CHAPTER II

LITERATURE REVIEWS

This literature review comprises of three sections. The first section provides a comprehensive review of concentric training, eccentric training and muscle architecture adaptation. The second section describes tendon structure, composition and mechanical properties. The third section provides an available evidence of resistance training on tendon structure, composition, and mechanical properties.

1. Effect of eccentric training on muscle architecture adaptation

Muscle architecture responds to eccentric training by an alteration of the muscle size (4, 18-20), pennation angle (6) and muscle fiber length (21, 22). Eccentric training induces increase muscle hypertrophy**,** which is obvious as an increase in muscle size reflected in increased muscle volume and muscle CSA (19, 23). For example, Seger et al. (19) compared pure eccentric and concentric isokinetic training on morphology of the knee. They demonstrated that both programs increased muscle CSA and eccentric training induce increased CSA greater than concentric training. Similarly, Norrbrand et al. (5) found that eccentric training increased in the muscle CSA than concentric training. In the aspect of pennation angle, eccentric training has a greater increase than concentric training (6, 7). For instance, Aagaard et al. (7) determined eccentric training on fascicle pennation angle and showed that fascicle pennation angle increased following 14 weeks training. Moreover, Blazevich et al. (6) examined the influence of concentric and eccentric resistance training on fascicle angle. They suggested that eccentric training induce increased in fascicle angle more than concentric training.

Eccentric training also induces increase in muscle fiber length or the number of sarcomeres in series (21). For example, Brockett et al. (22) found that eccentric exercise shift to optimal muscle length. The shift indicated a training effect that provided the muscle protection against further damage from eccentric exercise. Moreover, Butterfield et al. (21) elucidated the relationships between contraction type (concentric and eccentric contraction), exercise duration, and serial sarcomere numbers adaptation in the knee extensor muscles of rats. They found that serial sarcomere numbers changed differently for uphill and downhill exercise groups which concentric training worked in short muscle lengths, as a result in a loss of serial sarcomere number. While eccentric training worked in long muscle lengths as a result in an increase of serial sarcomeres. Increasing serial sarcomere numbers would be improving muscle function by altering the optimum torque angle (21, 24).

As indicated above, eccentric training altered muscle architecture that increased in muscle composition. As a result, eccentric training could induce muscle adaptation.

2. Tendon: structure, composition and mechanical properties

The role of tendon can be divided into two functions: tensile force transmission and storage and recoil energy. For the action in force transmission, force generated by muscle is transmitting to bone via tendon and produce body movement (25). The effectiveness of movement or locomotion depends on the structure, composition, and mechanical properties of tendon.

2.1 Tendon structure

The tendon has an organization that exhibited a multi-unit hierarchical structure, which consists of collagen molecules, fibrils, fibril bundles or collagen fiber, fascicles, and tendon units that run parallel to the geometrical axis (Fig.1) (25, 26). The smallest unit is collagen molecules which has a triple helix of long and thin protein. The fibril consists of rod-like collagen molecules aligned end-to-end in a quarter-staggered array. Fibril diameters are different; depending on species, age, and sample location (25). Fibers form the next level of tendon structure. Fibers are composed of collagen fibrils and bound by endotenons. Fiber bundles form fascicles, and bundles of fascicles are enclosed by the epitenon. The outermost sheath, paratenon encloses a fluid filled space to reduce friction (27). This type of hierarchical structure arranges fiber bundles with the long axis of tendon and provides the tendon's tensile strength.

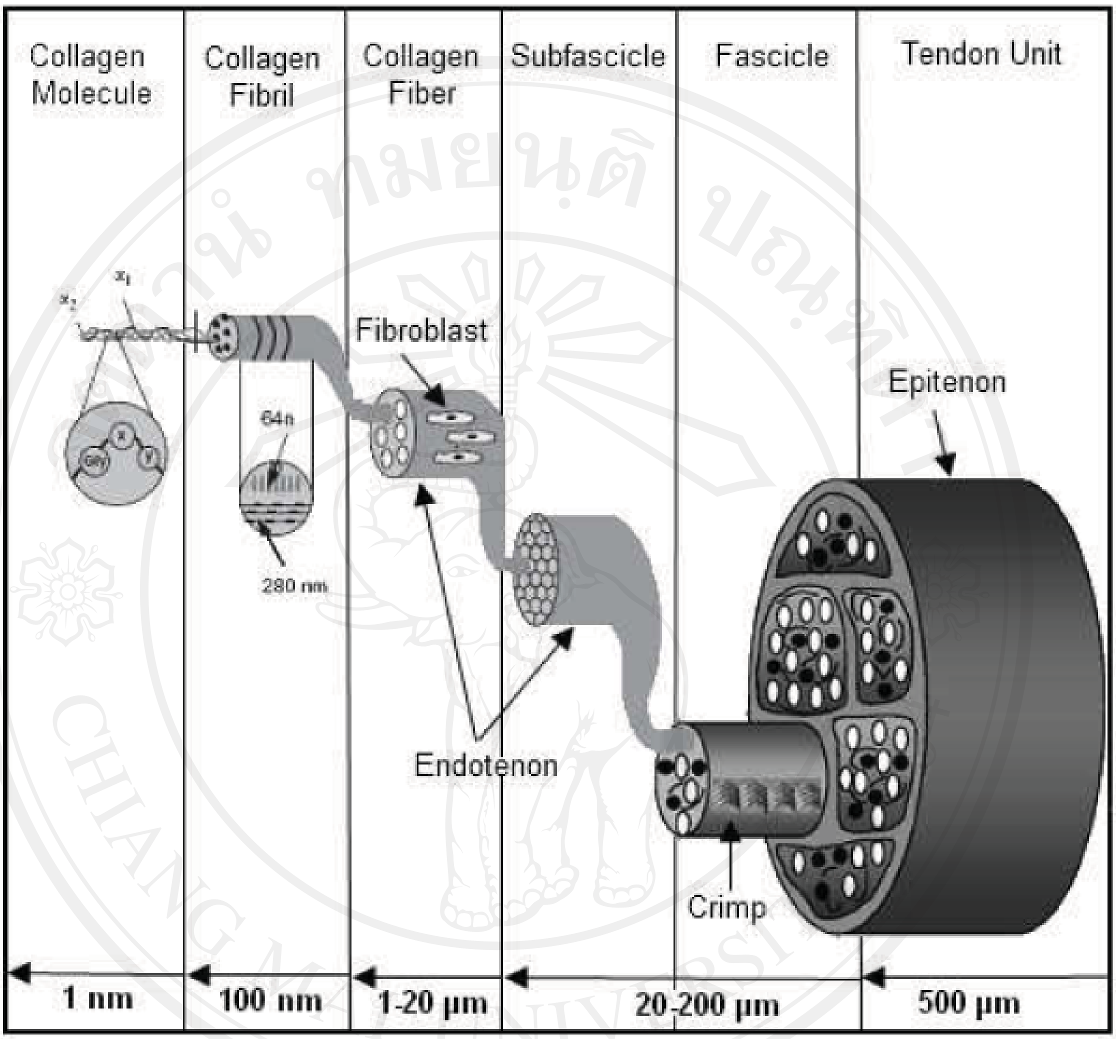

Figure 1 A multi-unit hierarchical structure of tendon (modified from *Silver et al., 2003*).

2.2 Tendon composition

The fundamental structure of tendon is made up of collagen fibers, proteoglycans, glycoproteins, water and cells (27). Tendons are rich in collagens that are important for muscle function, especially in relation to force transmission. It is composed predominantly of type I collagen (26). The type I collagen of tendon is rod-like with little flexibility and high mechanical strength. In addition, other collagens, including types type II to VI and IX to XI are present in trace qualities in tendon (25).

Tropocollagen triple helix is the basic structure unit of tendon, which is a long, thin protein. It is produced from the tenoblast and secreted into extracellular matrix as procollagen. With procollagen can be converted to collagen within cell, and fibril formation can occur in closed intracellular carriers (28). Collagens in the extracellular matrix are cross-linked. The strong, molecular cross-links of collagen provide tendon with tensile strength increases Young's modulus of tendon and reduces its strain at failure (25, 29).

2.3 Tendon mechanical properties

Tendon is a viscoelastic structure with unique mechanical properties. Characteristics of the viscoelasticity consist of two properties: fluid properties and solid properties. Viscoelasticity is a behavior of material that combination of viscosity and elasticity. Viscosity demonstrates viscous behavior as it responds to the rate of loading and elasticity demonstrates elasticity as it tends to return to its original size and shape. Creep and stress-relaxation are two phenomena of viscoelastic. Creep is a phenomenon in which a structure deforms with time under constant load while stress-relaxation is a phenomenon in which force or stress in a deformed structure decreases with time, while the deformation held constant. The stress-strain behavior of the tendon is the time-rate dependent (2, 30, 31).

The mechanical properties are direct consequence of the constituent components. The load-deformation curve is the relationship between the load applied (newtons: N) to structure and the deformation produced (millimeter: mm). This relationship describes the mechanical behavior of a tendon structure. The slope of this curve is called stiffness. The stress-strain curve describes an important aspect of a material. Stress is obtained by dividing the load by original cross-sectional area and strain is obtained by dividing the deformation by original length. Thus load-deformation curve is converted to the stress-strain curve. The slope of the stress-strain curve in linear region is defined as Young's modulus. It is a measure of the stiffness of the material (30). A typical of tendon mechanical behavior is the stress-strain curve. The stress-strain curve of tendon consists of four regions: (1) toe region, in which the tendon is stretching with a small increase in load as the collagen fibers express the stretching- out of the crimp-pattern and the tendon strained up to 2%; (2) linear region, in which the fibers strengthen-out less than 4% and loss crimped pattern, this slope of linear region refer to the Young's modulus of the tendon; (3) microscopic failure, in which tendon is stretched over 4% leading to tearing of tendon fibers; (4) macroscopic failure, in which loading continues beyond 8-10% and tendon could rupture if continues load (Fig. 2) (25, 29).

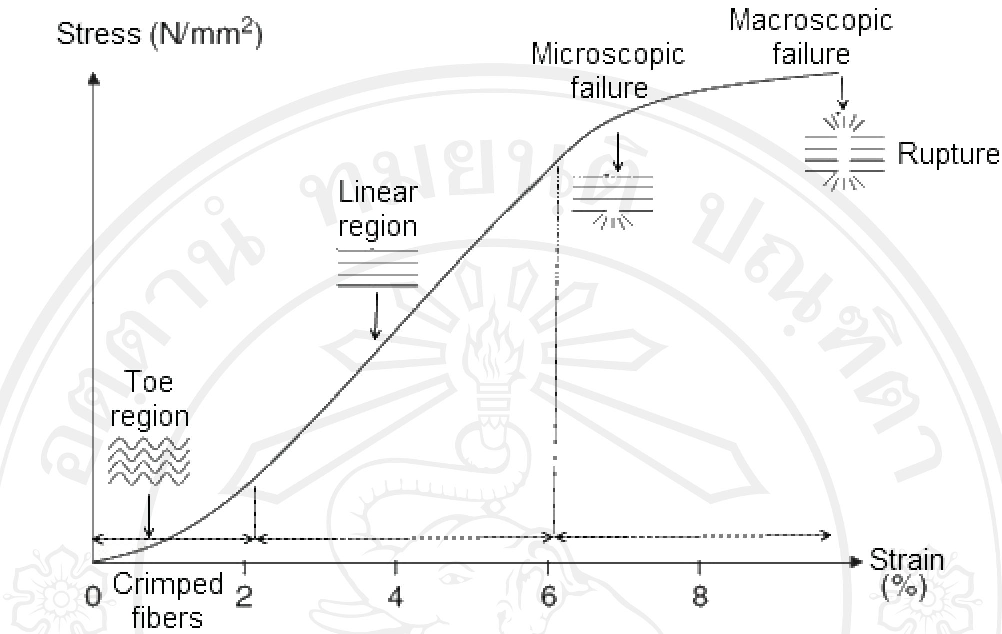

Figure 2 Stress- strain curve of tendon tissue (modified from *Wang*, *2006*).

3. Effects of resistance training on tendon structure, composition and mechanical properties

Tendon's response to exercise by changed their structure, composition and mechanical properties. It is evidence demonstrated that exercises in animals and humans induced change in tendon, known as tendon adaptation (14, 15, 23, 25, 29, 32).

3.1 Tendon structure

Exercise program or training has an effect on tendon CSA that provided an increase in CSA after training. A great tendon CSA would reduce the average stress (force/area) across the tendon and thereby provide a greater safety margin (33). Studies using animal model have shown that the CSA and strength of tendons increase in response to training (34-36). For example, Brich et al. (36) investigated the effect of treadmill-exercise on tendon CSA. They found that tendon CSA increased after training or called hypertrophy. Similarly, in human study, tendon CSA increased in long-term exercise and high tensile load (33). For example, Rosager et al. (37) determined CSA of tendon in runners and non-runners. They showed that larger CSA of tendon in trained runners (experience at least 5 year) than non-runner (normal activity). On the other hand, some studies showed unchanged or decreased in tendon CSA after training (23, 38-40). For example, Kubo et al. (40) investigated the effects of 12 weeks isometric training on CSA of tendon in human. They found that did not change in the size after training. An explanation for the above inconsistency may relate to interstudy difference in result due to tendons of immature but not mature animal may hypertrophy in response to training (41, 42) and different in duration of training and type of exercise . However, in patients with Achilles tendinopathy have a localize thickening of tendon area. Previous study (14) investigated the effect of eccentric training on tendon structure. They found that eccentric training was effective to decrease tendon thickness and equal to normal tendon structure.

3.2 Tendon composition

The tendon is predominantly type I collagen arranged in tensile resistance fiber. Physical training increases both synthesis and degradation of collagen. These changes modify the mechanical properties and viscoelastic characteristics of the tissue, decrease its stress-susceptibility and probably increase its resistance (23). Many researchers (5, 15, 32, 43) have investigated the effect of exercise on composition in healthy tendon, and they used the microdialysis technique for determined type I collagen turn over. They found that exercise increased turnover of peritendinous type I collagen after training. For example, Langberg et al.(44) investigated the effect of physical training on type I collagen synthesis and degradation in connective tissue of the Achilles' peritendinous. They found that physical training increased in turnover of collagen type I in connective tissue of the Achilles' peritendinous. With Achilles tendinosis, exercise also altered tendon composition after training (15, 43). For instance, Langberg et al. (15) investigated the effect of eccentric training on tendon composition in patients with chronic Achilles tendinosis. They reported that 12 weeks of eccentric training increases peritendinous type I collagen synthesis rate. Similarly, Heinemeier et al. (43) found that expression of collagens type I and III increased in response eccentric training.

3.3 Tendon mechanical properties

Tendon exhibits a viscoelastic property, which has important implication for modulation of the length and force of the serial sarcomere number of muscle (45). It is not an inextensible tissue, but deforms in response to the applied load in a manner dependent upon its mechanical properties (46). The evidence shows that exercise increases tendon stiffness and Young's modulus (17, 36, 38, 47, 48). The benefits of improving the mechanical properties of tendon such as increased stiffness and ultimate strength, capable of absorbing a larger amount of energy before failure could make tendon becomes larger, stronger, and more resistant to injury.

Previous studies have been investigated the effects of physical training or exercise on mechanical properties of tendon base on animal experiments (34, 38, 49). It was determined the tendon stiffness and Young's modulus. They found that mechanical properties altered following training. For example, Woo et al. (34, 38) found that endurance training for 12 month induced increased in strength and stiffness of tendon in pig. Similarly, Buchanan et al. (48) demonstrated that an increase in tendon stiffness and Young's modulus of the gastrocnemius tendon of helmeted guinea fowl after downhill running in 12 weeks training.

In vivo human experiments, real-time ultrasonography is used to determine the stiffness and Young's modus of tendon (17, 45, 47). There is evidence of resistance training on tendon mechanical properties in human. Reeves et al. (49) investigated the effect of resistance training on mechanical properties of patella tendon in elderly people. They found that tendon stiffness and Young's modulus increased by 65% and 69%, respectively following 14 weeks training. Similarly, Kubo et al. (40) investigated the effect of isometric training on elasticity of patella tendon in young people. They found that an increased in the stiffness from 65.5 $\pm$ 21.3 Nmm^{-1} to 106.2 $\pm$ 33.4 Nmm^{-1} and Young's modulus from 288 $\pm$ 26 MPa to 433 $\pm$ 35 MPa after 12 weeks of training. In addition, Kubo et al. (47) compared combined resistance training and stretching with resistance training only, in the respect with an alteration of the viscoelastic properties in humans. They have been reported that both programs increased in tendon stiffness. From these findings, the resistance training may have the effect on an increase of tendon stiffness and Young's modulus.

Eccentric training is a one form of resistance training that eccentric training has been widely use in clinical situation particularly in patients with tendinopathy. Information of eccentric training on tendon composition (15) and structure (14) have documented. However, effects of eccentric training on tendon mechanical properties are still limited and inconclusive. For example, Duclay et al. (16) investigated stiffness in Achilles tendon before and after 7 weeks of eccentric training using isokinetic dynamometer and reported an increase in tendon stiffness. In contrast, Mahieu et al.(17) also investigated the effects of eccentric heel drop training on tendon stiffness and they did not find any change after 6 weeks training. With methodology, both studies used a constant value of tendon moment arm length for calculating tendon force, and use the force-displacement values above 50% of MVC for calculating tendon stiffness. The inconsistent of findings could be due to the difference in training program (eccentric heel drop program VS eccentric training by calf machine). Concentric training is also a form of resistance training that it could induce tendon adaptation (48, 50). For example, concentric training induces an increase in collagen type III synthesis in rat tendon (50). Moreover, concentric training was also increased in mechanical properties (Young's modulus) in lateral gastrocnemius of guinea fowl (48). However, the information on effects of eccentric training and concentric training on mechanical properties of tendon are scarce.