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THE ACUTE TRANSVERSE STRAIN RESPONSE OF THE PATELLAR TENDON TO QUADRICEPS EXERCISE: A GENDER BASED COMPARATIVE PILOT STUDY.

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Abstract:

Introduction:

Tendons are highly adaptive to changes in loading forces put on them always from walking, running, jumping and in other sporting activities. There are few studies involving the Patellar tendon (35, 29), reported a studies on the Acute Transverse Strain response of the Patellar Tendon to quadriceps exercises, a response similar to the Achilles and other tendon studies reported. Resistive exercises are therefore shown to significantly alter the sonographic measures of the patellar tendon structure; the strain, entropy and echogenicity.

Method:

Ten adult males and ten adult females, with no previous ankle or knee pathology, between 22 and 55 years of age, an average age of 38.5 +/- 15 years; height of 1.60 to 1.80 m and weight of 60 to 90 kg, were recruited.

A 5- to 10- MHz linear array transducer was used to obtain standardized sagittal sonograms (8), of the patellar tendon immediately before and after 50 repetitions of leg extensions exercise, 20 mm distal to the inferior pole of the patellar. The transverse strain ε, (Hencky strain) was calculated as a percentage ratio of the post- to pre-exercise tendon thickness and the result statistically analysed (35).

Result:

There was immediate decrease in patellar tendon thickness ($P < 0.05$), after the quadriceps exercise in both groups. A transverse strain of -13.8% +/- 7.8% occurred in the males and the females had a transverse strain of -9.6% +/- 3.5%. There were echotexture changes; increased tendon echogenicity ($P < 0.05$), decrease in entropy ($P < 0.05$) in both groups.

The patellar tendon echogenicity was higher for all participants post exercise while the entropy dropped in the post exercise measurement in all participants. There was also a significant difference in the magnitude of transverse strain response ($P < 0.05$) between males and females; -13.8% for males against -9.6% for females a difference of 30%.

Conclusion:

This is a pilot study comparing the male and female acute strain response of the patellar tendon to quadriceps exercise and the consistency of the response in females. This strain response is consistent in both males and females but with a lower magnitude of response in females.

KEYWORDS: TENDONS, EXERCISE, IMAGING, STRUCTURE, PHYSIOLOGY, PATELLA, STRAIN, STRESS

INTRODUCTION:

This is a pilot study to compare the acute transverse strain response of the patellar tendon to quadriceps exercise between males and females. The aim of this study, therefore was to evaluate and compare the immediate response of the patellar tendon to quadriceps exercise between males and females.

Deformation is the ability of a material to change shape. In continuum mechanics it is the transformation of a body from a normal or natural *reference* configuration to a new *current* configuration or shape (37). A temporary shape change that is self-reversing after the force is removed, so that the object returns to its original shape, is called elastic deformation. In other words, elastic deformation is a change in shape of a material at low stress that is recoverable after the stress is removed. This type of deformation involves stretching of the bonds, but the atoms do not slip past each other.

The acute transverse strain response of the patellar tendon to quadriceps exercise is a form of elastic deformation, because the tendon recovers completely after the exercise.

The relative displacement of particles in the body of a material that excludes rigid-body motions is termed *Strain* and is defined with respect to the initial and the final configurations of the body in question, in this research the patellar tendon.

A strain is a normalized measure of deformation representing the displacement between particles in the body relative to a reference length and it is in general described as a tensor quantity. Strain is a measure of how much an object is being stretched. Tendons when subjected to physical loading undergo changes in four different ways, these mechanical properties are described as:

(1) Strain – deformation or elongation relative to the original length,

Strain = dL/Lo

the strain is calculated as the change dL/Lo, Lo being the original length.

(2) Stress – this is the tendon force (F) relative to the tendon cross sectional area (CSA),

stress = F/CSA,

(3) Stiffness – the change in tendon length in relation to the force applied. This is dependent on the CSA and length of tendon, stiffness = dF/dL,

(4) Tendon Modulus – this is the relation between tendon strain and tendon stress, and represents the properties of the tendon material not considering the CSA, the higher the modulus the stronger the tendon,

Modulus = Stress/Strain (14).

Tendons can withstand considerable forces during acute physical activity, adapting to changes due to chronic mechanical load over time (26). Positive tendon plasticity from long-term loading has been extensively studied and is well documented (27). Tendons transmit skeletal muscle forces to bones and thus are involved in all movements and because of these, tendon properties are affected by all physical activities. Tendons are stiff but resilient, possess a high tensile strength, and have the ability to stretch up to 4% before damage occurs and with a stretch greater than 8%, macroscopic rupture occurs in the tendon (20, 26).

Tendons are histologically composed of type 1 collagen and to a lesser extent the type 111 collagen fibrils held together by a complex extracellular matrix all enclosed in a sheath (endotendon) with blood vessels, lymphatics and nerves (14). Tendons consist of a few cells (fibroblast), the collagen fibrils are mainly arranged in a longitudinal direction, in line of the force imposed upon it during muscle contraction (20, 14).

The understanding of acute response of tendons to exercise remains limited, even with extensive research evidence lacking in certain areas. Current knowledge relies on studies that were limited to measuring one or two variables, and also relies heavily on data from a limited selection of tendons, mainly the Achilles and more recently the patellar tendon (9, 10, 40, 33, 35).

The normal human patellar tendon (Figure1. 3), measures 44mm to 52mm in length with a mean length of 46mm (+/- 4mm SD) and a mean thickness of 5mm +/- 3mm SD, (4.5mm in women and 5.3mm in men) with a normal range of 3-11mm (3-7mm in women and 3-11mm in men).

Acute bouts of exercising of less than 24 hours induces a thinning of the tendon, and this response could be measured *in vivo* using ultrasound technology. It is the best method to assess tendon mechanics, providing real-time data, clear and reliable images at a very low cost (27, 11).

The strain or the deformation of the tendon can be presented as the natural strain ε, called *true strain* or *Hencky strain*. The strain formula is:

$\varepsilon = dl / l_{o},$ this can be expressed as; $l_o - ln / l_o$

dl = change of length (m), l_o = initial length (m), ln = new length

MATERIALS AND METHOD:

In this study, 10 healthy males and 10 healthy females volunteers with no previous knee pain or pathology performed 50 dominant leg extensions against a 5kg fixed resistance, using a knee extension bench.

The males (Table 1), ranged in age between 23 and 55 years, a mean (+/- SD) age of 34.8 +/- 9.8 years; height of 1.65 to 1.80m, with a mean of 1.74 +/- 0.08m and a body weight of between 66 to 89kg, a mean of 77kg +/- 8.5kg. The females (Table 2), ranged in age between 22 and 41 years, a mean (+/- SD) age of 30 +/- 7 years; height of 1.55 to 1.69m, with a mean of 1.66 +/- 0.07m and a body weight of between 60 to 80kg, a mean of 70kg +/- 6kg. A health history questionnaire was used for selection and females on hormonal contraceptive pills were excluded. The volunteers gave informed written consents for participation in this study. It was approved by the University of Dundee Research Ethics Committee, UREC 14017.

Table 1 Male Anthropometric Values

ID/SN	AGE (yrs)	HEIGHT (m)	WEIGHT (kg)
1	34	1.76	79
2	36	1.67	77
3	44	1.60	84
4	55	1.76	79
5	28	1.67	60
6	41	1.70	89
7	32	1.82	78
8	31	1.76	66
9	23	1.89	83
10	24	1.80	75
Mean	**34.8**	**1.74**	**77**
SD	**9.8**	**0.08**	**8.5**

Table 2 Female Anthropometric Values

ID/SN	AGE (yrs)	HEIGHT (m)	WEIGHT (kg)
1	40	1.65	76
2	38	1.55	72
3	26	1.70	68
4	41	1.60	65
5	23	1.69	80
6	22	1.64	66
7	31	1.58	67
8	28	1.73	76
9	24	1.78	67
10	26	1.72	60
Mean	**30**	**1.66**	**70**
SD	**7.0**	**0.07**	**6.0**

The participants assembled at the Physiotherapy Unit and the Fracture Clinic of Eastbourne District General Hospital, on four separate occasions for data collection. There were no reports of any physical or medical condition that may negatively impact on or eliminate any participant from the project. The heights of the participants were measured to the nearest millimetre using a seca-217-stadiometer-for-mobile-height-measurement (Seca United Kingdom) and the weight with Silvercrest Z31912 Electronic scale (OWIM GmbH & Co.Kg, Stiftsbergstrabe 1, Germany). The weight and height of the participants were measured to the nearest kilograms and meters as recorded in tables **1** and **2**. The age of the participants were also recorded as part of the anthropometric data.

Pre-exercise ultrasound examination of the patellar tendon thickness, echogenicity and entropy was completed using an L5 – 10 MHz linear array transducer, 10 frequencies – 2D/M-mode ultrasound machine, (Sonosite M-Turbo Portable Ultrasound Machine, SonoSite, Inc., 21919 30th Drive SE, Bothell, WA 98021-3904, USA). The settings were standardized; the spatial pulse length and axial resolution were 310 and 160 µm respectively.

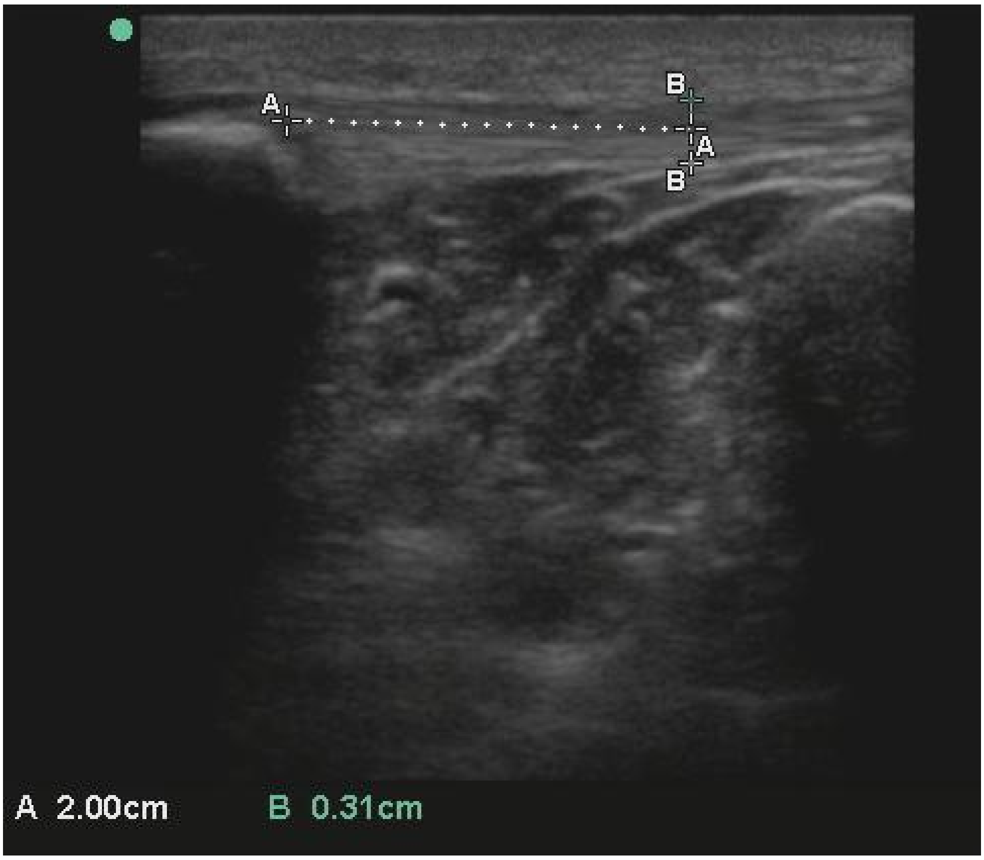

Figure 1: Grey Scale Image of the patellar tendon showing regular homogenous pattern of stripes or striations of light and dark bands; AA represents the 20mm tendon length from the attachment at the inferior pole of the patella; BB represents the tendon thickness anterior and posterior margins at the 20mm point from the proximal attachment at the inferior pole of the patella.

Accordingly, acquisition protocol was carefully followed to ensure that the ultrasound beam was perpendicular to the orientation of the tendon collagen fibers, the transducer was positioned perpendicular to the tendon surface, otherwise the expected sonographic appearance may be lost and the capture would simulate a diseased tendon which would increases the likelihood of an artifact called anisotropy which is unique to the musculoskeletal system (12, 25)

Each participant was supine and relaxed on an examination couch with a flexed knee at 90 degrees for the ultrasonograhic measurements of the patellar tendon before the exercise and again taken within two minutes post exercise. All participants performed 50 knee extensions against a 5kg resistance loading of the patellar tendon of the dominant leg.

The exercises lasted between 5 and 8 minutes per participant, and tendon thickness was determined approximately 20mm distal to the proximal attachment at the inferior pole of the patella, and the transverse Hencky strain was calculated as the natural log of the ratio of post- to pre-exercise tendon thickness and expressed as a percentage (34, 37) Measurements of tendon echotexture (echogenicity and entropy) were also statistically analysed from subsequent grayscale profiles using MATLAB R2014b (MathWorks) and the echogenicity and entropy evaluated with statistical values; P – the echogenicity and S – the entropy. The gray-scale images with byte-sized image values in the range 0 to 255 image data were displayed according to pixel and recorded without any further adjustments as the echogenicity.

RESULTS

The decrease in the sagittal thickness of the patellar tendon after quadriceps exercise was significant, ($P < 0.05$), for both groups (Table 3), it was consistent and reproducible even with the small resistant of 5kg.

The tendon pre- and post-exercise measurements were sonographically obtained at a standard site 20mm distal to the attachment of the patellar tendon to the distal pole of the patella (8). Female and male mean values were recorded in Table 3 and Table 4 respectively. The ultrasound scan greyscale image (Figure 1), captured showed the anterior and posterior margins (thickness) of the tendon and the collagen matrix arrangement and the density reflected in the echotexture of the tendon.

There was an intertester reliability and measurement precision test of the ultrasonographic measurements. The grey scale images (Figure 1), were reassessed independently for repeatability and reliability of tendon thickness measurements 20mm from the distal pole of the patella. The measurements were observed to be reliably accurate and readily repeatable. Tendon echotexture was obtained from the greyscale images showing the echogenicity as greyscale image density and entropy as collagen arrangement over the rectilinear region of the tendon at the 20mm zone. These parameters have arbitrary unit (P) for echogenicity and (S) for entropy, and are region specific.

Since ultrasound is now being used increasingly to assess and diagnose tendon pathology in sporting injuries (9, 27,10), and in general orthopaedic cases, the understanding of tendon echotexture is very important especially in detecting neuromuscular disorders (28).

Table 3: Patellar tendon acute strain response after quadriceps exercise

Males			Females		
Age (years)	Pre-exercise (mm)	Post-exercise (mm)	Age (years)	Pre-exercise (mm)	Post-exercise (mm)
34	3.6	3.2	40	3.3	3.1
36	3.6	3.2	38	3.4	3.1
44	3.7	3.3	26	3.0	2.7
55	3.8	3.3	41	3.2	3.0
28	3.8	3.1	23	3.1	2.8
41	3.6	3.2	22	2.9	2.4
32	3.6	3.1	31	3.0	2.8
31	3.7	3.2	28	3.1	2.7
23	3.5	2.9	24	3.5	3.1
24	3.8	3.1	26	3.0	2.8

Table 4: Female mean sonographic measurements of the patellar tendon characteristics before and after quadriceps exercises

Parameters	**Pre-exercise**	**Post-exercise**	**Strain %**
Tendon Thickness (Mean +/- SD)	3.1mm +/- 0.2	2.8mm +/- 0.22	- 9.6 +/- 3.5
Echogenicity (Mean +/- SD)	77.1 +/- 1.0	81.0 +/- 2.7	
Entropy (Mean +/- SD)	55.6 +/- 0.9	50.6 +/- 1.2	

The Statistical Package for the Social Sciences (SPSS Inc. Chicago, IL, USA) was used for statistical analysis. Participants were assumed to be normal and all measurements correct to the nearest decimal point in mm. The Mean (M) and Standard Deviation (SD) values, (Tables

3 and 4), were used for basic statistics to determine outcome assuming a normal distribution curve.

The two samples were compared using the paired t-test in terms of tendon strain response, echogenicity and entropy changes. The relationship between gender and tendon strain response was investigated and any possible association of the anthropometric variables of height, weight and tendon response were noted, there was none. (21) reported the lack of association between anthropometric (height and weight) values and BMI with tendon acute transverse strain response, but there is however an association of BMI with tendinopathy.

Table 5: Male mean sonographic measurements of the patellar tendon characteristics before and after quadriceps exercises

Parameters	**Pre-exercise**	**Post-exercise**	**Strain %**
Tendon Thickness (Mean +/- SD)	3.6 mm+/- 0.10	3.1mm +/- 0.11	- 13.8 +/- 7.8
Echogenicity (T) (Mean +/- SD)	77.6 +/- 2.0	84.2 +/- 2.0	
Entropy (P) (Mean +/- SD)	59.8 +/- 1.0	53.4 +/- 1.10	

There is a negative correlation between patellar tendon acute transverse strain response and participant's age, which was also reported by Wearing et al., (37).

Patellar tendon strain response was consistent in both groups; males: (t = -0.009 and P <0.05) with a mean transverse strain of -13.8% +/- 7.8% and females: (t = 0.002 and P <0.05) and also a mean transverse strain of -9.6% +/- 3.5 %. The difference between the female and the male pre-exercise tendon thickness was statistically significant, t = 0.0001 and P <0.05, and also the post-exercise tendon thickness, t= 0.0068, P <0.05. The difference in patellar tendon thickness between males and females before and after the exercises also resulted in a difference in the acute transverse strain response magnitude between males and females of approximately 30%, which is statistically significant, t = 0.003 and P <0.05.

The patellar tendon echogenicity was higher for all participants post exercise while the entropy dropped in the post exercise measurement in all participants. There is therefore a direct correlation between the transverse strain response of the patellar tendon with both the entropy and echogenicity (Figures 2, 3 and 4). The higher the strain response the higher the echogenicity and the lower the entropy post-exercise.

There is also a significant difference in the magnitude of transverse strain response between males and females; -13.8 % in males and -9.6 % in females. Many factors such as tendon size, quadriceps muscle strength, exercise technique and female hormones are involved in tendon acute transverse strain response and so may affect the magnitude of response.

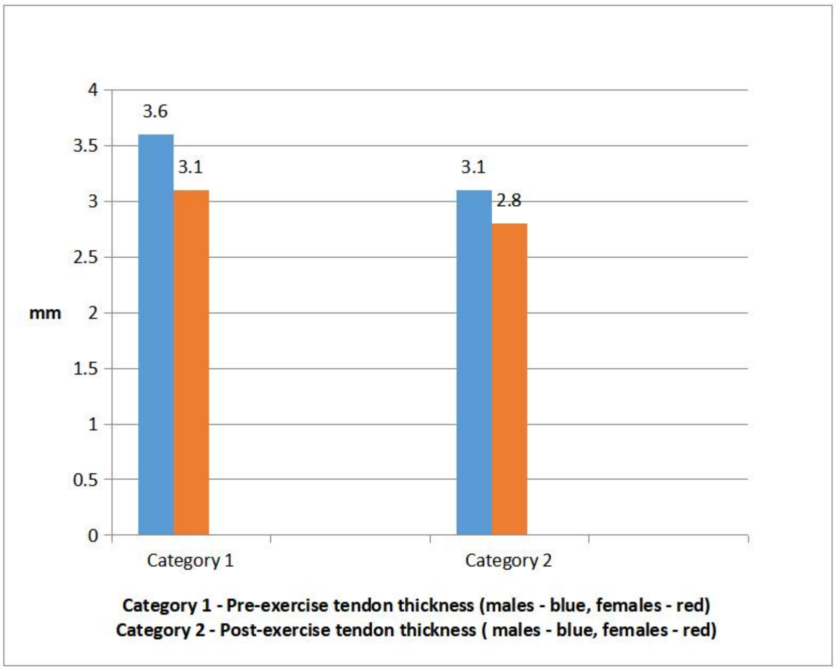

Figure 2.: Patellar tendon acute transverse strain response to quadriceps exercise.

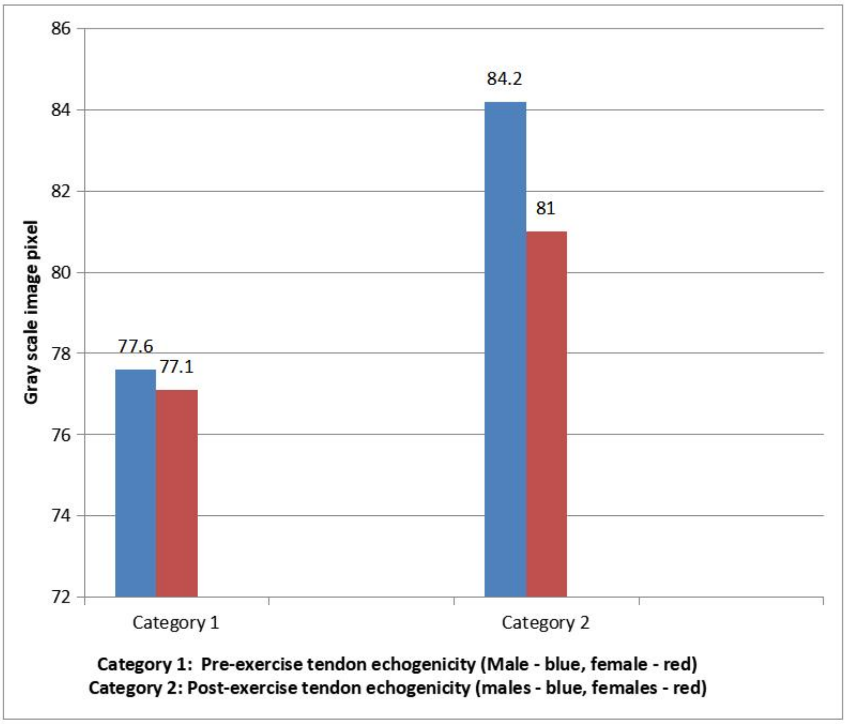

Figure 3: Patellar tendon echogenicity changes pre- and post-quadriceps exercise.

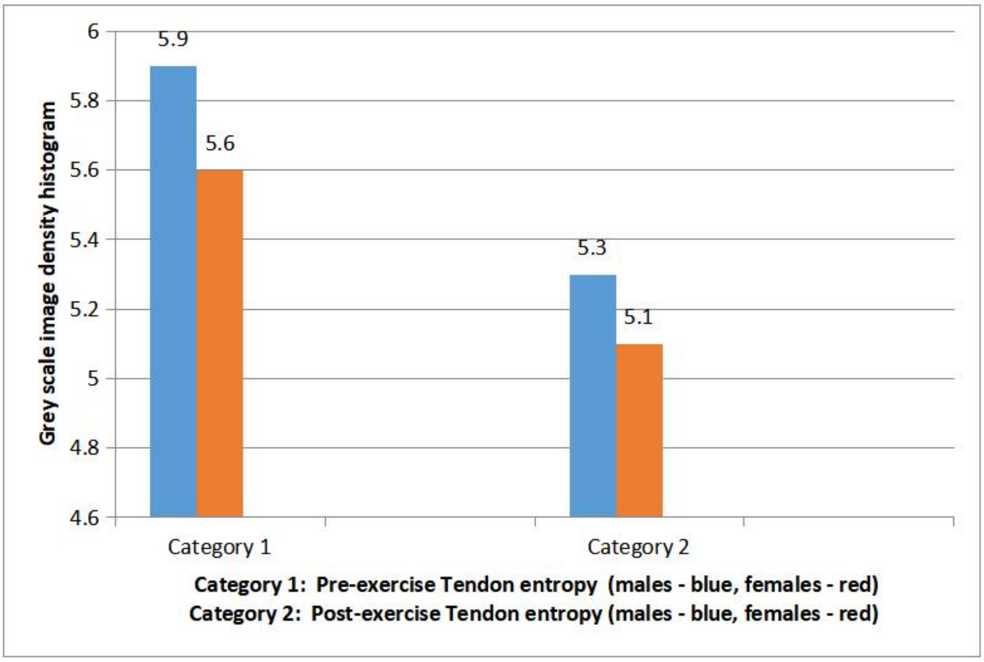

Figure 4: Patellar tendon entropy pre- and post-quadriceps exercise

There was no correlation between the weight and height of the participants and the magnitude of acute transverse strain response of the patellar tendon but age is negatively correlated to the acute strain response of the patellar tendon, the greater the age the less the response and vice versa.

DISCUSSION

This is a pilot study, the first study to compare the acute transverse strain response of the patellar tendon between males and females, not just in terms of the magnitude of response but also the consistency.

There was immediate reduction in patellar tendon thickness, an acute transverse strain response immediately after the knee extension exercises of -13.8% in males and - 9.6% in females. Higher magnitude strain response have been reported in other studies involving the patellar tendon (29,37), and the Achilles tendon (36, 8, 13, 18) of only male participants, where greater resistance was used and the exercise was intense and prolonged (32).

The male result in this study is in line with other studies of acute transverse strain response in tendons after exercise in male participants.

Tendons exposed to load have been observed *in vivo* to undergo load induced collagen alignment, water extrusions and loss of elastic functional properties (38, 1,14, 35). This observation is supported by the changes in the tendon echotexture during exercise in which both the echogenicity and entropy are altered and can be sonographically observed and recorded. The acute transverse strain response observed is a result of the exercise induced biomechanical changes in the patellar tendon (10, 35), which has a negative correlation with age but independent of other anthropometric measurements. Wearing SC, et al., (35), observed a 2% reduction in the acute transverse strain response of the patellar tendon after exercise with each decade of life, which in effect means the acute transverse strain response of a participant at age 50 will be 2% less than what it was 10 years earlier at age 40. Current study has shown that age is negatively correlated to the acute transverse strain response of the patellar tendon Figure 5 (males) and Figure 6 (females), the more the age the less the response and vice versa, which supports other studies.

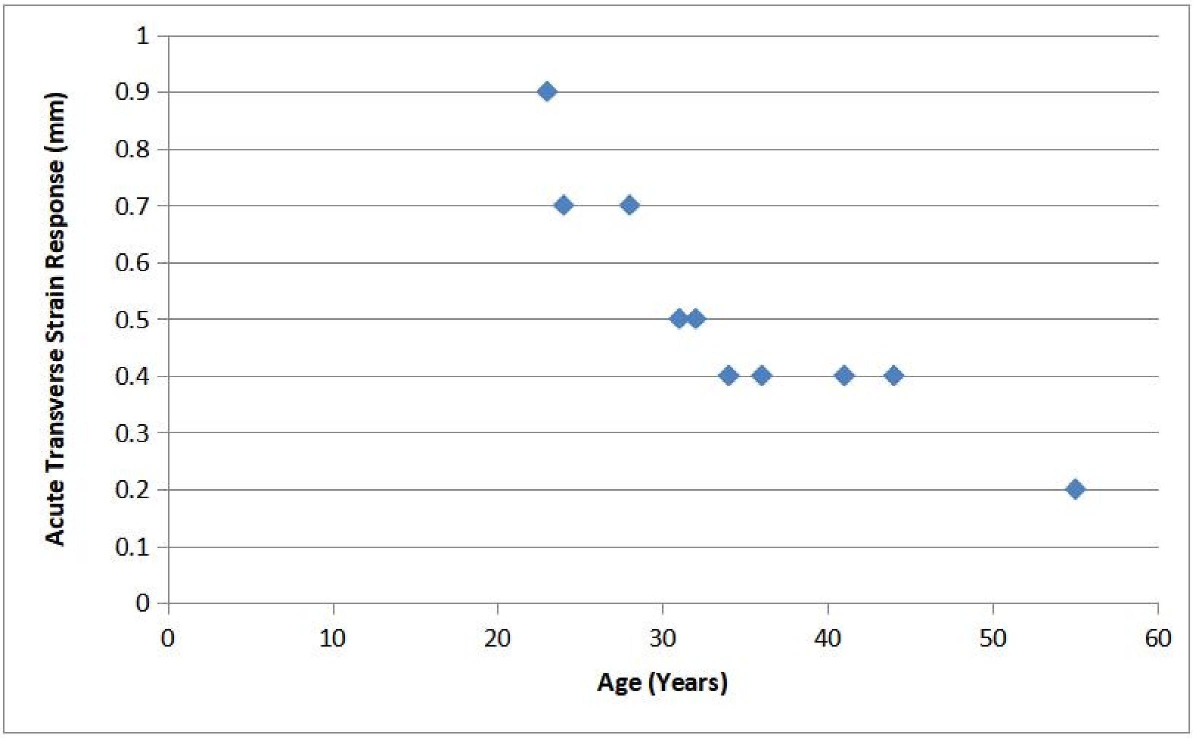

Figure 5: Male age correlation with patellar tendon acute transverse strain response

Exercises induce less collagen alignment, fluid movement and crimp in older individuals because older tendons have a more disorganised collagen structure, which is evidenced by the high pre-exercise entropy and also a lower transverse strain response. This is thought to contribute to the impaired capacity of the patellar tendon in older individuals to adapt to chronic loading (4).

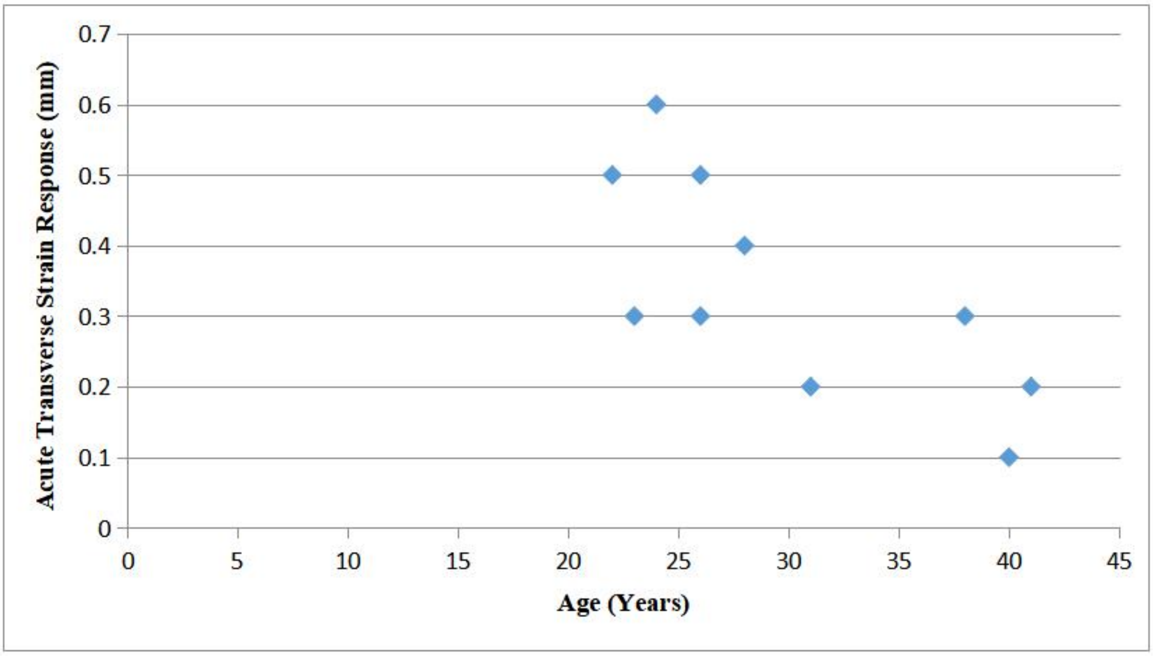

Figure 6: Female age correlation with patellar tendon acute transverse strain response

The patellar tendons of the female participants all showed acute transverse strain response to exercises. It was consistent but with a lower magnitude compared to the males, 30% less than males, there was also an increase in echogenicity and a decrease in entropy post-exercise. More studies are needed to try and explain the difference in strain response magnitude between males and females. Studies have shown that womens' tendons are oestrogen hormones protected and therefore lack the adaptive capacity to chronic loading seen in men (38, 17, 16).

The male and female patellar tendons are similar in terms of the acute transverse strain response to quadriceps exercises, though they differ in the magnitude of the strain response.

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