn.2).

$$\Delta\lambda_{m0} = \Delta t\dot{\lambda}_{m0} \quad (2)$$

Where, $\dot{\lambda}_{m0}$ is the stretch rate of the contractile element which corresponds to the maximum isometric tetanised force.

The stress $\sigma_m^{t+\Delta t}$ produced by the contractile element in the case of the eccentric contraction of the muscle at time $t+\Delta t$ is given by (Eqn.3).

$$\sigma_m^{t+\Delta t} = \sigma_0^t * \alpha_a^{t+\Delta t} * \left[d-(d-1)\frac{1-\Delta\lambda_m/\Delta\lambda_{m0}}{1+k_e k_c\Delta\lambda_m/\Delta\lambda_{m0}}\right] \quad (3)$$

Where, d is a parameter quantifying the force offset with respect to the isometric case due to the eccentric movement.

Where, $k_c = \sigma_0^t/a_v$ and k_e are the shape parameters of the hyperbolic tension force – velocity curve of contractile element.

a_v is the material parameter of skeletal muscle.

The above numerical formulation was implemented in the finite element model with the use of user defined subroutine for material in finite element simulation software. Using above mathematical formulation Tang et al calculated the stress in the contractile element with respect to the stretch rate, see figure 6.

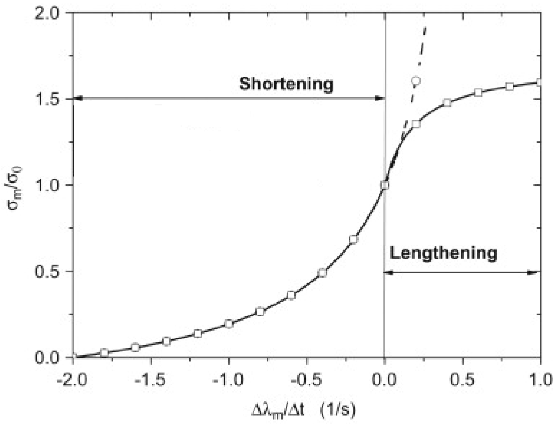


Figure 6: A plot of normalized stress-stretch rate of the CE element in Eccentric and concentric contraction

3.1.2 Finite Element Model

Finite element method is a widely used tool to simulate the mechanical properties and functioning of skeletal muscle. Several researchers have proposed the finite element model to simulate and determine the mechanical parameters of the muscle tissue with the pair of experimental data and the constitutive numerical models. Hill's (Hill, A.V., 1938) type muscle model is used for development of finite element model of contraction of skeletal muscle from one dimensional to three dimensional. Classical Hill's model was extended with the consideration of pennation angle of muscle and tendon (Zajac, FE, 1989). Van Leeuwen and Kier used the discrete model to formulate the finite element method of skeletal muscle response (Van Leeuwen & Kier, 1997). This model found difficulties to satisfy the volume incompressibility condition. It determines the pressure inside the element of the constraint equation to satisfy volume condition, but this pressure is not close to the pressure in reality that is calculated by continuum models. Bovendeered used weighted residual method as a key method to simulate the deformation of skeletal muscle, but is more time consuming (Bovendeered, PHM, 1990). One dimensional Hill's model was later refined into three dimensional models by Kojic et al. and gave the computational method to determine the nodal forces and stiffness of finite element (Kojic et al., 1998).

The finite element models based on the approach of Hill's three element models are used to determine the force-length relation of muscle and velocity-force characteristics of skeletal muscle with the use of activation function to define time dependent behavior of skeletal muscle (Kojic et al., 1998; Tsui et al., 2004; Chen & Zelter, 1992; Van der Linden et al., 1998 and Van der Linden, 1998). Researchers also used this model to determine the stress and strain distribution in the skeletal muscle with three dimension model (Johansson et al., 2000; Kojic et al., 1998 and Tsui et al., 2004), to simulate the deformation of a 3D skeletal muscle and its shape change (Martins et al., 1998 and Chen & Zelter, 1992). The model proposed on another approach was based on two states Huxley model

(Huxley, AF, 1974) in which cross bridges were considered. The resulting models estimated the strain distribution in skeletal muscle due to inhomogeneous fiber distribution in muscle mass (Oomens et al., 2003) and identified the muscle, tendon complex (Tsui et al., 2004) see figure 7. Another type of model was based on two separate domains: intracellular and extracellular matrix linked elastically by finite element meshes (Yucesoy et al., 2002). Blemker et al. proposed the model with the assumption that muscle is fiber reinforced composite to predict the effect of such architecture on the strain distribution in biceps brachii muscle (Blemker et al., 2005). The Finite element model also determined the effect of muscle fatigue induced by immense athletic and military marching on the stress rate and stability of the foot (Gefen, A., 2000) without the effect of fatigue on the distribution of stress in the muscle structure.

To this end, 3D finite element model proposed by C. Y. Tang was used to determine the effect of muscle fatigue on mechanical behavior of skeletal muscle (Tang et al., 2005). Finite element model of the human body was developed to study the deformations for static and transient loading (Raul et al., 2008). The non linear hyperelastic and viscoelastic passive behavior of skeletal muscle well explained the response of muscle under isometric, eccentric and concentric contraction of muscles (Martins et al., 1998; Bossboom et al., 2001; Tang et al., 2009 and Williams et al., 2011). The constitutive relation was formulated numerically and numerical algorithm was developed for finite element method. Deformation and stress- strain relation of skeletal muscle was simulated by finite element method using a numerical algorithm in ANSYS, PAK and ABAQUS software's with user defined subroutine for material as illustrated in figure 8. This numerical formulation satisfied the near incompressible and hyperelastic material condition with applied constraints. Hamid Khodaei et al. modelled the muscle tissue with a combination of discrete and continuum elements. Finite element model of skeletal muscle of rabbit was divided into five parts see figure 9. The model was simulated considering visco-hyperelasticity for three different force length curves. The parameters were used to define the viscoelasticity as illustrate in table 1. This FE model was meshed and elements were oriented as per the fiber orientation within the muscle to exactly simulate the muscle model. The geometry was meshed using eight node solid brick elements. Furthermore, the tendon parts of the muscle at both ends were modelled by linear elastic material. A user-defined material (see figure 8) routine was developed for LS-DYNA and Cauchy stresses were calculated. The simulations were performed for elongation of the passive as well as active muscle with strain rates of 1, 10, and 25s^{-1}. The results from several finite element models provide the good agreement with the experimental results. [Hamid Khodaei et al., 2013]

Table 1: Material parameters used for different parts of geometry (Hamid Khodaei et al., 2013)

Material Parameter	Part 1	Part 2	Part 3	Part 4	Part 5
C_1(MPa)	0.35	10.65	3.2	1.4	2.4
C_2	1.75	17.95	4.55	3.35	3.75
Bulk Modulus (MPa)	8.33	30	8.33	8.33	8.33
Shear Modulus (MPa)	0.168	0.368	0.168	0.168	0.168
η_1 (MPa s)	0.05	0.05	0.05	0.05	0.05
η_2 (MPa s)	15	15	15	15	15

Where, C_1 and C_2 are the passive fiber coefficients.

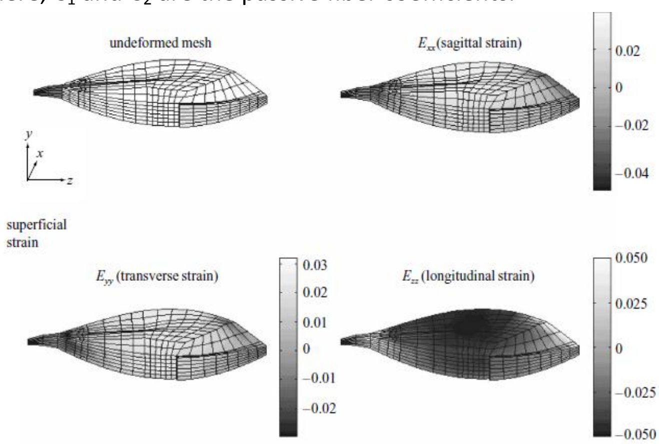


Figure 7: Strain field in tibialis anterior muscle in transverse and longitudinal direction.
(From Oomens et al., 2003)

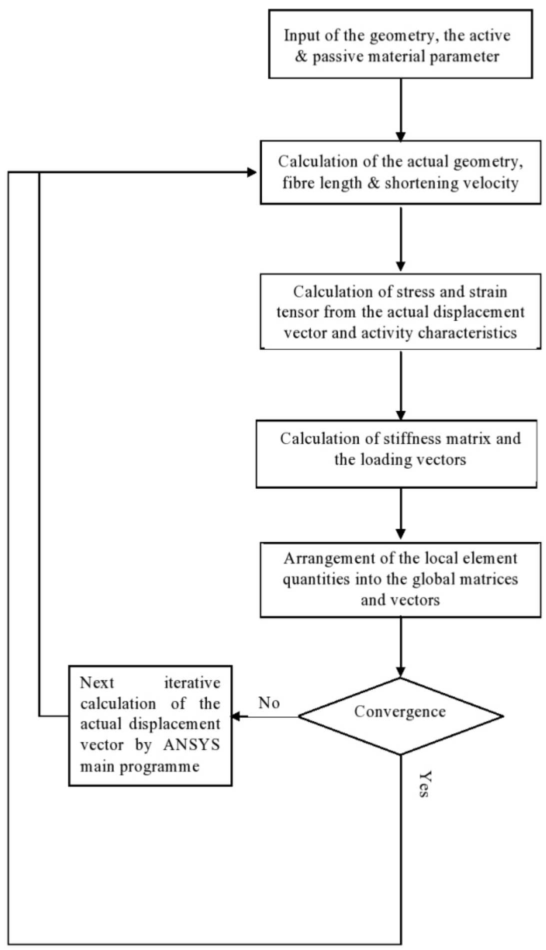


Figure 8: Flow chart of Finite element analysis of skeletal muscle using user defined material subroutine in Ansys (From Johansson et al., 2000)

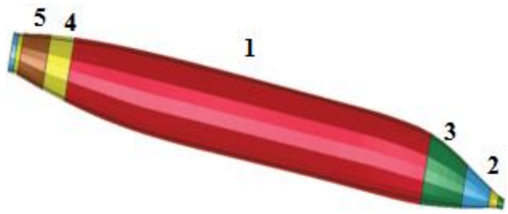


Figure 9: FE model of the rabbit leg muscle TA (Hamid Khodaei et al., 2013)

3.2 In vitro [Tension – compression Test]

As the biological soft tissue exhibits the non linear, viscoelastic and anisotropic behavior, with the same perspective fiber oriented, the muscle also exhibits the same material behavior (Morrow et al., 2010; Bol et al., 2012; Takaza et al., 2013). The skeletal muscle structure reveals that it can behave as transversely isotropic (Blemker & Delp, 2005). Some investigators characterized the muscle in the fiber direction, where as transversely isotropic behavior was characterized by testing the soft tissue under fiber direction (Longitudinal extension) and transverse extension. While some of the investigators measured the stress-strain characteristics of the muscle across the entire musculotendinous unit, results could not isolate the properties of muscle tissue itself (Gareis et al., 1992; Hawkins & Bey, 1997; Gosselin et al., 1998; Anderson et al., 2002; Davis et al., 2003; Linder-Ganz and Gefen, 2004; Van Loocke et al., 2006). Transversely isotropic material properties of skeletal muscle have been determined experimentally under tension, results reported that muscle is stiffer in fiber direction as compared to transverse direction (Van Ee et al., 2000; Mathur et al., 2001 ; Linder-Ganz and Gefen, 2004 ; Blemker & Delp, 2005 ; Morrow et al., 2008 and Morrow et al., 2010), and studies on muscle under compression reported that skeletal muscle tissue is much stiffer in the transverse direction than in the fiber direction (Van loocke et al., 2006 and Bol et al., 2012). In the pursue of this conflict, some authors could provide the experimental data for tensile loading that muscle is stiffer in transverse direction than in the fiber direction during the experiment for tensile loading (Van Loocke et al.,2006; Nie et al.,2011 and Takaza et al.,2013).

The mechanical behavior of skeletal muscle dependent on the fiber direction in tension has been studied at intermediate angles by Michael Takaza et al. (2013). Results show that the muscle could be more stiffer in transverse or cross fiber direction than the fiber direction, but the results from Van Ee et al. (2000), Morrow et al. (2010), Linder and Gefen (2004) and Blemker and Delp (2005) indicates the opposite, see Figure 10. Table 2 shows the difference in material properties of the skeletal muscle tissue. Therefore, it is concluded that there is a gap in understanding of the tensile response of passive muscle under loading. Experimental method to examine the tensile response of skeletal muscle recently used by Takaza et al. (2013) is illustrated in following section.

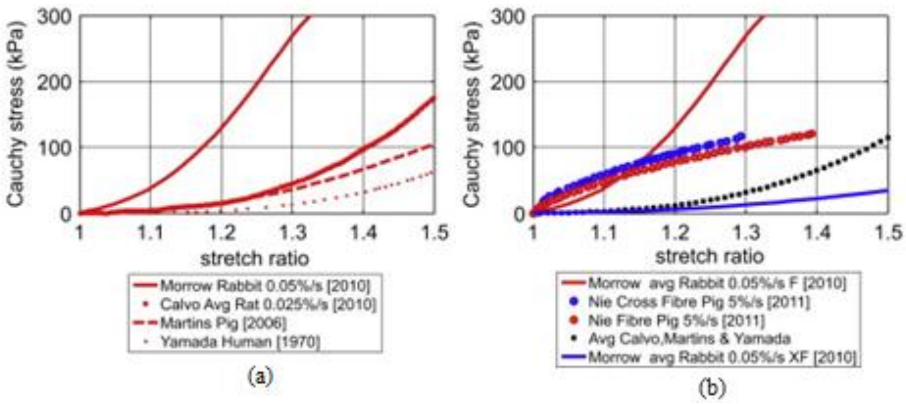


Figure 10: Tensile response of skeletal muscle and its comparison with literature data (a. Fiber direction b. Cross fiber direction) (Figure from Takaza et al., 2013)

Table 2: Comparison: Tensile response passive skeletal muscle.

Tensile Response of passive skeletal muscle				
Authors	Strain rate (% s^{-1})	Modulus of Elasticity(KPa)		Remarks
		Fiber direction	Cross fiber direction	
Morrow et al.,2008[Rabbit]	0.05	767	81	Fiber direction stiffer
Nie et al.,2011 [pig]	5.00	100	59	Fiber direction stiffer
Calvo et al.,2010 [Rat]	0.025	46		Fiber direction stiffer
Martins et al.,2006 [pig]		35		Fiber direction stiffer
Blemker and Delp,2005		2700	50	Fiber direction stiffer
Mathur et al.,2001		100-700		Fiber direction stiffer
Takaza et al.,2013	0.05	10	77	Cross fiber direction stiffer

3.2.1 Method of experimentation

Samples were harvested from female pigs and experiments done with the prior permission from the Dublin ethics committee for protection of animals. Samples of fresh skeletal muscle tissue were prepared with 10 mm wide and 10 mm thick as per the ASTM E8/E8M standards. Six samples were prepared for the muscle tissue group with fiber orientation, fiber direction, cross fiber direction, 45° and 60° orientation of fiber to the length of samples see figure 11 (a). A test was carried out within 2 hrs after mortise of animal to reduce the effects of rigor mortis on results. Grated plates were used on the clamps to minimize slippage of samples. A tensile test machine with 100 N load cell was used to perform the test.

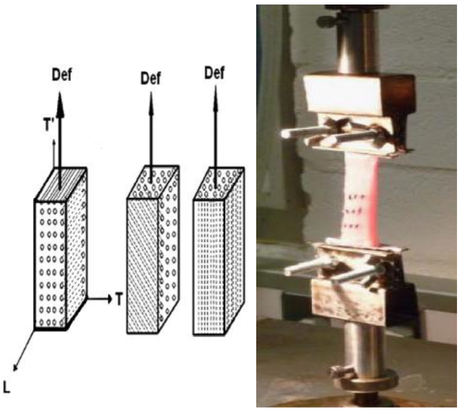
Samples placed between grated plates and clamps were clamped over grated plates see figure 11 (b).

Takaza et al used a completely different method for data analysis for strain evaluation. Dots were marked on the surface of the sample which was facing the camera and done before start of test. CCD camera was used to capture the image for dimensional analysis see figure 12 (a). Phosphate buffered saline was sprayed on skeletal muscle tissue sample to prevent drying. Temperature maintained during the test was of range 18-22° C and strain rate was 0.05 % s^{-1}.

(a) Schematic representation of fiber orientation in different samples

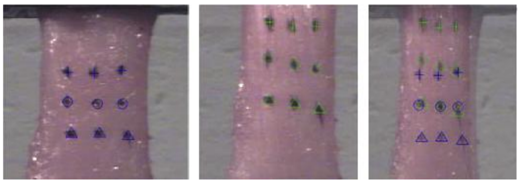
(b)Tissue sample with dots on the surface was used in image analysis to compute strain.

[L: fiber in longitudinal direction. T, T': fiber in transverse direction]

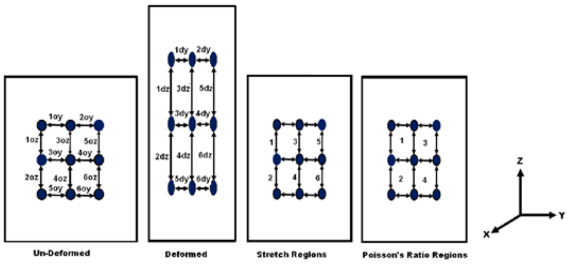


(a) (b)

Figure 11: Sample of skeletal muscle tissue for tensile test (From Takaza et al., 2013)



(a)



(b) (c) (d) (e)

Figure 12: Schematic illustration for image data analysis of the sample. (a) Typical fibre direction test sequence showing sequentially the un-deformed (initial, λ=1) image, the final deformed (λ=1.35) image and a superposition of the two (final and initial). Sample numbering before (b) and after (c) deformation, (d) and (e) the different arrow regions are shown labelled using ordinary numbers for simplicity.(From Takaza et al., 2013)

The strain was calculated from the image capture by using MATLAB script. The coordinates of each dot were recorded for each image and correlated with the coordinates of the image at the start of the experiment. Stretch ratio was computed from the difference between these coordinates, see figure12. (Where z represents fiber direction and y represents cross fiber direction). Local z direction stretch ratios were derived by using (Eqn.4)

$$\lambda_{nz} = \frac{ndz}{n0z} \quad (4)$$

Where, n: number specifying the specific location

d: deformed sample length

0: undeformed sample length

z: stretch direction

By assuming volume preserving condition, i.e. incompressibility condition,

$$V_o = V_d = V \quad (5)$$

$$A_o L_o = A_d L_d \quad (6)$$

$$A_d = \frac{A_o L_o}{L_d} \quad (7)$$

Therefore, Cauchy or true stress in the Z direction was computed from the force (F) from the machine load cell by using (Eqn.8)

$$\sigma = \frac{F}{A_d} = F/\frac{A_o L_o}{L_d} = F\lambda/A_o \quad (8)$$

In the same way Cauchy stress was computed in y direction.

The average logarithmic strains were calculated by using (Eqn.9) and(Eqn.10) in x and y direction respectively.

$$\epsilon_z = \frac{1}{6}\sum_{n=1}^{6} ln(\lambda_{nz}) \quad (9)$$

$$\epsilon_y = \frac{1}{6}\sum_{n=1}^{6} ln(\lambda_{ny}) \quad (10)$$

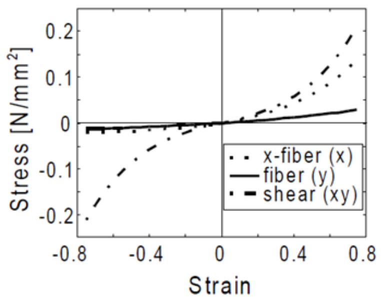
By using the above data analysis technique, the results were plotted for stress vs. stretch for fiber direction and cross fiber direction to compute the anisotropy of skeletal muscle, see figure 10 (Takaza et al., 2013).

4. Discussion and Conclusion

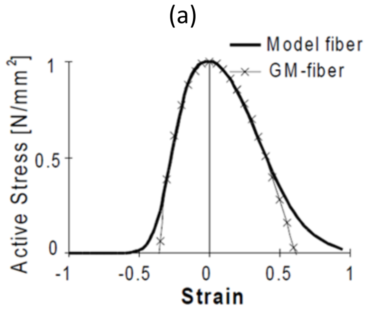
Mechanical properties of skeletal muscle were studied in terms of the length force relationship, force, velocity and stress, strain relationship in active and passive muscle conditioning. At the end, this article summarizes the numerical and experimental methods to predict the mechanical behavior of skeletal muscle. Isometric contraction of skeletal muscle is independent of the velocity of contraction; stress in the muscle reflects the time curve of the activation function means it is time driven. Isokinetic contraction of skeletal muscle depends upon the velocity of contraction.

Its stress behavior is slightly different than the force behavior due to deformation of a cross section of the element (Johansson et al., 2000 and Hedenstierna et al., 2008). Chen et al simulated the dynamic condition of the muscle using FEM with a modulus of elasticity 200 N/m^2 and 1049 Kg/m^3 as its density, force generators are added to the node points of the finite element mesh along the longitudinal direction of the muscle. Mechanical behavior of muscle was simulated with the consideration of linear, homogeneous and isotropy of the muscle, but volume preserving criterion could not be met. Some of the studies examined the viscoelastic behavior of skeletal muscle using the plane finite element model. This model estimated the viscoelastic parameters as 0.549 ± 0.056 and 6.01 ± 0.425 s, while elastic parameters are15. 6 ± 5.4 KPa and 21.4 ± 5.7 (Bosboom et al., 2001 and Khodaei et al., 2013). 1D to 3D finite element skeletal muscle model were formulated to study the fiber oriented based mechanical properties of skeletal muscle (Chen & Zelter, 1992; Johansson et al., 2000; Van der Linden, 1998;Yucessoy et al., 2002 and Tang et al., 2009). The 2D finite element model was formulated with nonlinear, anisotropy and incompressibility of the muscle by Linden et al. This model showed that the muscle cannot be considered as lumped fiber where as it has a different contribution to the muscle functioning. The muscle has more passive stress; 0.15 MPa at a strain of 0.8 in Cross fiber direction to that of 0.048 MPa at a strain of 0.8 along the fiber direction. On the other hand active stress decreases with increase in strain of the muscle in active behavior see figure 13 (a) and (b) (Van der Linden, 1998). Yucessoy et al examined the behavior of the muscle in tension as well as compression using a finite element model. In tension, Passive stress in cross fiber direction (3.1 MPa at strain=0. 6) is comparatively more than that along the fiber direction (1.95MPa at strain=0. 6). In compression, stress along the cross fiber direction was -2.2 MPa at a strain of -0.6 (Yucessoy et al., 2002).

Mechanical properties of skeletal muscle were also examined experimentally under tension, results reported that muscle is stiffer in the fiber direction as compared to cross fiber direction (Van Ee et al., 2000; Mathur et al., 2001; Linder-Ganz and Gefen, 2004; Blemker & Delp, 2005; Morrow et al., 2008 and Morrow et al., 2010), this held good agreement between numerical and experimental studies. Cauchy stress in active phase is smaller than in the passive phase (Martins et al., 2006 and Geilen et al., 2007). The evaluation of stress provided the location of maximum stress; which is useful information for the study of muscle fatigue and damage (Tsui et al., 2004). Later, C. Y. Tang et al examined the effect of muscle fatigue on the stress strain behavior of the muscle. The results concluded that muscle fatigue has large degraded about 25-31% in longitudinal direction. In contrast to the results in the tensile response of passive skeletal muscle, some of the studies based on the compression response of passive skeletal muscle reported that the muscle was much stiffer in the transverse direction than in the fiber direction (Van loocke et al., 2006 and Bol et al., 2012). To this end, with the keen perception of the previous studies further researches were carried out in the direction of experimentation to find the appropriate mechanical behavior of skeletal muscle. These recent experimental studies reported that skeletal muscle is stiffer in transverse direction than in the fiber direction in its passive tensile response (Van Loocke et al., 2006; Nie et al., 2011 and Takaza et al., 2013) See Figure10 and table 2.



(a)



(b)

Figure 13: (a) passive stress-strain relationship with fiber orientation (b)Active stress-strain relationship (From Van der Linden et al., 1998)

The results show that skeletal muscle has fiber orientation based mechanical properties which prove the anisotropy, hyperelasticity and viscoelasticity of the muscle. In addition to this, skeletal muscle also exhibits different mechanical behavior with force-length and force-velocity in active and passive state of its response. It is more intuitive to survey the literature based on the mechanical characterization of muscle from the past era to the present era. This may often be focused on the numerical and experimental methods to identify and examine skeletal muscle response. This article gives the collective information about the mechanical characteristics of skeletal muscle during its contraction. The survey may transport the methods and results of the mechanical study of skeletal muscle to improve the future research in the field of biomechanics, ergonomics, tissue engineering, crash analysis with a human model etc.

Conflict of Interest

No conflict of interest.

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