



Tensile properties of the human iliotibial tract depend on height and weight

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ABSTRACT

Background and aims: The human iliotibial tract (IT) is increasingly used in different types of musculoskeletal models. Previous findings indicate age-dependent changes of the human IT tensile properties, these lack confirmation to date. The relationship of the human IT and anthropometrical parameters, such as body height and weight has not been investigated before.

Materials and methods: 33 fresh human IT samples (age range 4 months to 93 years) were uniaxially tested using digital imaging correlation and the latest advances in 3D-printing to standardize biomechanical soft tissues testing.

Results: The tensile parameters of the human IT are not age-dependent, except for the maximum strain in males. Height significantly correlated to elastic modulus, tensile strength and maximum strain of the human IT in males. Females just showed a significant correlation between maximum strain and weight, which was contrary to the findings in males.

Discussion and conclusion: Age-dependency of human IT tensile parameters could not be confirmed in the larger sample size investigated in this study. Due to the strong correlation with the tensile IT parameters in males, we suggest that height should be integrated when the IT is used in simulations, such as finite element analyses of the hip and knee.

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1. Introduction

The iliotibial tract (IT) in humans is a ligamentous structure of biomechanical importance for load distribution and stabilization of the hip and knee joint [1,2]. The IT is increasingly used as a model which is integrated in various types of musculoskeletal modelling of the pelvis and lower limb, in order to assess kinematics in humans when standing or walking [1,3–5]. Recently, our group has reported the load-deformation properties of the IT, such as elastic modulus, ultimate tensile stress and maximum strain to gain a greater understanding about its mechanics under quasi-static conditions [6–8]. However, the reported tensile properties of the human IT are based on a limited number of tissues, with a maximum of 18 samples used within an individual study [1,6–11].

Consequently, the effects of age on the tensile properties of the IT could not be thoroughly evaluated, as the investigated age ranges of single studies are very limited. Thus, studies involving cadavers originating from anatomical bequeathal or legal medicine mostly result in sample cohorts with high or low mean ages [6–8,10,11]. Moreover, the potential impact of parameters such as sex, body height or weight on the load deformation behavior of the IT have not been investigated in detail before. Clarifying the potential effect of age, sex, height or weight on human IT kinematics may allow for more accurate adjustments to the mechanical parameters used in future modelling approaches and improve realistic simulation scenarios of the lower extremity. In the given study, elastic modulus, ultimate tensile stress and maximum strain of fresh and chemically unfixed human ITs were evaluated within a wide age range of 4 months to 93 years. Latest developments in standardizing soft tissue for testing, which have been reported

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Anthropometric parameters of the cadavers

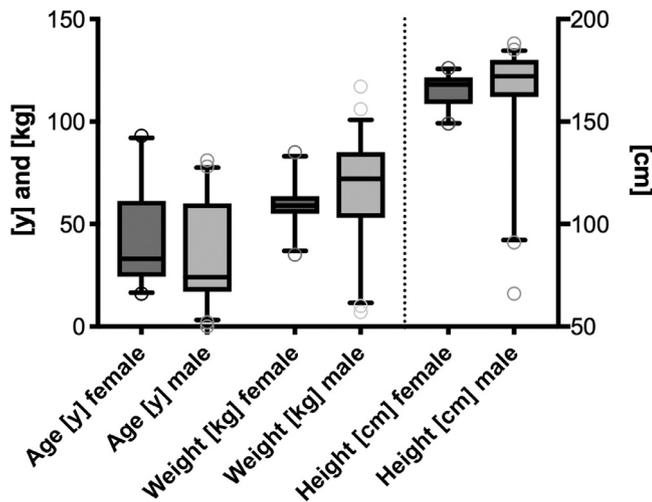


Fig. 1. Anthropometric parameters (age, weight and height) of the tissues grouped in sexes. Small grey circles represent the 10–90 percentile.

by our group, were used. The biomechanical properties were investigated in relation to age, sex, height and weight.

We investigated the following hypotheses:

1. The elastic modulus, ultimate tensile stress and maximum strain of the human IT change with age.
2. Anthropometrical parameters such as weight and height impact the biomechanical properties of the human IT.

2. Materials and methods

2.1. Preparation of human tissues

A total of 33 human IT samples (10♀; 23♂), were obtained at an age range from 4 months to 93 years (mean age 36 ± 27 years) as displayed in Fig. 1. The overall average weight of all cadavers was 70 ± 26 kg, with 59 ± 12 kg for females and 66 ± 39 kg for males (see Fig. 1). The average height of all cadavers was 161 ± 29 cm with 165 ± 9 cm for females and 159 ± 44 cm for males (see Fig. 1). Ethical approval was granted by the Ethics Committee of the University of Leipzig, Germany (156-10-12072010). Tissues from individuals with signs of musculoskeletal degeneration or pathology were not included. All tissues were removed from fresh and chemically unfixed cadavers, as described previously, sectioned into strips measuring 100–120 mm, pre-cooled and then shock frozen at -80°C for storage [8]. Before the mechanical tests were conducted, an osmotic stress protocol was applied to adjust the tissues to their native water content of 69 percent as reported previously [8]. To minimize material slippage during mechanical testing, the tissue ends were either plastinated or clamped with customized 3D-printed clamps [7,8,12,13].

2.2. Mechanical testing

The specimens were fixed at their partially-plastinated or clamped ends. Prior to the testing, the central parts of the specimens were uniformly tapered using a dog-bone shaped template for a predefined region of failure according to previous experiments [14]. Consequently, the clamp-to-clamp distance (testing area of the specimen) of all samples measured 60 mm in length with a minimal width of 12 mm. To determine the cross-sectional area, the tapered area of the specimens was set in a cast with siloxane impression material (medium-bodied, Exahiflex, GC Cor-

poration, Tokyo, Japan). Tensile tests were conducted using a uniaxial setup (Zwick/Roell, Ulm, Germany and Instron, Norwood, MA, USA and a 2.5-kN load cell). The specimens were preconditioned with a crosshead displacement of $v=20$ mm/min and a maximum strain of 5%. Load–displacement data was then obtained at the same crosshead displacement velocity until material failure (see Fig. 2). The linear elastic response of each sample was evaluated in the final load cycle, which was conducted after preconditioning and until material failure. The elastic modulus was evaluated by regression in the linear slope of the nominal stress–strain curve. Furthermore, scanning electron microscopy was performed of the failure area and also an area that was not used for biomechanical testing in one representative specimen (see Fig. 3).

2.3. Data evaluation

The casts of the cross-sections were scanned with a resolution of 1200 dpi (Perfection 7V750Pro, Seiko Epson Corporation, Suwa, Japan) and calculated using the software Measure 2.1d (Dat-Inf GmbH, Tübingen, Germany). Surface deformation was recorded perpendicular to the surface by a DIC system using a single charge-coupled camera with 2.8 megapixel resolution (Q400, Limes, Krefeld, Germany). Strain data during mechanical testing was evaluated with the ISTR4 4D software (VRS 4.4.1.354, Dantec Dynamics, Ulm, Germany). Elastic modulus, ultimate tensile stress and maximum strain were calculated from the DIC data and synchronized force readings using MATLAB R2017b software (Mathworks, Natick, MA, USA), except for 12 cadavers in which tensile stresses and maximum strains were calculated only by the machine data following a cross-check for consistency of the load cell and DIC data. Data processing and statistical comparisons were conducted using Excel Version 16.15 (Microsoft Corporation, Redmond, WA, USA) and GraphPad Prism software version 7 (GraphPad Software, La Jolla, CA, USA). The D'Agostino & Pearson normality test was used to determine normal distribution of the data. Subsequently, the data were correlated using Pearson (Gaussian distribution) or Spearman (no Gaussian distribution) correlations according to the normality test. Dunn's multiple comparisons test was performed to compare anthropometric and biomechanical parameters between sexes with no post hoc correction given the hypothesis generating nature of this study. Multiple t tests were used to compare the anthropometric and tensile parameters between the three different age-ranges (0–18 years, 19–44 years and 45–93 years) [15]. *P* values ≤ 0.05 were considered to be statistically significant.

3. Results

3.1. Tensile properties of the human IT showed high inter-individual variations in both sexes under standardized testing environments

No significant differences were found for the tensile properties between the sexes. The overall elastic modulus was 408 ± 232 MPa, with 502 ± 284 MPa for females and 366 ± 198 MPa for males. The ultimate tensile strength of specimens was 29 ± 17 MPa, with 35 ± 22 MPa for females and 26 ± 13 MPa for males. The maximum strain of the specimens was $15 \pm 5\%$, with $13 \pm 5\%$ for females and $15 \pm 4\%$ for males. The averaged values for all specimens are depicted in Fig. 4. The biomechanical properties of the human IT showed large range of standard deviations.

3.2. In all cadavers regardless of sex, the maximum strain of the human IT is age-dependent and both the elastic modulus and maximum strain of the IT depend on height

The mean ranks of anthropometric data (age, body size, weight) and tensile parameters (elastic modulus, ultimate tensile

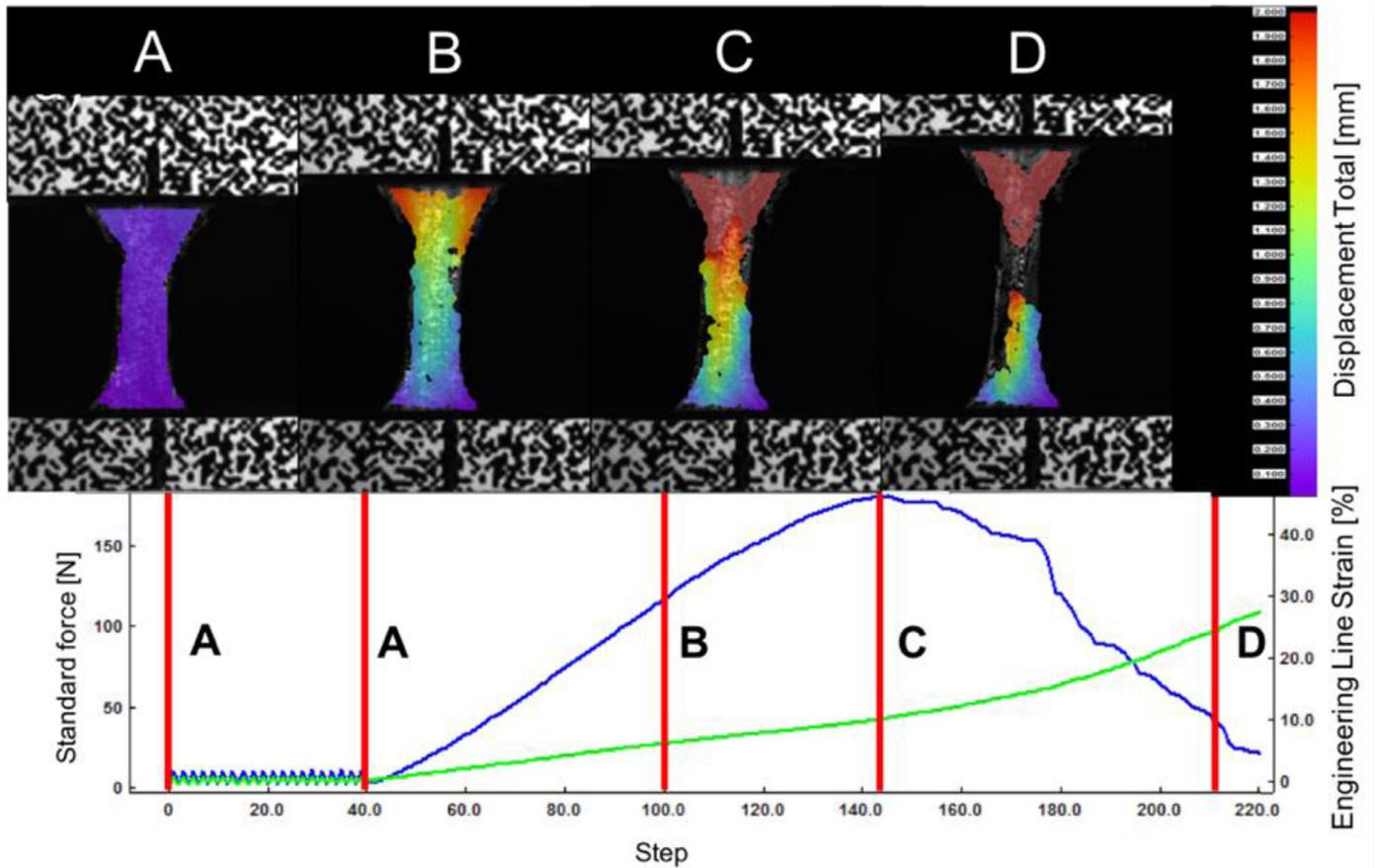


Fig. 2. Digital image correlation data of an exemplary human iliotibial tract specimen at different steps of the uniaxial tensile testing procedure. After pre-conditioning the specimen was stretched until failure. (A) displays the specimen when a preload of 10 N is applied. The here performed 20 preload cycles include repeated load applications of 10 N with subsequent complete unloading of the specimen. (B) Specimen at approximately 50% of the maximum force. (C) The specimen at the maximum of the stress–strain curve. (D) Specimen after failure that occurred in the tapered area. Blue curve, force curve; green curve, strain curve; red lines (A)–(D), different durations of uniaxial tensile testing.

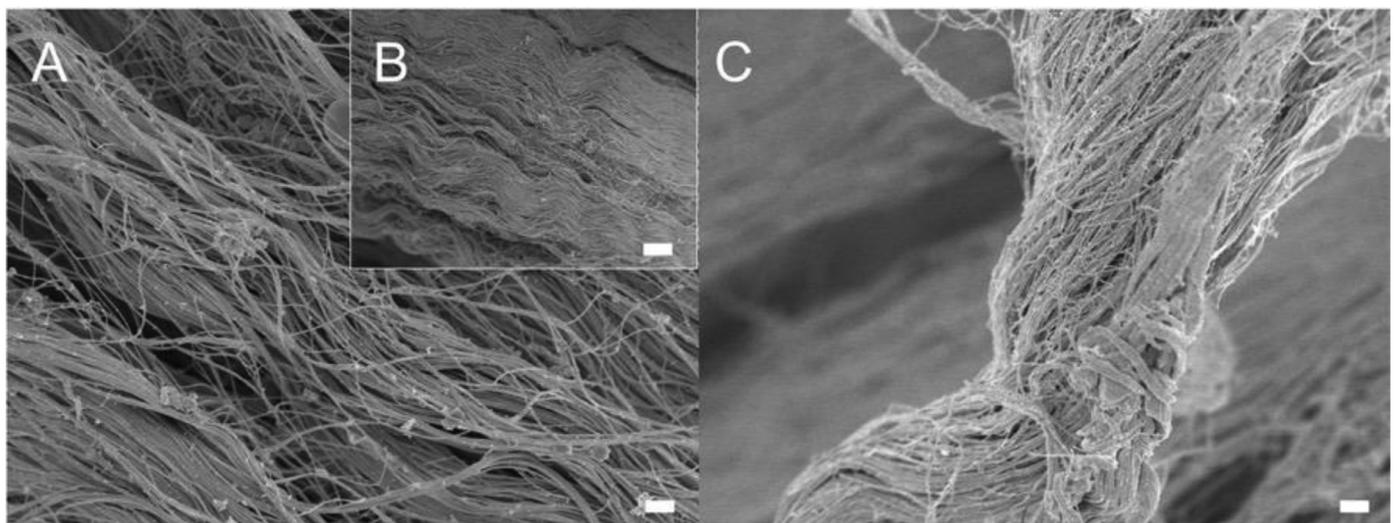


Fig. 3. Scanning electron microscopy of human iliotibial tract (IT) samples. (A) A sample at 5000× magnification (scale bar 1 μm). The collagens are fully intact. (B) Overview of A at 1000× (scale bar 10 μm). Parallel collagen fibers over long distances display the isotropic nature of the human IT. (C) IT sample at 5000× magnification (scale bar 1 μm) of the failure area of uniaxial tensile tests. Collagens are disarranged and ruptured in several sites.

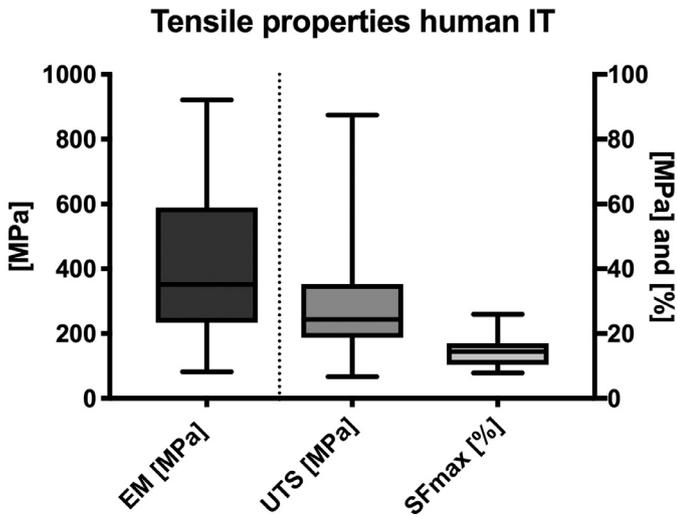


Fig. 4. Tensile properties of the human iliotibial tract (IT). EM, elastic modulus; SF_{max}, strain at maximum force; UTS, ultimate tensile strength.

strength, maximum strain) did not differ significantly between sexes.

Overall, the maximum strain of the human IT revealed a moderate negative correlation with age ($r = -0.438$; $p = 0.005$). Moreover, the elastic modulus ($r = 0.321$; $p = 0.034$) and the ultimate tensile strength ($r = 0.333$; $p = 0.029$) positively correlated with the height.

3.3. In males, tensile properties of the human IT correlated with height, but not with weight

Height significantly correlates with elastic modulus ($r = 0.630$; $p = 0.001$) in males only (Fig. 5(A)). For heights equal and bigger than 168 cm the elastic modulus of the human male IT can be calculated by the following formula:

$$\text{Elastic modulus (males)} = 21.759 * (\text{height [in cm]}) - 3457.7$$

The height of male cadavers also significantly correlates with the ultimate tensile strength ($r = 0.566$; $p = 0.002$) as shown in Fig. 5(B). For male heights equal or bigger than 168 cm the ultimate tensile strength of the human male IT can be calculated by the following formula:

$$\text{Ultimate tensile strength (male)} = 1.33 * (\text{height [in cm]}) - 208.39$$

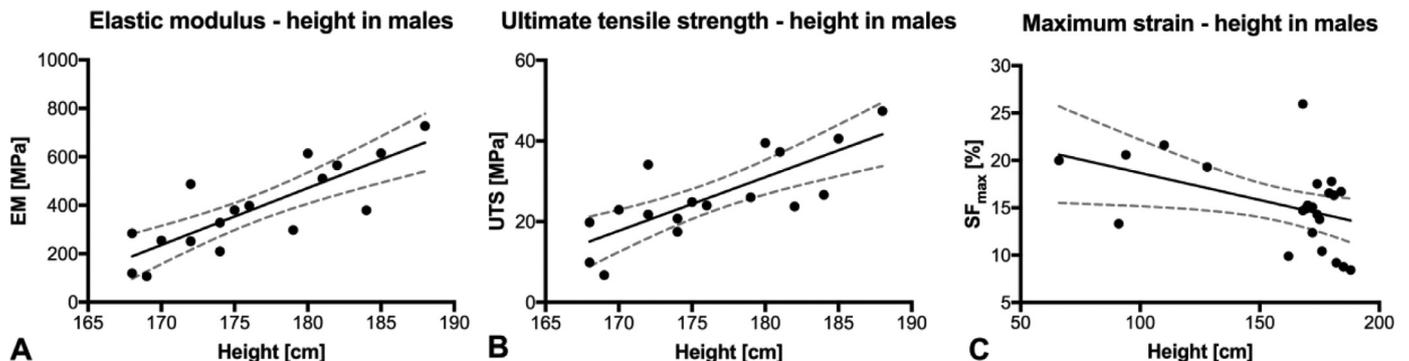


Fig. 5. Linear regression of the elastic modulus (EM) (A) and ultimate tensile strength (UTS) (B) for male cadavers with a height of 168 cm or more. (C) displays a negative correlation between height and maximum strain (SF_{max}) in males. The black line reflects the linear regression line. The dotted lines display the 95% confidence bands.

The height in male cadavers showed a significant negative moderate correlation with the maximum strain of the human IT ($r = -0.460$; $p = 0.014$) as can be seen in Fig. 5(C). However, in the given sample, no correlation was found comparing the male load-deformation data to weight.

3.4. In males, lower maximum strains were found for increasing age and weight for the IT

Age revealed a moderate negative correlation with maximum strain in males ($r = -0.473$; $p = 0.011$) as shown in Fig. 6(A). Moreover, a weak negative correlation was found between weight and maximum strain of the IT in males ($r = -0.394$; $p = 0.031$) which is reflected in Fig. 6(B).

3.5. In females, higher maximum strains were associated with larger weight, but not with height

A moderate positive correlation was seen between weight and maximum strain of the IT in females ($r = 0.571$; $p = 0.045$) as depicted in Fig. 7.

3.6. Tensile properties were similar throughout the life span, except for maximum strain which was different between infancy/adolescence and older adulthood

There were no significant differences between the tensile properties of the IT in each age group: infancy/adolescence (0–18 years), early to late middle adulthood (19–44) and older adulthood (45–93). Only the maximum strain of the IT revealed significant differences between infancy/adolescence and older adulthood (see Fig. 8). The medians of the elastic moduli and the ultimate tensile stresses of the three groups increase with age without reaching statistical significance. The medians of maximum strains decrease with age with statistical significance between infancy/adolescence and older adulthood. The standard deviations of the ultimate tensile stresses of the human IT increased with age, whereas the standard deviations of maximum strains decrease with age.

4. Discussion

The given study extends on our previous research, which aimed to assess the effect of age and sex on the tensile properties of the IT in humans [6,7,16]. Previous research of our group revealed a difference in the elastic moduli of about 100%, between donors of approximately 30 and 60 years of age with elastic moduli of 750 and 370 MPa, respectively [7,16]. Thus, it was hypothesized that normal ageing influences the tensile properties of the human IT, and therefore was investigated in this study.

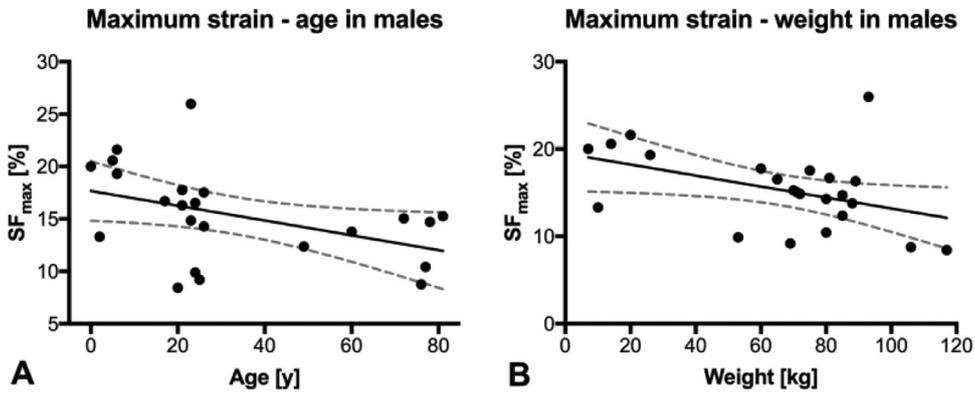


Fig. 6. (A) The maximum strain (SF_{max}) of the iliotibial tract moderately decreases with age in males. (B) Moderate decrease in maximum strain with increasing weight was seen in males. The black line reflects a linear regression line. The dotted lines display the 95% confidence bands.

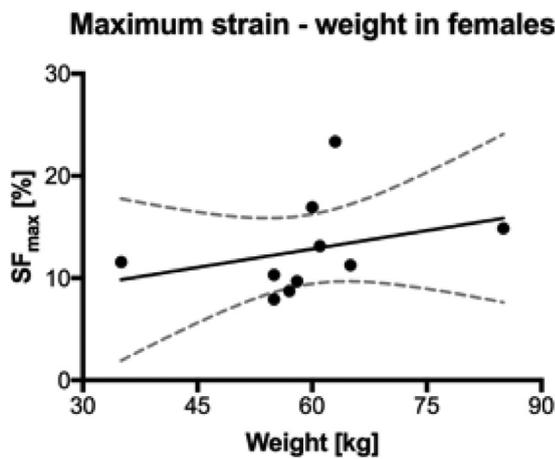


Fig. 7. Linear regression of maximum strain (SF_{max}) of the female iliotibial tract as a function of weight. Higher weights are weakly associated with higher maximum forces in females. The black line shows the linear regression of maximum force depending on the weight of the female cadavers. The dotted lines display the 95% confidence bands.

4.1. Ageing does not significantly influence tensile parameters of the human IT, except for maximum strain in males

Interestingly, a decrease of the IT maximum strain with age was only found in males. None of the other investigated tensile parameters correlated relevantly with age, neither in the overall population, in males nor females. Consequently, we have to reject our first hypothesis and state that age does not significantly impact tensile properties of the human IT in general. Subsequently, we grouped the investigated age ranges into three groups of 0–18 years (infancy/adolescence), 19–44 years (early to late middle adulthood) and 45–93 years (older adulthood) [15]. As displayed in Fig. 8, an increase was observed with age for elastic modulus and ultimate tensile stress. However, this tendency was not statistically significant. We assume that the small number of cadaveric tissues used in previous studies, with mostly less than ten donors with a maximum of 18 is likely to have biased the results [6–8,10,11,16]. Regarding the low specimen number in previous studies, it needs to be added that almost all of the reported tensile properties of the human IT to date were accompanied by large variations of one quarter up to 50 percent of the averaged elastic moduli [6–8,11,16]. One paper by Butler et al. reported a comparably lower standard variations of human IT elastic moduli in an investigated sample size of $n = 18$ [10]. The physical reason why the IT appears to remain unaffected by normal ageing might be due to the function of the IT being involved in hip flexion (associated with low-active

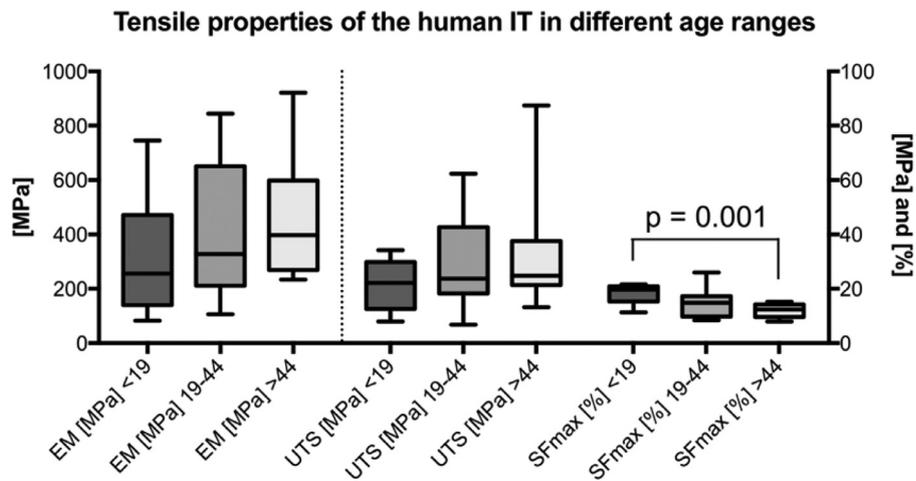


Fig. 8. Tensile properties of the human iliotibial tract (IT) in different age ranges. No significant differences in biomechanical properties were found comparing infancy/adolescence (0–18 years), early to late middle adulthood (19–43 years) and older adulthood people (44–93 years) except for the maximum strain between the youngest and oldest group. The mechanical data were accompanied by larger inter-individual variation. EM, elastic modulus; SF_{max} , strain at maximum force; UTS, ultimate tensile strength.

postures such as sitting) and knee extension (related to high-active movements such as running), serving as a passive stabilizer minimizing energy expenditure in both propulsion and one-leg stance. Through to the involvement of the IT in actions, which are likely to be maintained throughout life, it can be explained that the biomechanical elastic modulus or tensile strength of the IT may not significantly change during normal ageing in general. However, the extracellular matrix has been shown to become altered during normal ageing, for example reflecting by collagen cross-linking [17]. Therefore, the significantly decreased maximum strain seen here in older adulthood compared to the infancy/adolescent group can be explained.

4.2. Height considerably influences the tensile properties of the IT in males, whereas weight appears to have contrary effects between the sexes

We accept our second hypothesis and conclude that an impact of the anthropometric data, such as height and weight, exist on the biomechanical properties of the IT. Differences between sexes were found regarding weight and the maximum strain of the IT. Whereas the IT maximum strain tended to decrease with higher weights in males, it increased in females. This contrary behaviour might be caused by differences in hormone levels between the sexes. For instance, it has been shown that estrogen levels impact the synthesis, structure and biomechanical properties of collagens in humans, which the IT is predominantly composed of concerning its formed extracellular matrix [18]. Thus, different hormones or even different levels of the same hormone between sexes potentially lead to the differences in tensile properties of the human IT observed in this study.

The most striking finding of this study is that height is well related to tensile properties of the human IT in males, whereas this connection could not be detected in females. It has to be considered that ten female body donors are probably insufficient to identify potential relations between height and tensile properties of the IT. Moreover, the investigated heights range of females was 149–176 cm. This might have been too small to detect a possible relation between height and IT tensile properties. In contrast, the range of the 23 investigated heights in males was broader with 66–188 cm. ITs of taller males can withstand higher forces before the tissue fails in uniaxial tensile tests than ITs of smaller cadavers. Possibly, the IT of taller males is exposed to higher forces of the inserting muscles such as gluteus maximus or tensor fasciae latae during life when walking and thus collagen synthesis may be an adaptation to withstand higher loads. A comparison of IT collagenous structures, such as fiber arrangement or cross linking, on the potential impact on the IT biomechanical properties between people of different heights should be ruled out in future studies. Moreover, it might be interesting to investigate the correlation between the total length of the IT and its biomechanical properties in future follow-up studies. This is the first study that shows a relation between height and biomechanical properties of the human IT to date.

The effects of the PMI (time between death of the cadaver and the harvesting of the tissues), and storage temperatures on the resulting biomechanical properties are hardly investigated to date with varying results [19–21]. The PMI in this study revealed no significant correlation with the investigated tensile parameters, which can be interpreted as a biomechanical sign that the tissue is not deteriorating vastly within the here investigated PMI of 144 h under cooled conditions. The storage of the tested samples at -80°C in this study might have also affected the biomechanical properties of the ITs. Giannini et al. indicated that the collagen diameter might increase after storage of the samples at -80°C , which may lead to a potential decrease of applicable loads and

stresses until failure [22]. In this given study the IT samples were tapered and subsequently casted using a polysiloxane impression material, which allowed for the determination of the cross sections after the casts were scanned. Therefore, the individual cross section of every sample has been used to calculate the elastic modulus and the ultimate tensile strength, which are cross section dependent parameters. For the tensile tests performed here, 20 preload cycles of 10 N have been applied to assure collagen alignment, which subsequently increases the interindividual comparability of the testing results [23]. Although preconditioning is common sense in tissue biomechanics, the effect of preconditioning on human soft tissues, such as the IT, should be thoroughly investigated in the future [8,14].

Previous simulation findings from computational studies revealed a crucial role of the IT in hip centralization, during preloading, shortening and elongation of the IT when walking. Therefore, in future studies the IT must be accurately reflected in simulations to assure reliable simulations of hip joint arthroplasties or forces to the femur in displacement osteotomy [3]. The biomechanical properties of the IT consequently play a crucial role in creating realistic simulations of both stance and gait. Our findings indicate that several factors, such as age, sex, weight or height, influence the tensile properties of the human IT, but to different extent in males and females, underlining the necessity for sex-dependent modeling approaches of such tissues.

4.3. Limitations

Our present study has a number of limitations. Firstly, although superior to former studies, the number of specimens used in this study was limited. Second, the study only presents uniaxial data without additional properties in the other tissue axes. Additionally, it has been shown before that both temperature and hydration of the tissues have an impact on the tensile properties of soft tissue and may have contributed to results produced in this study [24,25]. These factors should be considered in future testing setups.

4.4. Conclusion

Tensile properties of the human IT are not age-dependent, except for maximum strain. Height in males shows a moderate to strong correlation to the tensile properties of the human IT. The IT maximum strain correlated positively with the weight in females, which was contrary to the finding in males. Due to the strong correlation with the tensile IT parameters in males, body size should necessarily be integrated when the IT is simulated in computational models.

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Conflict of interest

I hereby declare that there are no conflicts of interest in relation to the data presented to Medical Engineering and Physics.

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