Published in final edited form as:

J Biomech. 2017 August 16; 61: 258–262. doi:10.1016/j.jbiomech.2017.07.020.

The Challenges of Measuring *in vivo* Knee Collateral Ligament Strains using Ultrasound

Laura C. Slane^a, Josh A. Slane^a, Jan D'hooge^b, and Lennart Scheys^{a,c}

^aKU Leuven, Institute for Orthopaedic Research and Training, Leuven, Belgium

^bKU Leuven, Lab on Cardiovascular Imaging and Dynamics, Dept. of Cardiovascular Sciences, Leuven, Belgium

^cUniversity Hospitals Leuven, Dept. of Orthopaedics, Campus Pellenberg, Pellenberg, Belgium

Abstract

Ultrasound-based methods have shown promise in their ability to characterize non-uniform deformations in large energy-storing tendons such as the Achilles and patellar tendons, yet applications to other areas of the body have been largely unexplored. The noninvasive quantification of collateral ligament strain could provide an important clinical metric of knee frontal plane stability, which is relevant in ligament injury and for measuring outcomes following total knee arthroplasty. In this pilot cadaveric experiment, we investigated the possibility of measuring collateral ligament strain with our previously validated speckle-tracking approach, but encountered a number of challenges during both data acquisition and processing. Given the clinical interest in this type of tool, and the fact that this is a developing area of research, the goal of this article is to transparently describe this pilot study, both in terms of methods and results, while also identifying specific challenges to this work and areas for future study. Some challenges faced relate generally to speckle-tracking of soft tissues (e.g. the limitations of using a 2D imaging modality to characterize 3D motion), while others are specific to this application (e.g. the small size and complex anatomy of the collateral ligaments). This work illustrates a clear need for additional studies, particularly relating to the collection of ground-truth data and more thorough validation work. These steps will be critical prior to the translation of ultrasound-based measures of collateral ligament strains into the clinic.

Keywords

Ultrasound speckle-tracking; medial collateral ligament; lateral collateral ligament; instability

Current contact information for corresponding Author: Laura Chernak Slane, Institute for Orthopaedic Research and Training (IORT), KU Leuven, UZ Pellenberg, Weligerveld 1/Blok 1, 3212 Pellenberg, Belgium, laura.c.slane@gmail.com, Telephone: +32 0484 2013 72, Fax: +32 016 3388 03.

Conflict of Interest Statement

The authors have no conflicts of interest to report.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Introduction

Ultrasound-based methods are becoming more common for evaluating soft tissue biomechanics. Advantages of these approaches include that they are quantitative, noninvasive and relatively inexpensive, so there is significant potential for clinical translation. Most recent publications have focused on the evaluation of large energy-storing tendons (e.g. Achilles and patellar tendons), however there is potential for use in other regions of the body that as of yet have been largely unexplored. For example, quantitative ultrasound methods could provide an objective way of directly assessing knee medial/lateral stability. Although instability is a key clinical parameter for diagnosing ligament injury, and a major cause of early total knee arthroplasty (TKA) failures (Fehring et al., 2001; Mulhall et al., 2006; Schroer et al., 2013; Sharkey et al., 2014, 2002), current clinical techniques for assessing such stability are often indirect and subjective.

We previously performed a number of studies developing (Chernak and Thelen, 2012) and validating (Slane and Thelen, 2014a) an ultrasound speckle-tracking approach, which we then used to observe non-uniform deformation patterns within the Achilles (Franz et al., 2015; Slane and Thelen, 2015, 2014b) and patellar (Slane et al., 2017) tendons. Given the exciting clinical potential in the knee, we developed a pilot cadaveric study to test the ability of this approach to measure collateral ligament strain as a quantitative metric of frontal plane stability. However, even with this prior experience, we encountered a number of unexpected challenges during both data acquisition and processing. Because this is a developing area of research, and the clinical interest is so significant, we feel that sharing the challenges faced will encourage transparency and reduce research redundancy (van Hilten, 2015). Therefore, the goals of this text are to identify the specific challenges faced when attempting to use ultrasound-based approaches to quantify collateral ligament strains, describe our pilot study and its results, and finally to outline suggestions for future work.

Challenges

By tracking the ultrasound speckle pattern visible within tissues, speckle-tracking approaches can estimate complex tissue deformations, and unlike some other methods, do not require imaging of anatomical landmarks. To date, speckle-tracking studies have focused almost exclusively on large energy-storing tendons such as the Achilles (Arndt et al., 2012; Brown et al., 2013; Å. Fröberg et al., 2016; Nuri et al., 2016; Slane and Thelen, 2015, 2014b) and patellar (Lee et al., 2016; Pearson et al., 2014; Slane et al., 2017) tendons, with motivations often cited as their propensity for injury. However, there are also many practical advantages to studying these tendons, that thereby constitute complications when assessing the collateral ligaments. First, in contrast to the thick and broad Achilles and patellar tendons, the collateral ligaments are small, with complex anatomy (Table 1), and can be difficult to identify on ultrasound; the rope-like lateral collateral ligament (LCL) typically extends from the lateral femoral epicondyle to the fibular head, where it first conjoins with the biceps femoris tendon (Otake et al., 2007; Shin et al., 2014), though significant anatomical variation exists (Shin et al., 2014), and the flat and thin medial collateral ligament (MCL) (Otake et al., 2007) is composed of multiple structures (Robinson et al., 2002) that also display distinct mechanical properties (Robinson et al., 2005).

A second challenge is that strain estimates require the tracking of frame-to-frame movement, thereby requiring cine ultrasound. This presents two new challenges over the static imaging typical of ligament rupture diagnosis (Razek et al., 2009; Tsai et al., 2015). First, a method must be developed to enable controlled, repeatable loading of the tissues of interest. The LCL/MCL serve as the primary restraints to varus/valgus loading (Grood et al., 1981; Robinson et al., 2006; Seering et al., 1980), so applied varus/valgus moments may serve as the loading scenarios. However, applying pure varus/valgus loads *in vivo* can be challenging, and the range of motion is very small (~4 deg; Shultz et al., 2007) compared with other tasks (e.g. ankle plantar/dorsiflexion: 15–95 deg, or knee flexion/extension: 115–170 deg; Roaas and Andersson, 1982).

The next challenge is to collect high quality dynamic ultrasound data, with the tissue remaining in-plane through the entire loading trial. This can be a challenge when tracking any tissue, but again the collateral ligaments present a greater challenge; the nearness of the bones make the imaging surface uneven, and the complex anatomy of the ligaments, with tissue bone wrapping (Blankevoort and Huiskes, 1991), means that the primary direction of motion is lateral to the ultrasound beam which has inherently poor resolution (Chen et al., 2004). Further, the ligaments are subjected to a combination of compressive and tensile stresses which may contribute to structural variations within the tissues (Matyas et al., 1995), with evidence of non-uniform collateral ligament strains even during simple motions like passive flexion (Belvedere et al., 2012) and valgus loading (Gardiner et al., 2001; Hull et al., 1996; Peña et al., 2006). This complex motion further amplifies the challenge of trying to characterize 3D motion with a 2D imaging modality.

The small size of the ligaments also complicates data processing, as with a standard probe, fewer pixels, and thus less speckle, arise from within the tissue itself. This then requires smaller regions-of-interest (ROIs) for tracking, which can be prone to mismatch as well as lower repeatability and accuracy than larger ROIs (Fröberg et al., 2016). Further, the small varus/valgus range of motion means small frame-to-frame motion. The associated sub-pixel displacements are an aspect of tracking that can dominate the signal-to-noise ratio of displacement vector estimates (Kim et al., 2011), and lead to error propagation.

Pilot Study

To assess the potential for measuring collateral ligament strains using speckle-tracking, in spite of these challenges, we designed a pilot study. For a detailed description of the methods, please see the appendix. In short, following the receipt of ethical approval from the Committee on Medical Ethics of UZ Leuven, we obtained eleven intact lower limbs from six fresh-frozen specimens (5 F, 1 M, aged 68–101). Specimens were loaded in 10 Nm of valgus (MCL) or varus (LCL) during the synchronized collection of load cell, kinematic and ultrasound radiofrequency data (RF; 10 MHz, 70 fps, Ultrasonix Corp., Richmond, BC). Ultrasound trials were then cropped based on load cell data, and only trials observed to have little out-of-plane motion were retained for analysis. Tracking nodes were manually defined within B-mode images recreated from RF data along the mid-portion of the ligament. Frame-to-frame displacements and strains were then estimated using a speckle-tracking approach (Slane and Thelen 2014a), with tracking parameters defined based on standard

parameters used previously. During a secondary analysis, the effects of varying these parameters was tested; the specific parameters evaluated were the minimum correlation coefficient (0.5–0.95), kernel size (MCL: 0.8×0.8 mm LCL: 0.8×1.6mm, halved and doubled), and simulated frame rate (70 fps, 35 fps, 17.5 fps). After nodal tracking, a quality assessment was performed in which trials that showed seemingly poor tracking were removed from analysis.

Using standard tracking parameters, in the LCL, strains increased with load, with an average peak strain of $1.2\pm3.9\%$, and substantial variation between specimens and even between repeat trials. This average strain value is consistent with the literature; Delport *et al.* (2013) reported $1.6\pm0.6\%$ strain in the LCL under 7.5 Nm varus, but the standard deviations we observed are very large. In the MCL, there were also large variations in strain, with some trials measuring positive strain with increased load, and others the opposite. The average strain computed was $-3.6\pm5.4\%$. This value is counterintuitive, as valgus loading of the knee would be expected to induce positive MCL strains. Likewise, experimental studies have reported regional MCL strains during valgus loading to range from 2.1–6.4% (Delport et al., 2013; Gardiner et al., 2001; Hull et al., 1996; Lujan et al., 2007), with *in silico* models predicting strains of 3.2–5.8% under 15 Nm simulated load (Bendjaballah et al., 1997).

Given the strains reported in the literature, the numbers reported here should be considered with caution, and illustrate a common, but fundamental, challenge when developing these new approaches; a lack of ground-truth measurement. This is most clear in the MCL, where average strain values are the opposite of expectations. Yet, there are reports of nonintuitive behavior in the MCL, with evidence of highly non-uniform strain and even buckling during simple motions like passive flexion (Belvedere et al., 2012) and valgus loading (Gardiner et al., 2001; Hull et al., 1996; Lujan et al., 2007; Peña et al., 2006) and regions of negative stress within the MCL under compression and valgus load (Peña et al., 2006). Additionally, we have measured negative local strains in the MCL with digital image correlation (DIC) when loaded in valgus during other pilot experiments (Mihejeva, 2016). These observations, paired with increasing evidence that local strains within soft tissues can differ substantially from global measures (Bogaerts et al., 2016), and the fact that reference lengths, which influence absolute strain estimates (Fleming and Beynon, 2004), can be challenging to define *in vivo*, demonstrate why further work is necessary to better characterize true tissue behavior and enable validation.

In terms of data quality, on average, 73% (MCL) and 46% (LCL) of all trials were retained for analysis, with more trials removed in the second stage of quality assessment, suggesting that a greater current limitation in this pilot study was with analysis itself, rather than with the data collected. Likewise, variations in tracking parameters did influence results, with strain differences of –2 to 36% and –50 to 300% in the MCL and LCL, respectively, with average correlations remaining above 0.975 (*for more detailed results, please see the appendix*). This result shows the critical need for ground-truth data; as without it, determining which parameters are best is infeasible, particularly as correlation coefficients remained high for all parameter sets tested. Overall, this pilot study brings to the forefront some of the necessary areas of future work, which will be discussed further in the following section.

Discussion

The pilot study clearly illustrates the need for thorough validation studies to provide ground-truth data, as without such comparative metrics, it will be challenging to improve the methodology used here. In the pilot study, we observed that altering tracking parameters (notably frame rate) had substantial influence on the strains estimated, but without ground-truth measures, it is unclear which parameters provide the highest accuracy. Likewise, with comparative metrics, other aspects of the experiment (e.g. magnitude of applied moment) or data processing (e.g. method for strain computation) could be tested. Although acquiring true ground-truth data presents challenges, there are alternatives for acquiring a better database of validation data. For example, commercial DIC systems enable the measurement of local tissue strains, albeit only superficial strains which may differ from deep strains, but could nonetheless be used as a starting point for comparison with regional ultrasound measures. More advanced specimen-specific musculoskeletal models including factors such as ligament wrapping (Blankevoort and Huiskes, 1991) could improve on simple models, and could even be paired with synthetic ultrasound data for validation, though it should be noted that underlying assumptions must be carefully considered. Agreement between regional strain estimates from multiple methods (i.e. DIC and a musculoskeletal model) would be compelling as baseline validation data.

A fundamental challenge to these approaches is the inherent limitation of using a 2D imaging approach to evaluate 3D tissue motion. There is a high likelihood that the unexpected strain values from the pilot study, with large variability, arose from out-of-plane motion. Although we made an effort to remove trials with clear evidence of out-of-plane motion, discrimination between in-plane and out-of-plane motion is not always straightforward. In contrast with the large energy-storing tendons, in which distinct fascicles are often visible, it is harder to identify anatomical structures within the collateral ligaments, and thus more challenging to discriminate between high and low quality data. A better method for discriminating between these trials, perhaps one that is automated and quantitative, could improve tracking. The use of a higher resolution probe would also be helpful; not only would this enable a view of more structure from within the tissues, larger ROIs with a higher speckle density could improve tracking. However, even with a better ability to identify trials with significant out-of-plane motion, the challenge of collecting in-plane data remains. An alternate approach could be the use of 3D ultrasound, which is becoming more readily available, and may enable 3D motion tracking (Carvalho et al., 2017), though substantially more work is needed in this area. Factors such as microstructural sliding (Screen et al., 2004), may also play a role here, and could mean that the speckle pattern is not preserved during motion; such factors undoubtedly need further study.

The goal of this article was to assess the potential of a speckle-tracking approach to measure collateral ligament strains, but there are other ultrasound-based approaches that may be suitable for measuring knee frontal plane stability. For example, shear wave elastography (SWE) can estimate material properties from static images (Bercoff et al., 2004), which would eliminate the challenges associated with collecting dynamic data. Acoustoelastography, in which B-mode brightness is correlated with tissue strain, is another intriguing approach. However, these methods also have limitations; SWE is known to

produce noisy and erroneous data when collected close to bones, and a recent study using acoustoelastography found results to be unreliable during *in vivo* collections (Suydam and Buchanan, 2014). Thus, further work in these areas is also of interest.

Conclusions

Ultrasound-based methods have the potential to provide important insight into knee frontal plane stability, which could be used clinically to assess injury, rehabilitation and outcomes following TKA. Despite promise using ultrasound speckle-tracking in large energy-storing tendons, many challenges remain prior to clinical translation, and additional challenges in data acquisition and analysis make adaptation to collateral ligament strain measurement even more difficult. Results from our pilot study illustrate the critical need for ground-truth data and thorough validation work to further advance this exciting research area. Other possible next steps could include improving approaches for identifying out-of-plane motion, advancing techniques for displacement tracking and/or strain calculations, or testing alternate ultrasound-based approaches, such as 3D ultrasound, or shear wave elastography.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors gratefully acknowledge the support of members of the Vesalius Institute, specifically Goedele Liégeois, Kristof Reyniers, and Jo Verbinen, Brian Chernak, and funding from the National Institute of Arthritis and Musculoskeletal Skin Diseases (F32 AR069459).

References

- Arndt A, Bengtsson AS, Peolsson M, Thorstensson A, Movin T. Non-uniform displacement within the Achilles tendon during passive ankle joint motion. *Knee Surgery, Sport Traumatol Arthrosc.* 2012; 20:1868–1874. DOI: 10.1007/s00167-011-1801-9
- Belvedere C, Ensini A, Feliciangeli A, Cenni F, D'Angeli V, Giannini S, Leardini A. Geometrical changes of knee ligaments and patellar tendon during passive flexion. *J Biomech.* 2012; 45:1886–1892. DOI: 10.1016/j.jbiomech.2012.05.029 [PubMed: 22677336]
- Bendjaballah M, Shirazi-Adl A, Zukor D. Finite element analysis of human knee joint in varus-valgus. *Clin Biomech.* 1997; 12:139–148. DOI: 10.1016/S0268-0033(97)00072-7
- Bercoff J, Tanter M, Fink M. Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Trans Ultrason Ferroelectr Freq Control.* 2004; 51:396–409. DOI: 10.1109/TUFFC.2004.1295425 [PubMed: 15139541]
- Blankevoort L, Huijskes R. Ligament-Bone Interaction in a Three-Dimensional Model of the Knee. *J Biomech Eng.* 1991; 113:263. doi: 10.1115/1.2894883 [PubMed: 1921352]
- Bogaerts S, Desmet H, Slagmolen P, Peers K. Strain mapping in the Achilles tendon – A systematic review. *J Biomech.* 2016; 49:1411–1419. DOI: 10.1016/j.jbiomech.2016.02.057 [PubMed: 27113537]
- Brown PG, Alsousou J, Cooper A, Thompson MS, Noble JA. The AutoQual ultrasound elastography method for quantitative assessment of lateral strain in post-rupture Achilles tendons. *J Biomech.* 2013; 46:2695–2700. DOI: 10.1016/j.jbiomech.2013.07.044 [PubMed: 24001929]
- Carvalho C, Slagmolen P, Bogaerts S, Scheys L, D'hooge J, Peers K, Maes F, Suetens P. 3D tendon strain estimation using high-frequency volumetric ultrasound images. A feasibility study. *Ultrason Imaging.* 2017 in press.

- Chernak LA, Thelen DG. Tendon motion and strain patterns evaluated with two-dimensional ultrasound elastography. *J Biomech.* 2012; 45:2618–2623. DOI: 10.1016/j.jbiomech.2012.08.001 [PubMed: 22939179]
- Chen X, Zhody MJ, Emelianov SY, O'Donnell M. Lateral speckle tracking using synthetic lateral phase. *IEEE Trans Ultrason Ferroelectr Freq Control.* 2004; 51:540–550. DOI: 10.1109/TUFFC.2004.1320827 [PubMed: 15217232]
- Cook JL, Khan KM, Harcourt PR, Kiss ZS, Fehrmann MW, Griffiths LR, Wark JD. Patellar tendon ultrasonography in asymptomatic active athletes reveals hypoechoic regions: a study of 320 tendons. *Inst Heal Biomed Innov.* 1998
- Delpont H, Labey L, De Corte R, Innocenti B, Vander Sloten J, Bellemans J. Collateral ligament strains during knee joint laxity evaluation before and after TKA. *Clin Biomech.* 2013; 28:777–782. DOI: 10.1016/j.clinbiomech.2013.06.006
- Dundon JM, Markert RJ, Lawless MW. Correlation between patella and patellar tendon width: An anatomic study. *Clin Anat.* 2012; 25:398–400. DOI: 10.1002/ca.21241 [PubMed: 21853464]
- Fehring TK, Odum S, Griffin WL, Mason JB, Nadaud M. Early failures in total knee arthroplasty. *Clin Orthop Relat Res.* 2001:315–318. [PubMed: 11716402]
- Fleming BC, Beynnon BD. In Vivo Measurement of Ligament/Tendon Strains and Forces: A Review. *Ann Biomed Eng.* 2004; 32:318–328. DOI: 10.1023/B:ABME.0000017542.75080.86 [PubMed: 15095807]
- Franz JR, Slane LC, Rasske K, Thelen DG. Non-uniform in vivo deformations of the human Achilles tendon during walking. *Gait Posture.* 2015; 41:192–197. DOI: 10.1016/j.gaitpost.2014.10.001 [PubMed: 25457482]
- Fröberg Å, Cissé A, Larsson M, Mårtensson M, Peolsson M, Movin T, Arndt A. Altered patterns of displacement within the Achilles tendon following surgical repair. *Knee Surg Sport Traumatol Arthrosc.* 2016:1–9.
- Fröberg A, Martensson M, Larsson M, Janerot-Sjöberg B, DHooge J, Arndt A. High variability in strain estimation errors when using a commercial ultrasound speckle tracking algorithm on tendon tissue. *Acta radiol.* 2016; 284185115626471. doi: 10.1177/0284185115626471
- Gardiner JC, Weiss JA, Rosenberg TD. Strain in the human medial collateral ligament during valgus loading of the knee. *Clin Orthop Relat Res.* 2001:266–74. [PubMed: 11603680]
- Grood ES, Noyes FR, Butler DL, Suntay WJ. Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg Am.* 1981; 63:1257–1269. [PubMed: 7287796]
- Heyse TJ, El-Zayat BF, De Corte R, Scheys L, Chevalier Y, Fuchs-Winkelmann S, Labey L. Biomechanics of medial unicondylar in combination with patellofemoral knee arthroplasty. *Knee.* 2014; 21:S3–S9. DOI: 10.1016/S0968-0160(14)50002-6 [PubMed: 25382365]
- Heyse TJ, Slane J, Peersman G, Dworschak P, Fuchs-Winkelmann S, Scheys L. Balancing mobile-bearing unicondylar knee arthroplasty in vitro. *Knee Surgery, Sport Traumatol Arthrosc.* 2016; :1–8. DOI: 10.1007/s00167-016-4241-8
- Hull ML, Berns GS, Varma H, Patterson HA. Strain in the medial collateral ligament of the human knee under single and combined loads. *J Biomech.* 1996; 29:199–206. [PubMed: 8849813]
- Kamath GV, Redfern JC, Burks RT. Femoral Radiographic Landmarks for Lateral Collateral Ligament Reconstruction and Repair: A New Method of Reference. *Am J Sports Med.* 2010; 38:570–574. DOI: 10.1177/0363546509350066 [PubMed: 19966096]
- Kim S, Aglyamov SR, Park S, O'Donnell M, Emelianov SY. An autocorrelation-based method for improvement of sub-pixel displacement estimation in ultrasound strain imaging. *IEEE Trans Ultrason Ferroelectr Freq Control.* 2011; 58:838–43. DOI: 10.1109/TUFFC.2011.1876 [PubMed: 21507761]
- Laprade RF, Bernhardtson AS, Griffith CJ, Macalena JA, Wijdicks CA. Correlation of valgus stress radiographs with medial knee ligament injuries: an in vitro biomechanical study. *Am J Sports Med.* 2010; 38:330–338. DOI: 10.1177/0363546509349347 [PubMed: 19966093]
- Lee D, Barrett R, Ryan M, Saxby DJ, Newsham-West R, Obst SJ. *In vivo* strain in the deep and superficial regions of the human patellar tendon. *Scand J Med Sci Sports.* 2016; doi: 10.1111/sms.12721

- Lujan TJ, Dalton MS, Thompson BM, Ellis BJ, Weiss JA. Effect of ACL Deficiency on MCL Strains and Joint Kinematics. *J Biomech Eng.* 2007; 129:386.doi: 10.1115/1.2720915 [PubMed: 17536905]
- Matyas JR, Anton MG, Shrive NG, Frank CB. Stress governs tissue phenotype at the femoral insertion of the rabbit MCL. *J Biomech.* 1995; 28:147–157. DOI: 10.1016/0021-9290(94)00058-C [PubMed: 7896857]
- de Mello RAF, Marchiori E, dos Santos AASMD, Torres Neto G. Avaliação morfométrica do tendão de Aquiles por ultra-sonografia. *Radiol Bras.* 2006; 39:161–165. DOI: 10.1590/S0100-39842006000300003
- Mihejeva, I. Knee Stability: Evaluation of soft tissue behaviour during joint motion. KU Leuven; 2016.
- Mulhall KJ, Ghomrawi HM, Scully S, Callaghan JJ, Saleh KJ. Current Etiologies and Modes of Failure in Total Knee Arthroplasty Revision. *Clin Orthop Relat Res.* 2006; 446:45–50. DOI: 10.1097/01.blo.0000214421.21712.62 [PubMed: 16672871]
- Nuri L, Obst SJ, Newsham-West R, Barrett RS. Regional three-dimensional deformation of human Achilles tendon during conditioning. *Scand J Med Sci Sports.* 2016; doi: 10.1111/sms.12742
- Otake N, Chen H, Yao X, Shoumura S. Morphologic Study of the Lateral and Medial Collateral Ligaments of the Human Knee. *Okajimas Folia Anat Jpn.* 2007; 83:115–122. DOI: 10.2535/ofaj.83.115 [PubMed: 17380853]
- Pang BSF, Ying M. Sonographic measurement of achilles tendons in asymptomatic subjects: variation with age, body height, and dominance of ankle. *J Ultrasound Med.* 2006; 25:1291–6. [PubMed: 16998101]
- Pearson SJ, Ritchings T, Mohamed ASA. Regional strain variations in the human patellar tendon. *Med Sci Sports Exerc.* 2014; 46:1343–51. DOI: 10.1249/MSS.0000000000000247 [PubMed: 24389512]
- Peña E, Calvo B, Martínez MA, Doblaré M. A three-dimensional finite element analysis of the combined behavior of ligaments and menisci in the healthy human knee joint. *J Biomech.* 2006; 39:1686–1701. DOI: 10.1016/j.jbiomech.2005.04.030 [PubMed: 15993414]
- Razek AAKA, Fouda NS, Elmetwaley N, Elbogdady E. Sonography of the knee joint. *J Ultrasound.* 2009; 12:53–60. DOI: 10.1016/j.jus.2009.03.002 [PubMed: 23397073]
- Roaas A, Andersson GBJ. Normal Range of Motion of the Hip, Knee and Ankle Joints in Male Subjects, 30–40 Years of Age. *Acta Orthop Scand.* 1982; 53:205–208. DOI: 10.3109/17453678208992202 [PubMed: 7136564]
- Robinson JR, Bull AM, Amis AA. Structural properties of the medial collateral ligament complex of the human knee. *J Biomech.* 2005; 38:1067–1074. DOI: 10.1016/j.jbiomech.2004.05.034 [PubMed: 15797588]
- Robinson JR, Bull AMJ, Thomas RRD, Amis AA. The role of the medial collateral ligament and posteromedial capsule in controlling knee laxity. *Am J Sports Med.* 2006; 34:1815–1823. DOI: 10.1177/0363546506289433 [PubMed: 16816148]
- Robinson JR, Sanchez-Ballester J, de Thomas RW, Bull AMJ, Amis AA. The posteromedial corner revisited: Anatomical description of the restraining structures of the medial aspect of the human knee. *Orthop Proc.* 2002:84-B.
- Schroer WC, Berend KR, Lombardi AV, Barnes CL, Bolognesi MP, Berend ME, Ritter MA, Nunley RM. Why Are Total Knees Failing Today? Etiology of Total Knee Revision in 2010 and 2011. *J Arthroplasty.* 2013; 28:116–119. DOI: 10.1016/j.arth.2013.04.056 [PubMed: 23954423]
- Screen HRC, Bader DL, Lee DA, Shelton JC. Local strain measurement within tendon. *Strain.* 2004; 40:157–163.
- Seering WP, Piziali RL, Nagel DA, Schurman DJ. The function of the primary ligaments of the knee in varus-valgus and axial rotation. *J Biomech.* 1980; 13:785–794. DOI: 10.1016/0021-9290(80)90240-7 [PubMed: 7440593]
- Sharkey PF, Hozack WJ, Rothman RH, Shastri S, Jacoby SM. Why are total knee arthroplasties failing today? *Clin Orthop Relat Res.* 2002:7–13. [PubMed: 12439231]
- Sharkey PF, Lichstein PM, Shen C, Tokarski AT, Parvizi J. Why Are Total Knee Arthroplasties Failing Today—Has Anything Changed After 10 Years? *J Arthroplasty.* 2014; 29:1774–1778. DOI: 10.1016/j.arth.2013.07.024 [PubMed: 25007726]

- Shin YK, Ryu KN, Park JS, Lee JE, Jin W, Park SY, Yoon SH, Lee KR. Biceps Femoris Tendon and Lateral Collateral Ligament: Analysis of Insertion Pattern Using MRI. *J Korean Soc Magn Reson Med*. 2014; 18:225.doi: 10.13104/jksmrm.2014.18.3.225
- Shultz SJ, Shimokochi Y, Nguyen AD, Schmitz RJ, Beynnon BD, Perrin DH. Measurement of varus–valgus and internal–external rotational knee laxities in vivo—part I: assessment of measurement reliability and bilateral asymmetry. *J Orthop Res*. 2007; 25:981–988. DOI: 10.1002/jor.20397 [PubMed: 17457828]
- Slane LC, Bogaerts S, Thelen DG, Scheys L. Non-uniform deformation of the patellar tendon during passive knee flexion. *J Appl Biomech*. 2017 in review.
- Slane LC, Thelen DG. Achilles tendon displacement patterns during passive stretch and eccentric loading are altered in middle-aged adults. *Med Eng Phys*. 2015; 37:712–716. DOI: 10.1016/j.medengphy.2015.04.004 [PubMed: 25962378]
- Slane LC, Thelen DG. The use of 2D ultrasound elastography for measuring tendon motion and strain. *J Biomech*. 2014a; 47:750–754. DOI: 10.1016/j.jbiomech.2013.11.023 [PubMed: 24388164]
- Slane LC, Thelen DG. Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading. *J Biomech*. 2014b; 47:2831–2835. DOI: 10.1016/j.jbiomech.2014.07.032 [PubMed: 25150898]
- Stenroth L, Peltonen J, Cronin NJ, Sipilä S, Finni T. Age-related differences in Achilles tendon properties and triceps surae muscle architecture in vivo. *J Appl Physiol*. 2012; 113:1537–44. DOI: 10.1152/japplphysiol.00782.2012 [PubMed: 23042907]
- Suydam SM, Buchanan TS. Is echogenicity a viable metric for evaluating tendon properties in vivo? *J Biomech*. 2014; 47:1806–1809. DOI: 10.1016/j.jbiomech.2014.03.030 [PubMed: 24726653]
- Tsai WH, Chiang YP, Lew RJ. Sonographic Examination of Knee Ligaments. *Am J Phys Med Rehabil*. 2015; 94:e77–e79. DOI: 10.1097/PHM.0000000000000313 [PubMed: 26186559]
- van Hilten, LG. Why it's time to publish research “failures” [WWW Document]. Elsevier Connect; 2015. URL <https://www.elsevier.com/connect/scientists-we-want-your-negative-results-too> [accessed 3.16.17]
- Wiesinger HP, Rieder F, Kösters A, Müller E, Seynnes OR. Are Sport-Specific Profiles of Tendon Stiffness and Cross-Sectional Area Determined by Structural or Functional Integrity? *PLoS One*. 2016; 11:e0158441.doi: 10.1371/journal.pone.0158441 [PubMed: 27362657]
- Wijdicks CA, Griffith CJ, LaPrade RF, Johansen S, Sunderland A, Arendt EA, Engebretsen L. Radiographic Identification of the Primary Medial Knee Structures. *J Bone Jt Surgery-American* Vol. 2009; 91:521–529. DOI: 10.2106/JBJS.H.00909
- Wilson WT, Deakin AH, Payne AP, Picard F, Wearing SC. Comparative Analysis of the Structural Properties of the Collateral Ligaments of the Human Knee. *J Orthop Sport Phys Ther*. 2012; 42:345–351. DOI: 10.2519/jospt.2012.3919
- Chen, Xunchang, Zohdy, MJ., Emelianov, SY., O'Donnell, M. Lateral speckle tracking using synthetic lateral phase. *IEEE Trans Ultrason Ferroelectr Freq Control*. 2004; 51:540–550. DOI: 10.1109/TUFFC.2004.1320827 [PubMed: 15217232]
- Zooker C, Pandarinath R, Kraeutler MJ, Cohen SB, Ciccotti MG, Deluca PF. Clinical Measurement of the Patellar Tendon: Accuracy and Relationship to Actual Tendon Dimensions (SS-73). *Arthrosc J Arthrosc Relat Surg*. 2012; 28:e38–e39. DOI: 10.1016/j.arthro.2012.04.131

Table 1

Approximate dimensions of the Achilles tendon, patellar tendon, MCL and LCL in various ultrasound (US) planes. The collateral ligaments are substantially thinner than the two energy-storing tendons, and the width of the LCL is much smaller than the other tissues.

	Thickness <i>Depth in US image</i>	Width (breadth) <i>Perpendicular to US plane</i>	Length <i>Length in US image</i>
Achilles Tendon	3.8 – 6.9 mm ^a	11 – 15 mm ^b 18 mm ^e	58.5 – 166.2 mm ^a
Patellar Tendon	3.9 – 5.0 mm ^c	18 – 33 mm ^d 25 – 40 mm ^h	48 ± 6 mm ^f 30–52 mm ^h
MCL <i>At the joint line</i>	2.1 ± 0.6 mm ^g	32.1 ± 3.1 mm ^g	112.1 ± 5.9 mm ^g
LCL <i>At the joint line</i>	2.6 ± 0.3 mm ^g	4.7 ± 1.1 mm ^g	69.9 ± 6.4 mm ^g

^aPang and Ying, 2006,

^bMello et al., 2006,

^cCook et al., 1998,

^dDundon et al., 2012,

^eStenroth et al., 2012,

^fWiesinger et al., 2016,

^gWilson et al., 2012,

^hZooker et al., 2012