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Research Article

Analysis of Motor Unit Recruitment in Human Skeletal Muscle Using Finite Element Method

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Abstract:
Motor unit recruitment is an essential factor in understanding muscle behavior. Skeleton muscle is associated with force generation and transmission to perform daily activity. The present study aims to compare the number of motor units recruited in human skeleton muscle by finite element analysis. The finite element model is constructed based on the mechanism of the sarcomere. The geometry of the model is focused on the fascicle level which consists of many fibers and is enveloped with an endomysium sheet. Each subunit of fiber is compressible and elongated similar to the sliding filament theory. The fully instrumented model provides information on self-contraction and force distribution along the skeletal muscle. The result of contraction behavior from the finite element model can be applied to designing functional ankle-foot orthosis for various physiology of humans. Results show that the equal distribution of muscle fiber type in a single fascicle achieves the greatest outcome in isotonic contraction toward other activation patterns. The culmination of contraction behavior from the finite element model can be applied to designing functional ankle-foot orthosis for various physiology of humans.

Keywords: *Muscle, Finite element model, Sarcomere, Sliding filament theory, Motor unit recruitment*

1. Introduction

Skeletal muscles are the biological structure that takes the main role in human locomotion. Like any material in nature, skeleton muscle has mechanical properties such as Young's modulus and Poisson's ratio. The integration between boundary conditions and mechanical properties makes it possible to solve an enormous issue mathematically.

According to previous research, the skeletal muscle is an organ primarily composed of striated muscular tissue. It is the major actuator of the human body and provides movement capabilities. It is the only type of muscle tissue classified as voluntary, whose contraction is regulated by our conscious cerebral activity [1]. The hierarchy of the musculoskeletal system begins with the tendon, a composition of many strands of fascicles. Each fascicle is composed of bundles of fibers. Muscle fiber was made up of thousands of myofibrils. Single myofibril may contain hundreds of thousands of sarcomeres which are the fundamental element of utmost human. Sarcomere has the substructure of myosin and actin which may call the thick filament and thin filament, the overlapping between each other is the basic mechanism for muscle contraction or the sliding filament theory [2].

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Motor unit recruitment is a mechanism in which motor neurons innervate nearby fibers to spread the signal command and increase muscle contraction strength. Differences in the number of each type of fiber may present divergently in muscle contraction duration, strength, and velocity which cause the variant in human muscle activity behavior. To understand this phenomenon, the finite element was chosen because it can excellently illustrate the complexities of the continuum model of contracting muscle structure [3]. The research on the finite element model by Teklemariam et al. [4] presents the finite element model which can describe the skeletal muscle properties by modeling a finite element model with a bundle of 19 fibers covered with connective tissue. This research performs the simulation with the different fiber activation patterns, distributed and clustered patterns, and which result shows that both patterns have the behavior of strain distribution changed with an increased deformation toward the center of the bundle. Marcucci et al. [5] developed a mathematical model to study fast and slow muscle fibers using experimental data from human muscle and then comparing it to numerical simulation obtained from the finite element model. The study unveils the characterization of the force-velocity curve during isotonic contractions that the bundle curve deviates substantially toward the fast fibers at low loads. The objective of this research was inspired by the work of Teklemariam et al. [4] and Marcucci et al. [5] which is the designing of a finite element model to simulate the contraction of skeleton muscle based on sliding filament theory, muscle fiber contracts toward the center to replicate the behavior of myosin and actin overlapping inside the sarcomere, which may provide a variety of force generation and transmission models that are suitable for numerous boundary conditions.

2. Material and Method

2.1. Size and Geometry

2.1.1 Muscle Fiber Geometry

Muscle fibers are typically large cells, some 20–100 μm in diameter and the longest fibers are about 12 cm [6]. In this research, muscle fiber is categorized into 2 types, fast-twitch, and slow-twitch. Each one of them has a different size due to distinct functions (Table 1), but the geometry is similar with a depth of 2.5 μm. Fast-twitch muscle fibers provide powerful forces in a short duration because of anaerobic characteristics and less blood supply, but the size is bigger than its counterpart. Slow-twitch muscle fibers are fatigue resistant and focused on sustained forces via aerobic characteristics, the size is much smaller than the other one [7]. According to a recent investigation on size alteration between fast-twitch and slow-twitch muscle fiber, fast-twitch muscle fiber tends to be 1.16 times bigger in diameter than slow-twitch muscle fiber [8].

Table 1: Fast-twitch and Slow-twitch diameter size comparison

Fast-twitch	**Slow-twitch**
104.4 μm	90 μm

2.1.2 Endomysium Geometry

Endomysium is a connective tissue that surrounds muscle fibers and the existing collagen fibrils inside are changing their orientation if the muscle is stretched [9]. In this study, the endomysium is fixed in cylindrical geometry and size of 500 μm in diameter which represents a portion of a single fascicle [10].

2.2 Material

Endomysium and muscle fiber are assumed to be linear elastic materials since the deformation in the mechanism is small. Young's modulus and Poisson's ratio are determined based on experimental data in Table 2 [11].

Table 2: Material mechanical properties

Parameter	**Muscle Fiber**	**Endomysium**
Young's Modulus (MPa)	0.0465	0.2415
Poisson's ratio	0.4999	0.4999

2.3 FEM Model and Arrangement

The finite element models are designed and simulated by the conventional program named Marc Mentat 2020 [12]. The studied fiber activation patterns could not be represented by normal physiological conditions as fibers belonging to the same motor unit are typically described as randomly distributed across the muscle cross-section. However, the simulated activation pattern did not reveal evident quantitative changes in force transmission, but the pattern of stress and strain distribution were affected depending on the position of the active fiber [4]. In this research, the muscle fiber mesh is constructed in hexahedron mesh for 3D modeling with a length in the Z-direction of 2.5 µm. Endomysium mesh is meshing by hexahedron automesh function, the Marc mentat function that lets the program mesh by itself, the length in Z-direction is 2.5 µm. The size of the endomysium is fixed to be represented as a single 1 mm length fascicle. Muscle fiber and endomysium contact each other by glued contact, the function in Marc Mentat 2020 which let the different mesh such as muscle fiber and endomysium be stitched together using the direct constraint method to solve the elastic contact problems without friction [12], while the fiber contracted, the contraction force transmits cross the contact interface to endomysium. Naturally, the pattern of activation is random thus we divide the model into A and B types (Fig. 1), model A has a maximum number of fast-twitch and slow-twitch fibers are 13 and 12. In contrast, the maximum number of fast-twitch and slow-twitch is 12 and 13. We adjust the proportion between fast and slow twitch by reducing and increasing the number of each fiber type by deviating the fiber cluster percentage which represents the motor unit recruitment in a single fascicle. As shown in the assumption arrangement in Table 3. Coordination of fiber arrangement has been fabricated to identify each fiber location (Fig. 2). We assume that the reduction of surplus fiber is prioritized in elimination according to the pattern (1E) > (5E) > (1A) > (5A) > (3E) > (3A) respectively. The addition of required fiber is prioritized to the pattern (2C) > (4C) > (3B) > (3D) > (1B) > (5B) > (1D) respectively.

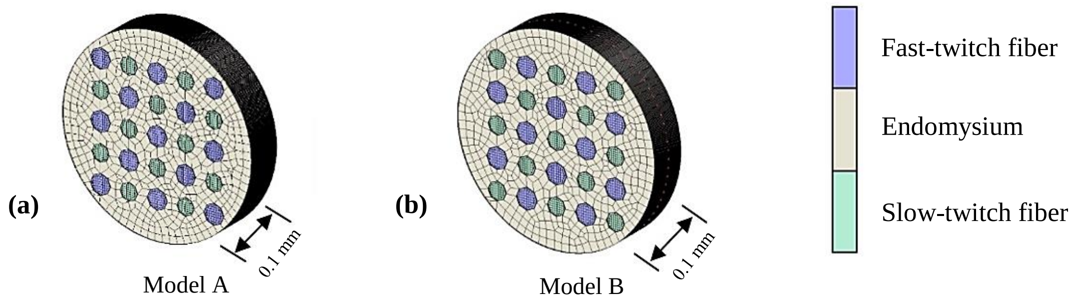


Fig. 1. The pattern of arrangement; (a) Pattern of model A and (b) Pattern of model B

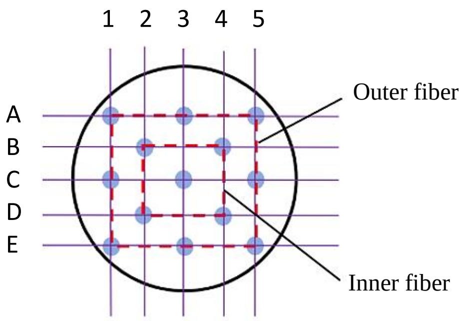
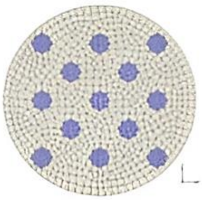
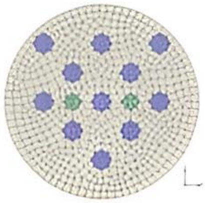
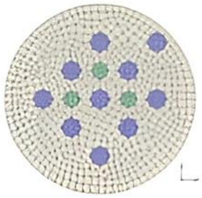
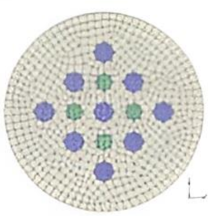
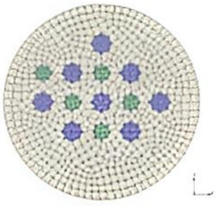
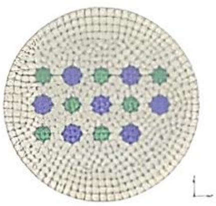
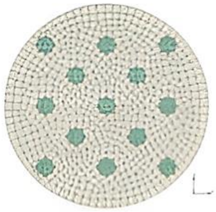
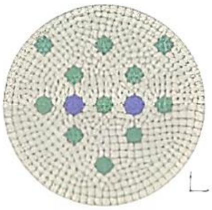
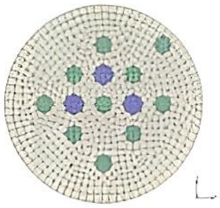
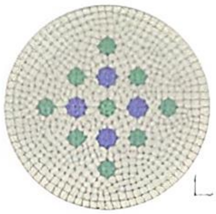
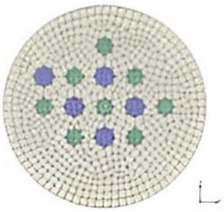
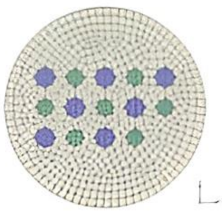


Fig. 2. Coordination of fiber arrangement

Table 3: The pattern of arrangement

	Pattern		
A	 FT13-ST0	 FT11-ST2	 FT10-ST3
	 FT9-ST4	 FT8-ST5	 FT7-ST7
B	 ST13-FT0	 ST11-FT2	 ST10-FT3
	 ST9-FT4	 ST8-FT5	 ST7-FT7

2.4 Boundary Condition

2.4.1 Load and Displacement

Each cross-section face is applied with face load except for 4 faces in the center of the fiber to replicate the overlapping between actin and myosin inside the sarcomere. Also, the displacement in the Z direction is only fixed in the middle of the fiber to create muscle enlargement due to compression, 9 nodes of the middle face cross-section are fixed in X and Y directions (Fig. 3).

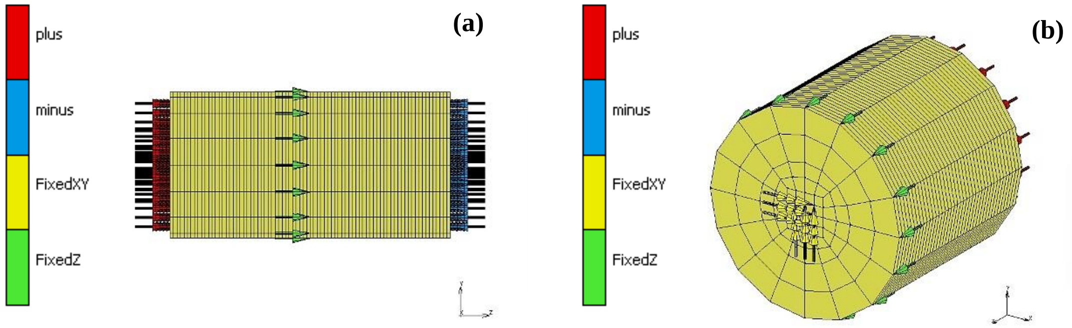


Fig. 3. Boundary condition of muscle fiber; (a) Face load, (b) Fixed XY and Z directions.

2.4.2 Twitch Response

Muscle fibers are innervated by motor neurons, small motor neuron has a relatively long duration (slow-twitch) and small amplitude which gives the slower contractile characteristic to innervated fibers. On the contrary, the big motor neuron has a relatively swift duration (fast-twitch) and higher amplitude such as innervated fiber has a faster contractile characteristic [13]. We tried to replicate the natural activity by applying the response for each type of fiber to give their characteristic (Fig. 4).

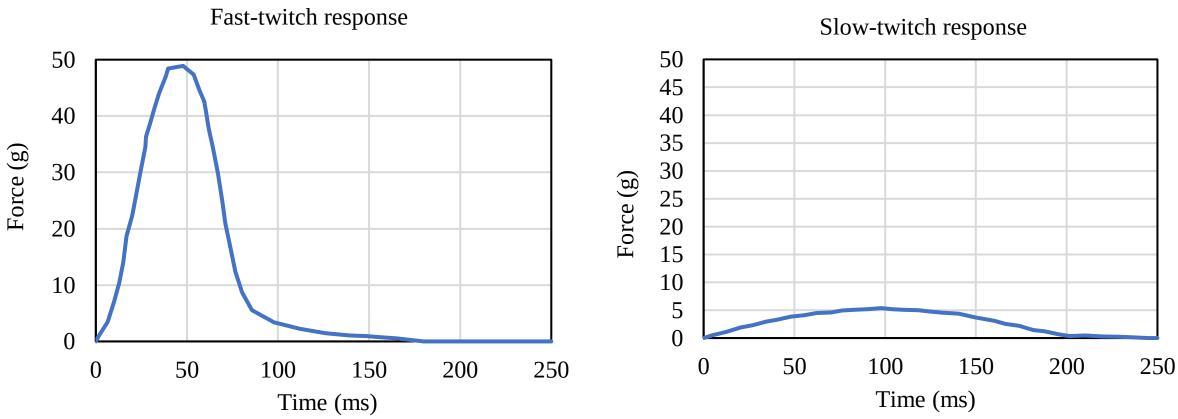


Fig. 4. Twitch response; (a) fast-twitch response, (b) slow-twitch response

3. Result and Discussion

The motor unit recruitment behavior of 2 patterns that prioritize different fiber characteristics of fast-twitch and slow-twitch fiber, was investigated by adjusting the proportion of each fiber type in a single fascicle.

According to the fast-twitch fiber-based fascicle (model A) (Fig. 5), the velocity of fast-twitch muscle fiber contraction swiftly declines in a short period, upon increasing the slow-twitch muscle fiber, the velocity of FT11-ST2 is the only case that dropped significantly than FT13-ST0, then climbs rapidly, the other cases share the same behavior of zero dropped in velocity then rapidly climb, this behavior also shown consistently in the study of Marcucci et al. [5] which state that the contraction length initially drops for rapid shortening of the elastic element of muscle fiber (Fig. 6), and then starts to shorten at a constant velocity (Figs. 7 and 8). The displacement of fast-twitch fiber (model A) (Fig. 9) is significantly increased between FT13-ST0, FT11-ST2, and FT10-ST3 then slightly grew at constant due to balancing the number of each fiber type. However, in the slow-twitch fiber-based fascicle (model B) (Fig. 10), the velocity is greatly declined and then slowly starts to climb upon increasing fast-twitch muscle fiber. Slow-twitch muscle fibers consist of a portion of opposite velocity direction in the time range of 0 – 50 ms (Fig. 11) due to some fast-twitch muscle fibers having a faster response than slow-twitch muscle fibers, resulting in slow-twitch muscle fibers to be turned inside out which causes the velocity toward minus - Z direction instead of plus - Z direction. Fast-twitch fiber has a greater value than slow-twitch fiber in both velocity and displacement dimensions, but slow-twitch has constantly changing results in different cases, early fast-twitch cases have a significant changing result and then begin to show the constant characteristic changing result. The displacement and velocity of fast-twitch and slow-twitch muscle fibers share the same behavior when the number of each fiber type is equal, resulting in the highest velocity and largest Z-direction displacement. The position of each type of muscle affects contraction velocity and displacement, slower fiber is influenced by the surrounding faster fiber causing the velocity and displacement to shift, on the contrary, a faster fiber has a short accelerating time, after the end of the fast-twitch response, the velocity of stopped faster fiber is expanding depend on the number of surrounding slower fiber which results in constant acceleration. Hence, FT13-ST0 has no acceleration after rapid response resulting in the lowest velocity in fast-twitch-based fiber, the accumulation of each type of muscle fiber, and different fiber arrangements representing the various human demeanor that affected distinct muscles.

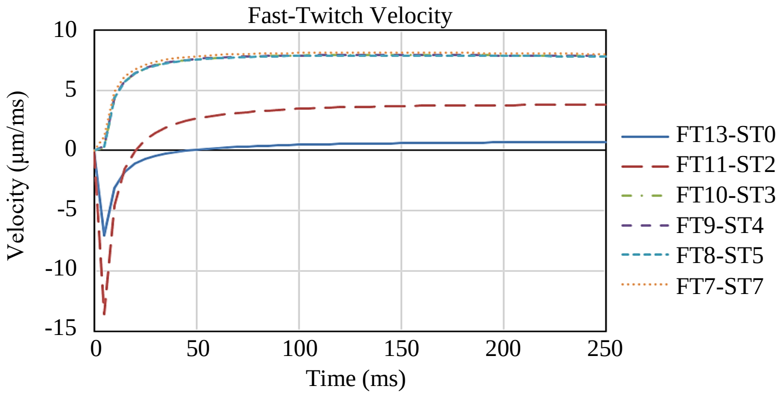


Fig. 5. The fast-twitch fiber-based fascicle (model A) velocity

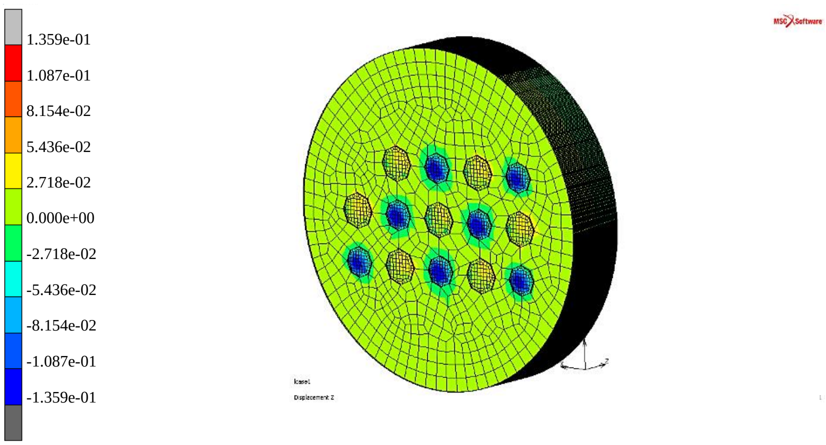


Fig. 6. The deformation of the FT7-ST7 model (model A) at 1^{st} increment

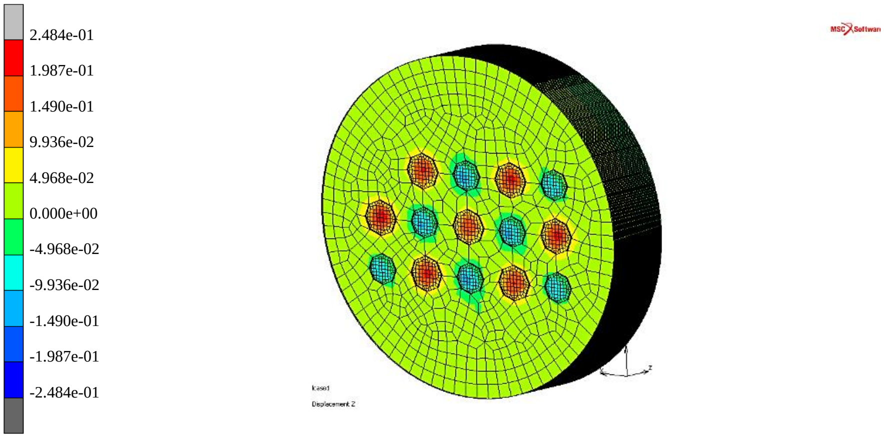


Fig. 7. The deformation of the FT7-ST7 model (model A) at 2nd increment

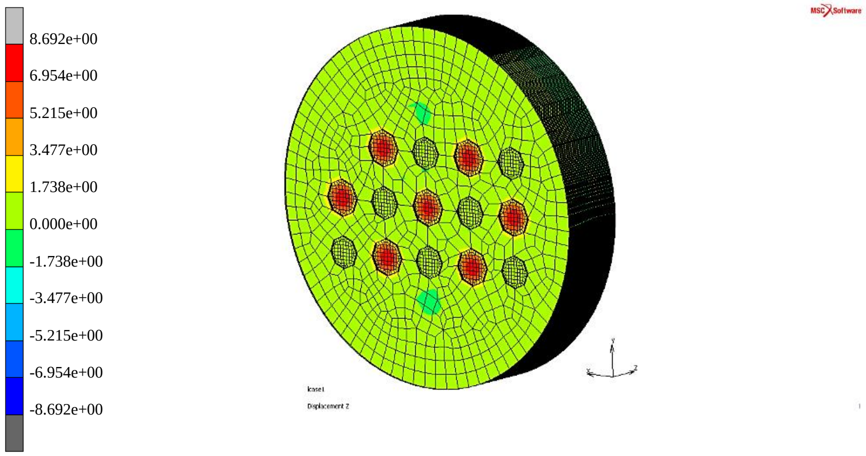


Fig. 8. The deformation of the FT7-ST7 model (model A) final increment

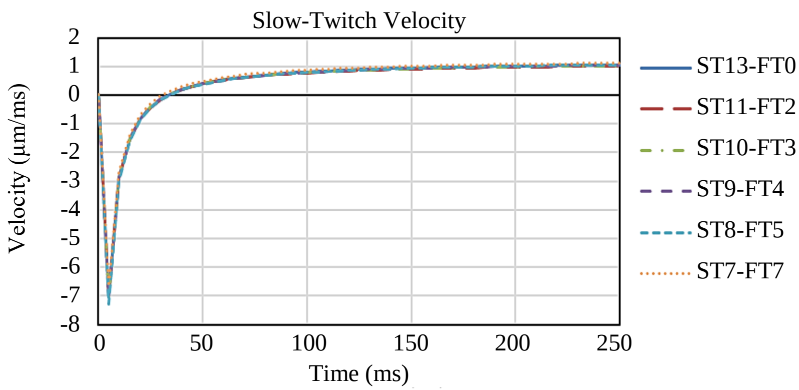


Fig. 9. The slow-twitch fiber-based fascicle (model B) velocity

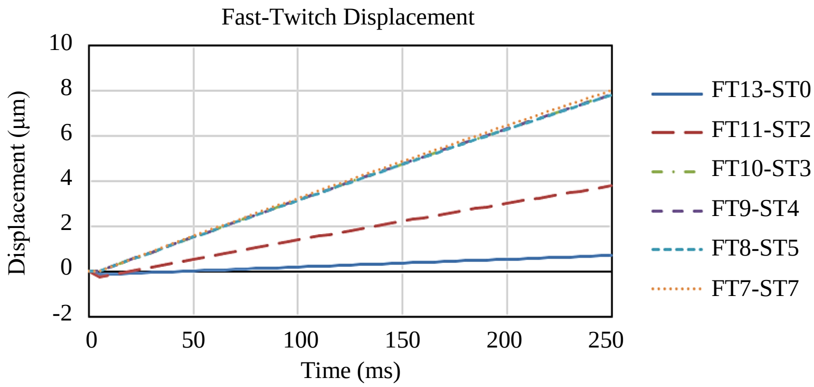


Fig. 10. The fast-twitch fiber-based fascicle (model A) displacement

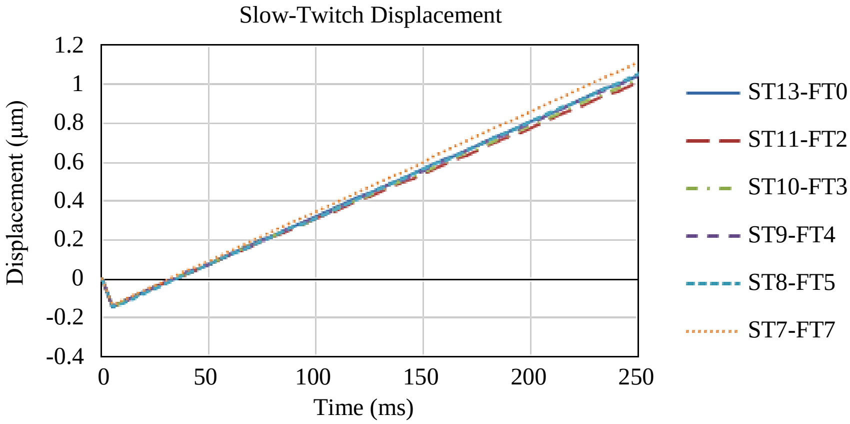


Fig. 11. The slow-twitch fiber-based fascicle (model B) displacement

4. Conclusion

The finite element method has shown us the potential way to explore the mechanism behind the natural phenomenon of muscle contraction, our effort is to understand muscle contraction from another perspective. In previous research, the discovery of fast and slow-twitch muscle fiber showed that each type has different characteristics, fast fiber has a rapid response, faster muscle contracts, and slow fiber gives the ability to sustain an amount of strength for a longer duration than fast-twitch muscle fiber. In the present study, we discovered that changes in the number of each type of fiber in a single fascicle show the difference in self-contraction behavior, the equal number of each type of muscle fiber gives the best performance in muscle contraction velocity and displacement, which make people act faster and sustain more strength. In general, this simulation presented an ideal subject with further factors to be investigated, considering real tissue is viscoelastic material and arranged in a random pattern hence the perfect simulation required a precise specimen detail. For force transmission and generation, this research only acquired information on 1 mm fascicle, the future study will put pieces of fascicle together in parallel to imitate fascicle in real length and confine them into a bundle to demonstrate a muscle tendon which further will be packed into a single human muscle.

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