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Functional Adaptation of Connective Tissue by Training

Funktionelle Anpassung von Sehnen

REVIEW

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Summary

- **Tendons transmit** the forces produced by the muscles to the skeleton and, therefore, contribute to performance during various movements. However, increases in muscle forces e.g. due to training need to go in line with adaptations of the tendinous tissue to avoid impairments of tissue integrity and prevent injury. Tendons can adapt by changes in the material and morphological properties, leading to increased resilience of the tendon (stiffness) beginning in childhood to old age, but effective mechanical stimuli and temporal dynamics of adaptation are different compared to the muscle. Consequently, periods of imbalanced muscle and tendon capacities can occur throughout a training period and may compromise optimal functioning of the muscle-tendon unit or affect tendon health.
- **Using an appropriate diagnostic setup** of muscle strength and tendon stiffness or tendon maximum strain, it might be possible to monitor the adaptation of muscle and tendon and provide individualized training recommendations promoting either muscle or tendon adaptation. We provide an evidenced-based effective training paradigm for tendon adaptation, characterized by five sets of four repetitive contractions with an intensity of ~90% of the isometric voluntary maximum maintained over 3 seconds, providing high magnitude tendon strain over an effective duration.
- **This tendon-specific training programm** can be applied to achieve performance increases, to prevent injuries and for rehabilitation purposes in the context of sports and daily life.

Zusammenfassung

- **Sehnen übertragen** die vom Muskel generierten Kräfte auf das Skelett und tragen somit zu unterschiedlichen Bewegungsleistungen bei. Eine Zunahme der Muskelkraft z. B. infolge von Training muss allerdings durch eine adäquate Anpassung der Sehne begleitet sein, um das Sehnengewebe nicht zu beeinträchtigen oder gar zu schädigen. Sehnen passen sich einer gesteigerten mechanischen Belastung durch eine Veränderung ihrer Materialeigenschaften oder morphologischen Eigenschaften bereits im Kindesalter und bis ins hohe Alter an, die zu einer erhöhten Widerstandsfähigkeit der Sehne (Steifigkeit) führt. Im Vergleich zum Muskel sind die mechanischen Stimuli, die eine Anpassung hervorrufen, sowie die zeitliche Anpassungsdynamik jedoch unterschiedlich. In Konsequenz können daraus Perioden mit Dysbalancen zwischen Muskel- und der Sehnenkapazitäten resultieren, die wiederum die Funktion der Muskel-Sehnen-Einheit beeinträchtigen oder der Gesundheit der Sehne schaden können.
- **Mit einer adäquaten Diagnostik** der Muskelkraft und Sehnensteifigkeit bzw. maximalen Sehnendehnung wäre es möglich, den Adaptationsverlauf von Muskel und Sehne zu kontrollieren und individuelle Trainingsempfehlungen zur Verbesserung von entweder Sehnen- oder Muskelkapazitäten zu geben. Dazu wird ein evidenz-basiertes Trainingsparadigma zur optimalen Anpassung von Sehnen vorgestellt, dass durch fünf Sätze mit jeweils vier wiederholten Kontraktionen mit einer Intensität von ~90% des isometrischen Maximums gehalten über drei Sekunden gekennzeichnet ist und eine wirksame hohe Dehnungsmagnitude über eine effektive Zeit erlaubt.
- **Dieses spezielle Sehnentrainingsprogramm** kann bei der Verbesserung der Leistung, Prävention von Verletzungen oder Rehabilitation im Kontext des Sports oder Alltags Anwendung finden.

KEY WORDS:
Tendon Adaptation, Locomotor Function, Tendinopathy, Injury Prevention

SCHLÜSSELWÖRTER:
Sehnenanpassung, Bewegungsleistung, Tendinopathie, Verletzungsprävention

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Tendon Function and Muscle-Tendon Unit Interaction

Tendons are connective tissue working in unit with the muscle by transferring the generated force to the skeletal system, and therewith enabling all kinds of movements (Fig. 1). The compliance of the tendinous tissue can considerably influence the force-length and force-velocity potential of the corresponding muscle, as well as provide elastic strain energy in a spring-like manner (14, 27). During active loading of the muscle-tendon unit (MTU), the tendon may stretch and recoil, taking a proportion of the length changes of the MTU and providing mechanical work. Consequently, the muscle fascicles can operate with comparably smaller length changes compared to the MTU (19, 23), enabling favourable force generating conditions (7, 32, 36) (Fig. 1). This was concluded to be beneficial not only for maximum force outputs but also for economic force generation (36), yet a fine neural control of the muscle-tendon interaction (38) ›

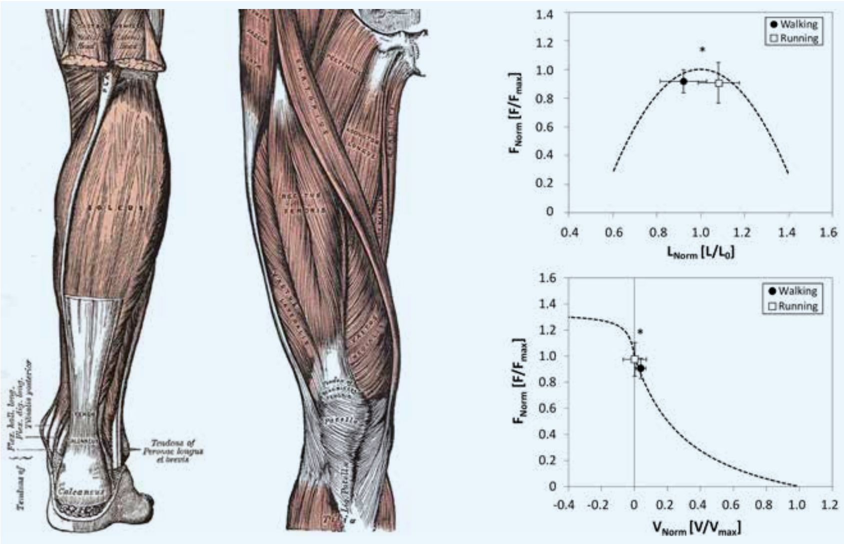

Figure 1

Achilles and patellar tendon as the series elastic elements of the triceps surae (left) and quadriceps muscle-tendon unit (right) (16). Tendon mechanical properties facilitate favourable muscle contraction conditions as shown exemplarily for the M. vastus lateralis, were the fascicles operate on the plateau of the force-length curve (top) almost isometrically (bottom) during locomotion, i.e. high force-length-velocity-potential (7).

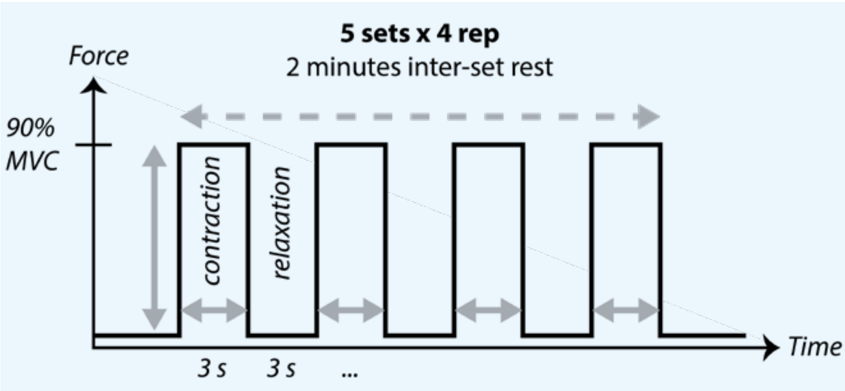

Figure 2

Evidence-based recommendations for an effective stimulus for tendon adaptation. High intensity loading to the tendon should be applied in five sets of four repetitions with a contraction and relaxation duration of 3 seconds each, and an inter-set rest of around 2 minutes. We suggest the training to be conducted three to four times a week for at least 12 weeks.

is required to drive effective motor performance (7, 32). The magnitude of tendon elongation as a function of applied muscle force is described by the mechanical parameter stiffness (11), reflecting the resilience of the tissue. It has been shown that tendon stiffness is attuned for effective muscle tendon interaction (e.g. correlated with jump (10), sprint (4), endurance (1) and recovery performance (20), indicating that a certain elongation or strain is required while higher or lower strain values would compromise the MTU function (24). Furthermore, high levels of strain due to an imbalance of muscle strength and tendon stiffness might challenge tissue integrity and increase the injury (33).

Mechanisms of Tendon Adaptation

Tendinous tissue is sensitive to the habitual loading profile and may adapt to increases or decreases in mechanical loading as e.g. due to training (for review (8)) or immobilisation (for review (25)). Two mechanisms of adaptation to increased loading can be identified: 1) changes in the material properties (e.g. increases in collagen content or collagen cross-linking) and/or 2) an increase in tendon cross-sectional area (morphological property) (3, 17, 40), with the latter as a more long-term response (8). The stimulus that triggers adaptation is the mechanical strain in terms of longitudinal deformation of the tendon induced by the contraction of the adjacent muscle.

The external strain is transmitted through the extracellular matrix to the cytoskeleton of the mechanosensitive tendon cells, initiating expression of genes and growth factors responsible for catabolic and/or anabolic cellular and molecular responses (e.g. collagen synthesis) (40), which in turn increase the resilience of the tissue (11). It can be argued that increases in stiffness compensate for loading-induced strength gains of the muscle that would consequently increase the strain of the tendon to non-physiological ranges. Since ultimate strain cannot be significantly altered (21), increases of stiffness may, therefore, serve as a protective mechanism (28).

From a lifespan perspective, evidence suggest that tendons can adapt to training already in childhood (for review (22)). Youth athletes present thicker tendons or higher stiffness compared to age-matched controls, respectively (12, 13, 30). Furthermore, an increase in material properties and corresponding stiffness after 10-week resistance training in prepuberal children has been reported as an immediate training effect (42). In old adults tendon properties tend to change, resulting in decreased stiffness (26,31). However, the potential of adaptation to training has been shown to be preserved (26), indicating the applicability of training to counteract age-related degeneration (for review (26)).

Optimal Training Stimulus for Tendon Adaptation

From a mechanobiological point of view, the application of mechanical strain to the tendon is characterized by the factors strain magnitude, frequency, duration and rate. In a series of systematic experiments, we investigated the effects of these factors on tendon mechanical, material and morphological properties. We identified an training (loading) paradigm that consisted of high magnitude loading over a duration of at least 3 seconds repetitively applied for 4 times in 5 sets over 14 weeks to be most effective to trigger tendon adaptation (Fig. 2) (3, 6, 9). Therefore, this evidenced-based loading paradigm, being short (~15 min) and easy to apply might be applicable to promote tendon adaptation in the context of performance, prevention and rehabilitation (for practical guidelines (2, 5)).

Imbalances of the Adaptation of Muscle and Tendon

Although muscle and tendon can adapt, the development within a training period is not necessarily balanced (for review (28)). First, the temporal adaptation dynamics of both tissues are different with slower response rates of the tendon due to a lower tissue turnover (18). And second, the mechanical stimuli to elicit adaptation of muscle and tendon are not the same (3, 28). Resistance training with moderate intensities (39) and plyometric training (37) shows significant effects on muscle strength, but induce comparably small responses of the tendon (3, 6, 9). Accordingly, an imbalance between the force generated by the muscle and the resilience of the tendon may occur throughout the training (Fig. 3) (28). However, ultimate strain is rather constant, which means a greater and even non-physiological mechanical demand for the tissue, while given a balanced adaptation of muscle and tendon the mechanical demand would remain the same despite higher loading (Fig. 4). Indeed, a current study on adolescent volleyball athletes evidenced that over the time course of one year, athletes were characterized by chronically higher maximum tendon strains in comparison to the control group but also greater fluctuations, indicating greater demand of the tissue due to periods of imbalanced adaptation (29). In consequence, the fine-tuned interaction of the MTU can be disturbed and the risk of injury and tendinopathy might increase (15, 43).

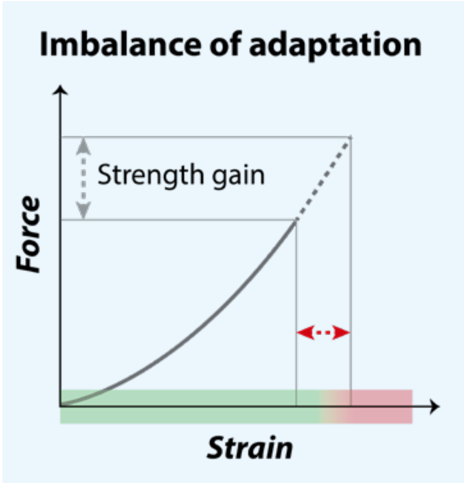

Figure 3

If the muscle force that is applied to the tendon during a contraction increases without an accompanying adaptation of the resilience of the tendon, the tissue is subjected to a higher demand (strain) at high levels of force, indicating higher risk of injury.

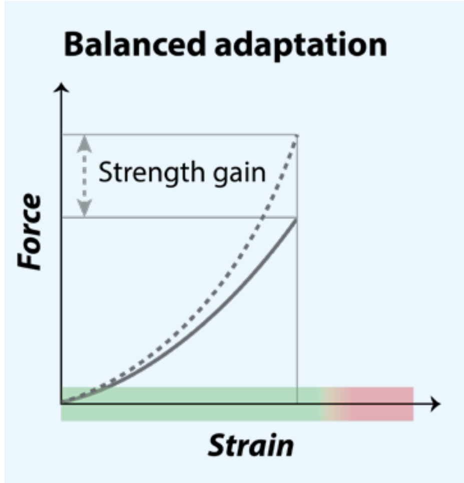

Figure 4

Given a balanced adaptation of muscle and tendon, the demand for the tendinous tissue remains constant despite higher loads (forces).

Individualized Control of Training by Differentiated MTU Diagnostics

Based on our investigations we can conclude that a strain of 4.5 to 6.5% of the tendon repetitively applied over 3 s is an optimal training stimulus, while lower magnitudes of strain seem ineffective (3, 6, 9). Other research supports the superior adaptive response in this particular strain range, while strains below or above were again not effective or even disruptive (35, 41). Our loading paradigm implements contraction intensities of 90% MVC, i.e. a submaximal intensity to allow for the volume of 4 repetitions within each of the 5 sets. Maximum contractions (100% MVC) should in turn reach levels above approximately 6.5% of strain, however, maximum strain higher than around 9% may be indicative of tissue degeneration (35, 41). Thus, if strain at maximum contractions is higher than around 9%, tendon stiffness is too low compared to the muscle's strength and a training of the tendon using comparably lower contraction intensities is indicated. The reduced intensities would provide effective levels of strain for tendon adaptation but the low training volume and respective moderate mechanical and metabolic stress would lead to marginal changes in muscle strength. In this way the imbalance could be neutralized. On the contrary, when maximum strain is lower than approximately 4.5%, muscle strength is deficient and so tendon contribution to the MTU function, therefore, a training that targets muscle strength gains should be considered. As it has been demonstrated that training until muscular fatigue with moderate loads is a potent stimulus for muscle hypertrophy and strength development (34 for a review) but the associated low levels of strain do not trigger tendon adaptation (3, 6), this type of training should be applied when aiming to increase muscle strength but not tendon stiffness.

Figure 5 presents a data set of maximum strain values of the patellar tendon during maximal knee extension contractions of 134 male and female athletes (9-18 y.). It can be recognized that some athletes show very low or high strain values, indicating the need of very different targets in the training (muscle strength vs. tendon training). Furthermore, it is obvious that several athletes reached strain values higher than 11-12% were an intervention seems very acute and others with values around 9-10% were a correction of the training is easier to implement. In figure 6 the maximum patellar tendon strain of volleyball athletes was measured five times over one training year alongside to a control group (data from (29)). During the training period variations in maximum strain can be observed, giving evidence for the need of monitoring the training to ensure balanced adaptation within the MTU. It can also be seen that the non-athletes required muscle strength training rather than tendon training.

A simple frequently applied diagnostic of the current MTU capacities could be the basis for individualized training programs. Muscle strength and tendon stiffness or maximum strain can be quantified, providing the desired information about the relationship of the current muscle and tendon adaptation level. Technically, a simplified diagnostic setup can be realized by using ultrasound to measure tendon stiffness or strain and dynamometry to measure the joint moment as an estimator of muscle force during a maximal isometric contraction (for detailed description see (2)). The information can be used to monitor the training status and further to determine the required training intensity for tendons. Regularly the effective magnitude of strain (app. 4.5-6.5%) can be achieved by a contraction intensity of around 90% MVC (3,6,9). ›

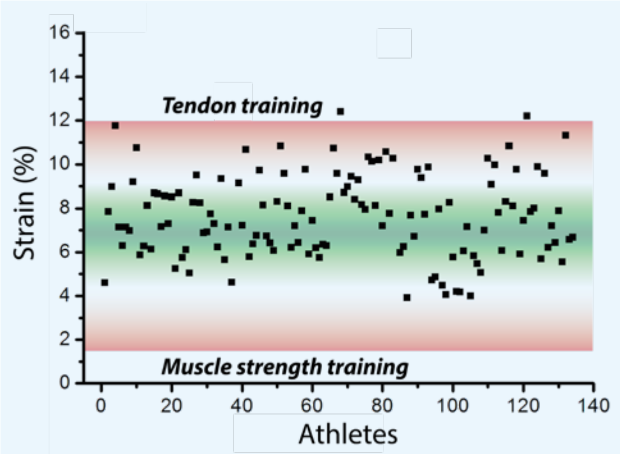

Figure 5

Individual values of maximum tendon strain of the patellar tendon during maximum voluntary knee extensions. The green shading indicate a balanced adaptation of muscle force and tendon stiffness while the red shading shows strain ranges indicative of an imbalance of adaptation. Athletes with values in the upper red range of strain would benefit from training of the tendon to increase stiffness and athletes with values in the lower red range from a training of muscle force.

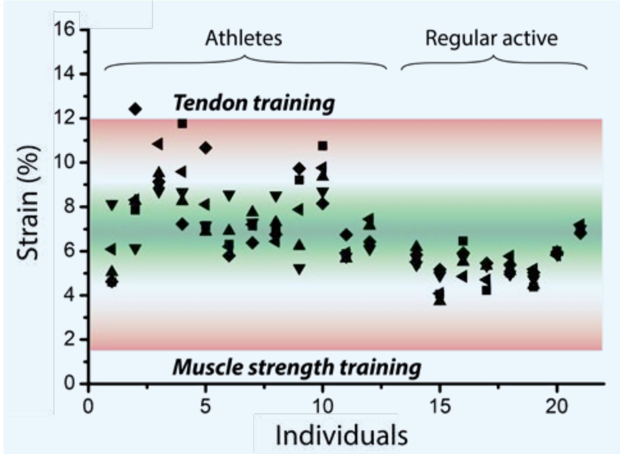

Figure 6

Maximum patellar tendon strain values of young volleyball athletes (n=12) and non-athletes (n=8) throughout a period of one year (five measurements). The green shading indicate a balanced adaptation of muscle force and tendon stiffness while the red shading shows strain ranges indicative of an imbalance of adaptation. Periods of imbalanced adaptation can be recognized during training. This continous diagnostic allows for an evaluation of muscle and tendon capacities to adjust the training process if necessary (data taken from (29)).

However, in case of imbalances the given intensity could either be too high to induce targeted strain or even to low (35,41). Implementing regular diagnostics, the optimal range of intensity as percentage of MVC (according to app. 4.5-6.5% strain) could be adjusted for a personalized training.

Conclusion

In conclusion, muscle and tendon can both adapt following training, but differences in the physiology of the tissues may lead to a temporary imbalance of muscle and tendon capacities. A differentiated diagnostic of muscle strength and tendon stiffness or maximum strain is necessary to identify periods of imbalanced adaptation and provides the opportunity to tailor the training process by individualized exercise recommendations (muscle strength vs. tendon training). In this regard, our evidenced-based loading protocol provides an effective training paradigm for tendons.

Conflict of Interest

The authors have no conflict of interest.

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