ABSTRACT

Objectives Although exercise is considered the preferred approach for tendinopathies, the actual load that acts on the tendon in loading programmes is usually unknown. The objective of this study was to review the techniques that have been applied in vivo to estimate the forces and strain that act on the human tendon in dynamic exercises used during rehabilitation.

Design Scoping review.

Data sources Embase, PubMed, Web of Science and Google Scholar were searched from database inception to February 2021.

Eligibility criteria Cross-sectional studies available in English or Spanish language were included if they focused on evaluating the forces or strain of human tendons in vivo during dynamic exercises. Studies were excluded if they did not evaluate tendon forces or strain; if they evaluated running, walking, jumping, landing or no dynamic exercise at all; and if they were conference proceedings or book chapters.

Data extraction and synthesis Data extracted included year of publication, study setting, study population characteristics, technique used and exercises evaluated. The studies were grouped by the types of techniques and the tendon location.

Results Twenty-one studies were included. Fourteen studies used an indirect methodology based on inverse dynamics, nine of them in the Achilles and five in the patellar tendon. Six studies implemented force transducers for measuring tendon forces in open carpal tunnel release surgery patients. One study applied an optic fibre technique to detect forces in the patellar tendon. Four studies measured strain using ultrasound-based techniques.

Conclusions There is a predominant use of inverse dynamics, but force transducers, optic fibre and estimations from strain data are also used. Although these tools may be used to make general estimates of tendon forces and strains, the invasiveness of some methods and the loss of immediacy of others make it difficult to provide immediate feedback to the individuals.

INTRODUCTION

Tendinopathy is the preferred term for persistent tendon pain and loss of function related to mechanical loading. The high incidence and prevalence of this disorder alters the ability of people to work, exercise or perform activities of daily life, causing a great social and economic burden.

Current knowledge supports the need to integrate an active approach for tendinopathy, based on a conservative management that includes education, exercise (with appropriate management and modification of loads) and support interventions for pain and symptom control. Thus, loading interventions with a progressive exercise programme are considered an essential part of the management of tendinopathies due to the vast evidence published in the last decades. These approaches focus on producing an adequate stimulus for tendon adaptations and aim to increase the patients’ loading capacity. Regarding the adaptations in the tendon, research data suggest that tenocytes respond to mechanical loading by inducing anabolic and catabolic processes of matrix proteins, respectively, through a process known as mechanotransduction. Therefore, tendon strain is an important factor for the maintenance and adaptation of the tissue.

Different exercise modalities and intensities have been applied in tendinopathy with reasonably good results. Likewise, different strategies have been implemented for handling and modifying the applied loads. However, although some concepts...
such as repetition maximum have made it possible to parameterise and quantify the applied dose based on the subject’s ability to perform an activity a specific number of repetitions, the actual load that acts on the tendon in these activities is usually unknown. In both prevention and treatment of tendinopathy, load management would benefit from a greater understanding of the loads that act on the tendon during exercises and the strain that occur under load, especially considering that there may be a ‘sweet spot’ of tendon strain for stimulating adaptation.

In the analysis of the loads that act on the tendon, it is relevant to differentiate between physical quantities such as force and strain. Tendon force is a measure of the absolute load that acts on the tendon, while strain refers to the deformation of the tendon relative to its resting state. Strain has a different nature depending on the force that produces it. Thus, tendons are subjected to compression, tension or shear forces in daily activities, but it is the tensile load (and the strain it produces) that plays a leading role in the function of the tendon. Therefore, the evaluation of the tensile strain is especially relevant for the study of the loading programmes.

Regardless of the parameter evaluated, it is important to take into account a factor that makes studying in vivo tendon mechanics difficult: tendons are not uniaxial structures but are usually made up of different bundles. This causes regional variations in mechanical properties, and the distribution of forces and strains throughout the tissue is not uniform. Tendon forces have been calculated through in vitro studies, as well as have been estimated through in vivo indirect calculations based on body position, joint reaction forces and inverse dynamic models. Additionally, as underlined by a previous review, invasive evaluations using force transducers and optic fibre techniques have enabled the direct measurement of forces in tendons of the hand and the Achilles and patellar tendons.

Medical imaging techniques such as ultrasound or MRI have previously made it possible to directly measure strain during isometric contractions, walking, running, cycling and hopping. However, transducer position may affect the ultrasound measurements significantly, and it is necessary to use a rigid fixation over the tissue that may alter movement patterns. Therefore, its use in some dynamic activities is still limited.

Some reviews have been previously published focused on the evaluation of tendon loads. These reviews are not specific to dynamic rehabilitation exercises and include mainly methods developed for the study of isometric contractions or cyclic activities such as running, cycling or walking. Some of these methods have been adapted to the study of dynamic exercises (such as rehabilitation exercises), but the study of this type of exercises is still scarce due to the limitations of these tools. Therefore, there is still a lack of studies addressing the direct measurement of loads and the evaluation of dynamic exercises commonly used during rehabilitation processes.

The aim of this study is to review the techniques that have been applied in vivo, directly and indirectly, estimate the forces and strain that act on the human tendon in dynamic exercises commonly used during rehabilitation processes.

METHODS
This scoping review was undertaken following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Extension for Scoping Reviews (PRISMA-ScR) guidelines. This review has not been registered in PROSPERO because this platform does not currently accept registrations for scoping reviews, literature reviews or mapping reviews.

Information sources and search strategy
According to the recommendations of a recent study for biomedical reviews, four databases were searched by two reviewers (AE-E and JCG) from database inception to February 2021: Embase, PubMed (including Medline), Web of Science and Google Scholar. The following combinations of terms were used in the first three databases: “Tendon (Title) AND Load (Title)”; “Tendon (Title) AND Force (Title)”; “Tendon (Title) AND Biomechanics (Title)”; “Tendon AND wave”; “Tendon (Title) AND Properties (Title)”. Additionally, “Tendon AND Load” was searched in Embase and PubMed. The combinations of terms “Tendon AND Force”, “Tendon AND Biomechanics”, “Tendon AND Properties”, “Tendon AND Load” and “Tendon AND wave” were used in Google Scholar, retrieving the first 200 relevant references of each search. Detailed information on the sources of information and the combinations of terms used is available in the online supplemental appendix 1.

Eligibility criteria
All studies that met the following eligibility criteria were included:

a. Cross-sectional studies published in scientific journals.
b. Focused on evaluating the forces and strain (tendon strain evaluation was included if it was described as a way to quantify loads) of tendons in vivo using direct or indirect techniques.
c. During dynamic exercises.
d. Available in English or Spanish language.

Conversely, those studies meeting any of these exclusion criteria were discarded: (A) studies with evaluation of neuromuscular or joint forces that do not describe evaluating the tendon; (B) investigated tasks were running, walking, jumping, landing or other everyday tasks that are not rehabilitative exercises; (C) conference proceedings; and (D) book chapters.

Study selection
All retrieved references were imported into Mendeley to later be included in Rayyan (https://www.rayyan.ai/), a systematic review support tool. Duplicates were identified
and removed. The remaining references were screened by title and abstract by one author (AE-E) to exclude clearly irrelevant articles. Finally, two reviewers (AE-E and JC) screened the full texts of identified articles to select those that met the eligibility criteria. A third reviewer solved any disagreements (AIC-V).

Data extraction
Two reviewers (AE-E and JC) assessed the full texts of the selected studies. To obtain the information from the studies, an extraction form was used including the following data: authors and year of publication; study setting; study population; participant demographics; details of the evaluation technique; dynamic exercises evaluated; and tendon forces/strain results.

In this review, they were included those studies that analysed the forces and strain on the tendon in dynamic exercises, especially those commonly used in tendon rehabilitation. Dynamic analysis based on running, walking or cycling, and batteries of exercises based on day-to-day or work activities were not taken into account.

Synthesis of results
The studies were grouped by the types of measurement techniques applied and by the tendon location, summarising the type of settings, populations and article types for each group, along with the broad findings.

Methodological quality
Current guidelines on conducting a scoping review describe the inclusion of a methodological quality analysis as not necessary. Likewise, the lack of a standardised tool for the methodological evaluation of the heterogeneous type of studies included in this review makes methodological analysis difficult. In this context, this review focuses on analysing the forces and strain evaluation methodologies used in the included studies rather than in the magnitude of the results obtained, with the lack of methodological quality analysis influencing the results and conclusions of this review to a lesser extent.

Patient and public involvement
None.

RESULTS
A total of 16571 records were identified in PubMed, Embase, Web of Science and Google Scholar. Then, duplicates were removed, remaining 8536 references. Additionally, eight records were identified by additional sources. Among these, 153 were identified as potentially eligible after reading the title and the abstract, retrieving the full texts of all of them. After evaluating the fulfilment of the eligibility criteria, 21 studies were finally included in the current review. The figure 1 represents the flow diagram of the selection process. A detailed list of the studies excluded in the last stage is available in the online supplemental appendix 2.

In total, 300 subjects were included in the analysed studies. Among these, 202 correspond to healthy samples, while 98 of them were open carpal tunnel release surgery patients. However, due to the similarity in the characteristics of the sample and the concurrence of most of the authors in the case of three studies (12 subjects in each study), it is pertinent to think that they are the same participants.

Modelling and in vivo evaluation methodologies
Different evaluation methodologies were identified in the included reports, including inverse dynamics, force transducers and optic fibre sensors for the evaluation of tendon forces, and ultrasound imaging techniques for strain evaluation. The tendon locations evaluated were the Achilles, quadriceps, patellar and different tendons of the hand. Table 1 shows the groups of evaluation techniques associated with the tendon location and the references of the records that included each one. Table 2 includes expanded information about the measurement methodology.

Force
Inverse dynamics
Fourteen studies used an indirect evaluation methodology of tendon forces based on inverse dynamics, nine of them in the Achilles tendon and five in the patellar tendon. When inverse dynamics are used, tendon forces are estimated using different equations based on joint torque and moment arms or integrating kinematic and kinetic data in musculoskeletal models. This methodology uses kinematics, often complemented with applied external forces, to calculate net joint moments. Moment arms are estimated from previous literature data or estimated specifically for each patient through imaging techniques such as MRI or ultrasound.

Most of the included studies used motion capture systems for kinematics, while force plates were the most
Table 1  Forces and strain evaluation methodologies identified in the included studies

| Measurement methodology | Tendon | References |
|-------------------------|--------|------------|
| Force transducers (Buckle force transducer, S-shaped force transducer, load cell) | Hand | Buckle 44-46, Load cell 61-62, S-shaped 63 |
| Force transducers | Patellar | 48-58 62 68 69 |
| Force transducers | Achilles | 55 57 68 |
| Strain | Patellar | 67 |
| Strain | Quadriceps | 69 |

used device for obtaining kinetic data. Some studies used generic moment arms based on the published literature,48 49 other used previously described procedures and equations,50-53 while other estimated subject-specific moment arms based on imaging techniques.54 55 Kine- matic and kinetic data were integrated into different musculoskeletal models: three studies56-58  used the Human Body Model,59 one study used the OpenSim model,60 one study54 used the FreeBody model,61 while other studies5 2 56 62 implemented other codes or models. Most of the studies reported normalised force values by body weight (BW), obtaining the lowest values in the Achilles through the seated heel raising exercise (0.41–0.5 BW).48 54 The single-leg heel raising and lowering obtained values between 3–5.12 BW for the Achilles tendon.48 54 56 62 In the patellar tendon, the results were mainly reported in Newtons (N), obtaining mean values between 2899 and 5683 N for different variants of the squat.49 53

Force transducers
Six studies implemented force transducers for measuring tendon forces, all of them in open carpal tunnel release surgery patients. The introduction of the force transducers was carried out during surgery with local anaesthesia. Three modalities of force transducers were applied: buckle force transducer,44-46 S-shaped force transducer53 63 and load cell.64 65

Optic fibre sensor
Dillon et al67 applied an optic fibre technique to detect forces in both the anterior and the posterior regions of the proximal patellar tendon. This methodology was implemented inserting two 0.5 mm optic fibre sensor perpendicular through the entire cross section of the tendon under local anaesthesia. For the purpose of the study, one sensor was placed 1–2 mm anterior to the posterior border of the tendon, while the other sensor was placed 1–2 mm posterior to the anterior border of the tendon.67 The optic fibre was attached to a transmitter-receiver unit for light intensity monitoring. Then, tendon forces were registered during dynamic exercises, removing the sensor at the end of all tests.67 In this study, the sensors were not calibrated to record forces in N. Therefore, the data are only available through the differential output of the fibre signal.67 In general, higher values were found in the posterior area of the proximal tendon (0.77–1.00 V) than in the anterior area (0.21–0.42 V). The highest values were found in the one-legged squat exercise (1.00 V).67

Strain as a load measure
Four studies55 57 68 69 carried out additional measurements for quantifying loads on the tendon through strain or elongation measurement. Rees et al68 and Chaudhry et al55 calculated the Achilles tendon length as the distance between the medial gastrocnemius myotendinous junction (tendon origin) and the tendon insertion, using ultrasound imaging. Rees et al68 established and tracked the position of these anatomical sites in terms of three-dimensional (3D) coordinates over time by using an active marker motion analysis system through a previously detailed methodology.32 Chaudhry et al55 implemented an algorithm that provides an intensity map of the ultrasound images, from which the two-dimensional (2D) position and angular orientation of the most intense points can be established.55 Thus, the authors used this mechanism to locate and track the myotendinous junction.55 Elongation was calculated as the difference between the instantaneous length and the initial length. In these studies, standing eccentric heel-drop and concentric heel-raises exercises were
Table 2. Characteristics of the included studies

| Author and year | Population | Tendon | Type of exercise | Evaluated parameter and evaluation methodology |
|-----------------|------------|--------|------------------|-----------------------------------------------|
| Baxter et al2021| n=8; healthy; 6M, 2F; 30±4 years; BMI: 24.1±3.2 | Achilles | Dynamic exercises: seated single-legged heel raise with 15kg placed on the thigh, single-leg and double-leg heel raises done at both comfortable and fast speed, lunges, squats and step ups and step downs from a low box (12 cm) and a high box (20 cm). | Force; inverse dynamics: Achilles tendon force was estimated as the plantarflexion moment calculated with inverse dynamic analysis divided by a plantarflexor moment arm of 5 cm and normalised tendon load by participant body weight. Musculoskeletal model: OpenSim. A motion analysis system and force plate data were used for the procedure. |
| Chaudhry et al2015 | n=11; healthy; 6M, 5F; 26.5±1.9 years; weight: 65.92±10.5 kg; height: 173±8 cm | Achilles | Dynamic exercises: concentric (heel raising) and eccentric (heel lowering) ankle plantar flexion. | Force; inverse dynamics: Achilles tendon force was calculated by dividing the externally applied ankle joint moment by the moment arm and normalised across subjects by body weight. The perpendicular distance to the ankle joint centre from the line joining the calcaneus marker and the Achilles tendon marker was taken as the moment arm after correction for skin thickness measured by ultrasound. Data analysis: Matlab. A motion analysis system and force plate data were used for the procedure. |
| Sinclair et al2015 | n=18; healthy; 18M; 22.1±1 years; weight: 74.2±11.3 kg; height: 177±8.4 cm | Achilles | Dynamic exercises: unilateral and bilateral heel raising, squat and lunge. | Force; inverse dynamics: muscle forces were estimated from a musculoskeletal model. Moment arms were based on previous literature (graphics-based model). The calculated muscle forces were used to quantify total Achilles tendon force by summing the muscle forces of the medial and lateral gastrocnemius and soleus during the stance phase of each exercise. Musculoskeletal model: Human Body Model. A motion analysis system and force plate data were used for the procedure. |
| Rees et al2018 | n=7; healthy; 4M, 3F; 19–41 years; | Achilles | Dynamic exercises: eccentric heel-drop and concentric heel raises exercises. | Force; inverse dynamics: Achilles tendon force was calculated by dividing the ankle joint moment by the moment arm between the Achilles tendon and the ankle joint centre. A motion analysis system and force plate data were used for the procedure. |
| Revak et al2017 | n=21; healthy; 21M; 21.59±1.92 years; weight: 75.81±24 kg; height: 178±10 cm | Achilles | Dynamic exercises: seated bilateral heel raising and lowering, standing bilateral heel raising and lowering, unilateral heel raising and lowering and unilateral heel raising and lowering. | Force; inverse dynamics: muscle forces were estimated from a musculoskeletal model. The muscle forces were then used to quantify total Achilles tendon force by summing the muscle forces of the medial and lateral gastrocnemius and soleus for each exercise. Musculoskeletal model: Human Body Model. A motion analysis system and force plate data were used for the procedure. Strain: the Achilles tendon length was calculated as the distance between the medial gastrocnemius myotendinous junction (tendon origin) and the tendon insertion (ultrasonography and active motion analysis system). |
| Weinert-Aplin et al2015 | n=19; healthy; 8M, 11F; M: 28±3 years; weight: 73±12 kg; height: 176±10 cm; F: 25±6 years; weight: 58±10.2 kg; height: 163±5 cm | Achilles | Dynamic exercises: barefoot and in shoes eccentric heel lowering (with knee extended and flexed). | Force; inverse dynamics: kinematics and kinetics were used to calculate the angles and intersegmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics. Musculoskeletal model: lower limb musculoskeletal model implemented in Matlab. A motion analysis system and force plate data (all conditions), and an in-shoe plantar pressure measurement system (for shod conditions) were used for the procedure. |
| Yeh et al2021 | n=18; healthy; 11M, 7F; 29.6±3.8 years; weight: 70.7±12.4 kg; height: 171.8±7.5 cm | Achilles | Dynamic exercises: HSR and ECC protocols modification: standing knee-straight heel drop and rise (100, 108–115, 125 and 160 of %BW); seated heel drop and rise (13, 21–28, 38 and 63 of %BW) | Force; inverse dynamics: Achilles tendon force was calculated by dividing the ankle torque by the participant-specific effective moment arm estimated from the MRI. Musculoskeletal model: FreeBody. A motion analysis system, force plate data and MRI were used for the procedure. |
| Dillon et al2008 | n=7; healthy; 7M; 26.4±3.9 years; BMI: 24.6±1.5 | Patellar | Dynamic exercises: CONC and ECC one-leg squat (110°), CON and ECC knee extension with a 10 kg weight attached to the foot (90°), step up and step down. | Force; optic fibre: an optic fibre technique was used to detect forces in both the anterior and the posterior regions of the proximal patellar tendon. The technique entails the optic fibre being inserted through the entire cross-section of the tendon and the ends being attached to a transmitter-receiver unit for light intensity monitoring. |
### Table 2

| Autor and year | Population | Tendon | Type of exercise | Evaluated parameter and evaluation methodology |
|---------------|------------|--------|------------------|------------------------------------------------|
| Earp et al. (2016) | n=10; healthy; 10M; 25.8±2.8 years; weight: 83.8±9.4kg; height: 177±6cm | Patellar | Dynamic exercises: depth back squat lifts with 60% of 1RM at three different speeds: slow fixed tempo, volitional speed without a pause and maximum speed jump. | Force: inverse dynamics: PTFs were estimated by multiplying knee moment by the joint-derived moment arm length of the patella, as determined using a previously published model. The relative ankle, knee and hip joint moments were estimated by combining force platform and kinematic using standard inverse dynamics equations and with segmental masses estimated using the cadaver-derived equations provided in a previous study. A motion analysis system and force plate data were used for the procedure. |
| Frohm et al. (2007) | N=14; healthy; 14M; N1; 13; 36±9 years; weight: 87±4kg; height: 183±5cm; N1; 11; 39±10 years; weight: 87±5kg; height: 183±5cm | Patellar | Dynamic exercises: eccentric squats holding a weight (barbell disc) of 10kg in decline board and horizontal surface, eccentric squat in is isometric/mian device in decline board and horizontal surface. | Force: inverse dynamics: PTF was estimated dividing the knee moment by the patellar tendon moment arm, specific for the corresponding knee flexion angle. Moment arms were based on data for different angles reported in previous literature. A motion analysis system and force plate data were used for the procedure. |
| Reilly and Martens (1972) | n=3; healthy; 3M; 24, 26 and 30 years | Patellar | Dynamic exercises: leg raising, stair climbing and deep knee bends. | Force: inverse dynamics: the calculation for the leg raise exercise was a purely mathematical formulation (based on the moment arm and angles), whereas the other cases are a combination of a mathematical formulation with experimentally determined parameters (strain gauge instrumented force plate). Moment arm of the PTF was measured from roentgenograms. A stroboscopic photography system and force plate data were used for the procedure. |
| Richards and Richars (2016) | n=18; healthy; 9M, 9F; 20-46 years; weight: 75.1±4kg (58.3–100) | Patellar | Dynamic exercises: decline squats at different angles of declination (0°, 5°, 10°, 15°, 20° and 25°) | Force: inverse dynamics: PTF was determined by dividing the extensor moment (ME) by the patellar tendon moment arm (PTMA). The moment arm was quantified as a function of the knee flexion angle by fitting a second order polynomial curve to data published in previous literature. A motion analysis system and force plate data were used for the procedure. |
| Zellner et al. (2019) | n=25; healthy; 25F; 22.69±0.74 years; weight: 61.5±9.74kg; height: 169.39±6.44cm | Patellar | Dynamic exercises: forward step lunge with knee in front of toes, forward step lunge with knee behind toes | Force: inverse dynamics: muscle forces were estimated from a musculoskeletal model. The calculated muscle forces were used to quantify the total PTF by summing the muscle forces of the rectus femoris, vastus medialis, vastus lateralis and vastus intermedius throughout each repetition. Musculoskeletal model: Human Body Model. A motion analysis system and force plate data were used for the procedure. |
| Zwerver et al. (2007) | n=5; healthy; 2M, 3F; 19-24 years (mean 22); weight: 58–84kg (mean 72); height: 168-200cm (mean 180) | Patellar | Dynamic exercises: single-leg decline squats at different angles of declination (0°, 5°, 10°, 15°, 20° and 30°) with and without a backpack of 10kg | Force: inverse dynamics: normalised PTFs were estimated according to the following formula: FPTM=M/d, where M is the ankle moment and d is the normalised moment arm of the patellar tendon. The calculation of moment arms were based on previous literature. A motion analysis system and force plate data were used for the procedure. |
| Edsfeldt et al. (2015) | n=12; open carpal tunnel release surgery patients; 4M, 8F; 42 (32-52) years | Hand | Dynamic exercises: unresisted fingers extension and flexion of all fingers, unresisted isolated flexion of FDP, unresisted isolated flexion of FDS | Force: buckle force transducer: after the transverse carpal ligament was released with a longitudinal incision, the FDP and FDS tendons of the index finger were isolated and buckle force transducers were mounted on each. The experiment was conducted during surgery with local anaesthesia injected at the incision site. |
| Kursa et al. (2006) | n=12; open carpal tunnel release surgery patients; 4M, 8F; 42±10 years | Hand | Dynamic exercises: unresisted finger flexion and extension at different angles (MP extension, 15° MP, 45° MP, 60° MP, MP flexion). | Force: buckle force transducer: After the transverse carpal ligament was released with a longitudinal incision, the FDP and FDS tendons of the index finger were isolated, and buckle force transducers were mounted on each. The experiment was conducted during surgery with local anaesthesia injected at the incision site. |
| Nikanjam et al. (2007) | n=12; open carpal tunnel release surgery patients; 4M, 8F; 42±10 years | Hand | Dynamic exercises: unresisted finger flexion and extension. | Force: buckle force transducer: after the flexor retinaculum ligament was released with a longitudinal incision, the FDP and FDS tendons of the index were isolated, and buckle force transducers were placed around each. The experiment was conducted during open carpal tunnel release surgery with local anaesthesia. |

Continued
### Type of exercises

Different types of exercises were analysed in the included studies. Heel raising and lowering exercises, involving concentric or eccentric plantarflexion, are commonly applied in Achilles tendinopathy rehabilitation. Seven studies included this type of exercises. In patellar tendon disorders, different modalities of squats are commonly prescribed, as well as exercises involving knee flexion and extension. Eight studies analysed these types of exercises, respectively. Another exercise commonly applied for lower limb disorders such as lunge was analysed in two studies and three studies analysed step-up and step-down exercises or stairs climbing. Table 2 includes the type of exercises analysed in each study.

### DISCUSSION

The aim of this study was to review the techniques that have been applied in vivo to estimate the forces and strain that act on the human tendon in dynamic exercises commonly used during rehabilitation processes. The main finding of this review is that most studies used an indirect method such as inverse dynamics, while there is a lack of direct measurements due to the difficulties and limitations in its application.
Indirect force measurement: inverse dynamics

Most of the studies included in this review used inverse dynamics as an indirect evaluation of tendon forces. This methodology uses measured kinematics and external forces to indirectly calculate net joint torques and forces in a body segment model. These calculations are usually based on the joint moments produced by the muscle or muscles to which the tendon is inserted. Then, the biomechanical study is based on a single agonist force vector in line with the tendon direction and, in some cases, on a single antagonist force vector in the opposite direction. Although this method is widely used, it is suggested that the results obtained differ from the actual ones due to incorrect modelling assumptions and measurement errors. For example, classical inverse dynamics assumes idealised pin joints and the existence of rigid body segments and that does not match reality. Kinetics are introduced in the procedures with the intention of limiting these errors. However, due to the aforementioned difficulties of kinematics measurements, the kinematics and kinetics data are not always consistent. This creates a new problem due to the concurrency of data that does not match, forcing part of the data to be discarded.

There are different procedures based on inverse dynamics for the calculation of forces. Thus, although most of the included studies used similar kinematics (motion capture devices) and kinetics (force plates) assessment systems, these data were processed in different ways. Some studies integrated these data in musculoskeletal models such as Human Body Model, FreeBody, among others. These models make more or less precise assumptions that allow us to transform the kinematics and kinetics data into net torques of body segments. Likewise, models such as the Human Body Model made an additional indirect estimate, first calculating the muscle forces and assuming that the forces in the tendon will be equal to the sum of the muscle forces of the agonist muscle group. This fact could imply an additional error in the estimation since there may be differences between the agonist muscle group and tendon forces, and a potential error is made when only some of the muscles involved in the movement are taken into account. Different methods were used for estimating the moment arms. Some musculoskeletal models used previous estimations of the moment arms, with some differences both in the models and in the equations used. Some studies performed subject-specific calculations based on imaging techniques to minimise error, and other studies used data from previously published literature (eg, 5 cm ankle moment arm). Alternatively, some studies used an intermediate method based on the use of new or previously published equations together with specific data from each patient. Thus, the results obtained may be influenced by the specific limitations of each methodology. Using generic moment arms based on normative data ignores anatomical differences between individuals, and, sometimes, this value is not scaled to the rest of the anatomical structures. Previous studies also suggest that the moment arm cannot be estimated from easily measured anthropometric characteristics or joint size differences, supporting the use of imaging techniques. In cases where the moment arm is directly measured, it should be noted that the values in a resting position may not correspond to the values in another position or to those that would be obtained with the addition of muscle contraction. The chosen method is relevant because, according to previous studies, there could be differences of up to 40%-50% depending on the technique used (for the patellar tendon moment arm length at a knee angle of 90°). Likewise, these differences could translate into up to 67% differences in the estimated values of tendon force.

Despite all the previously mentioned limitations, modelling approaches have been widely employed to estimate tendon forces. This may be due to its main advantage: it is a non-invasive procedure.

Direct force measurement

In the last decades, an attempt has been made to develop direct measurement techniques. However, this approach is limited due to the need to insert sensors into the body. This characteristic makes it a highly invasive procedure, making its use in healthy subjects difficult to justify. Sensors must be biotolerable (for short-term measurements) and biocompatible (for long-term use), as well as easy to implant. Additionally, devices should avoid damaging body tissues and alter the tendon and joint mobility and neuromuscular function. It has been suggested that these sensors should also be flexible and allow wireless data transmission to facilitate their clinical use. The transducers are implanted with an incision of several centimetres. Thus, the wound usually impedes normal activity for 2-3 weeks and sometimes makes it difficult to measure activity during the same session in which the sensor is inserted. Additionally, potential complications such as local pain or infections have limited the use of this methodology to a restricted research population.

Force transducers

Buckle transducers were one of the first devices to show a successful ability to directly assess these forces in various activities such as walking, running, cycling or jumping. This kind of transducer consists of a metallic buckle with strain gauges through which a tendon is looped. When a tensile force is applied to the tendon, the buckle deforms and produces a voltage output proportional to the force. Due to their configuration, these buckle transducers enable the measurement of force of the entire cross-section of the tendon. This is an advantage over other implantable transducers (eg, optic fibre) that only record forces in a specific area, since it is known that the load may not be uniformly transmitted throughout the entire tendon section. However, the placement of the tendon through the buckle shortens the tendon and can alter its natural movement. Additionally, small changes in the placement may...
cause measurement differences, so it is recommended to carry out the calibration of these transducers within the specific tissue under study, and once the sensor is placed and calibrated, it should be avoided to modify or remove it until the measurement is finished.23

In this review, six studies introduced force transducers for measuring tendon forces during wrist and fingers flexion and extension rehabilitation exercises, all of them in open carpal tunnel release surgery patients. Taking advantage of surgery to place the sensor makes it possible to compensate for part of the invasiveness that this procedure entails. However, reducing its application to this context limits the contexts in which it may be applied. In this regard, the development of biodegradable sensors that are reabsorbed after a certain time could increase the situations where their application can be justified, since the avoidance of a second surgery to remove the sensor would reduce some drawbacks of the technique.83 In all cases, the procedure was carried out after the application of anaesthesia, which together with the surgical procedure itself could have some impact on the measurement results.

**Optic fibre sensor**

The use of optic fibre sensors appeared as a smaller solution compared with previous force transducers.84 This kind of sensor is inserted perpendicular through the tendon. When a longitudinal tension is produced in the tendon, negative transverse tension is produced that squeezes the optical fibre.23 85 The functioning of the optical fibre sensor is based on the amplitude modulation of the transmitted light that occurs when the optical fibre changes its shape due to the forces acting on it.23 85 These differences can be seen in the receiver, which provides a voltage output proportional to the intensity of the light detected and therefore related to the tendon tensile strain.23 85 This effect can be achieved using two types of sensors: intensity-based and spectral-based optical sensors.76

During the last decades, different devices based on optic fibre have been developed and applied to directly measure tendon forces in vivo in humans during isometric contractions86 and during dynamic activities such as walking or jumping.39 76 84 87 88 These sensors have evolved from the earliest models (approximately 500 µm)89 to modern spectral-based models incorporating fibre Bragg gratings and microfabricated stainless steel housings (approximately 200 µm).76 Modern optic fibre sensors offer some advantages such as small size, high sensitivity, fast response time, large dynamic range and insensitivity to electromagnetic interference.76 However, the main limitation of this measurement technique is still the invasiveness of the procedure for introducing and removing the sensor.76 The procedure is usually performed under local anaesthesia, causing a little wound in the tissue that can interfere with movement.76 Due to its smaller size, compared with the buckle transducer, the insertion process, the wound and the recovery process are of lesser magnitude. Thus, its use in volunteers is more easily justified.23 Also, the possible interference of the sensor during movement and changes in the natural shape of the tendon are reduced compared with other transducers, although still existing.23 84

This technique has other limitations to take into account. Previous studies have found that skin movement, cable migration and loading rate may influence the accuracy of the sensor.89 Therefore, this technology may be considered an appropriate option for in vivo evaluation as long as these artefacts can be minimised.76

Furthermore, this kind of sensor records forces in a specific area of the tendon, and this could be a source of differences between measurements due to the fact that force may not be uniformly transmitted throughout the entire tendon section.23 80 82 This phenomenon could be related to the relative sliding between the different tendon fascicles.80 81

The lack of studies using this technique in dynamic exercise could be because of the current limitations that, although lower than those of other invasive techniques, still represent a significant barrier to its implementation. Thus, further study of the matter is encouraged.

**Strain**

Tenocytes are sensitive to strain.7 21 90 91 Thus, it has been suggested that it is the strain magnitude experienced by tendon fibres, not force, that is more directly related to the positive or negative effects triggered in the tissue.7 21 90 Previous studies have shown that tendon strain during activities such as walking or running is between 4.0%–4.3% and 4.6%–9.0%, respectively. The only study that reported the percentage of tendon strain in this review found a strain between 0.71% (seated heel raising and lowering) and 8.80% (standing unilateral heel raising and lowering exercises).57

The use of imaging techniques (eg, 2D7 28 92 93 and 3D94 ultrasound or MRI92) has been previously reported, especially during isometric contractions, but most of these methods have not been transferred to the study of dynamic rehabilitation exercises.

Tendon are viscoelastic, and their mechanical and viscoelastic properties of the tendon may imply a time-dependent behaviour of the tendon when a force is applied to it.11 69 However, the hysteresis of tendons has been reported to be approximately 10%,95 and the loading rate effect does not seem to be decisive in the range of loading rates applied during physical activities.56 97 Furthermore, current strain evaluation techniques (ultrasound-based methods) seem not to be sensitive enough to detect the small effects that this range of loading rates produces.98 To further minimise these loading rate effects, the application of conditioning contractions may allow a state of certain stability and reliability to be reached at the moment of the application of forces for its evaluation.99 100 However, this is not done or at least described in most studies.
In this review, four studies included a tendon elongation measurement for assessing tendon loads. Revak et al. calculated the tendon strain by dividing the tendon stress (previously obtained) by the average Young modulus reported (819 N/mm²). This methodology again requires making various assumptions to estimate the tendon strain through the tendon stress, which in turn has been calculated using the tendon force value calculated indirectly using inverse dynamics. Therefore, this indirect method could accumulate the error of all the intermediate steps, some of which have been discussed in previous sections. Additionally, it also does not seem justified to assume a constant Young modulus for different individuals. Earp et al. estimated the myotendinous unit length of the distal vastus lateralis using derived models based on joint position and individual limb lengths and calculated tendon lengthening based on muscle fascicle behaviour, a method that has been found to be reliable. Differently, Rees et al. and Chaudhry et al. calculated the Achilles tendon length as the distance between the tendon origin and the tendon insertion. Thus, they tracked the position of these anatomical sites by using an active marker motion analysis system. To do this, it is necessary to define what is the position for the initial length, also known as zero-length. Although the neutral position of the joint is often used as zero-length position, it should be noted that this position of the ankle seems to be already associated with longitudinal tendon strain, and the zero-length has been previously related to a different position (knee angle of 180° and ankle angle of 110°). Thus, the joint position corresponding to the zero-length is not always precisely known. It is important to normalise this parameter to allow comparison between studies, for example, using a standardised position of the joint. In these cases, we usually speak of ‘relative strain’ with respect to that previously determined position. While this methodology may be useful when comparing the peak strains of a tendon under different exercises within a particular study or with studies that use that same position, this methodology does not allow for comparing these results with those of in vitro studies, where the position of zero-length is precisely determined. The use of a force sensor in conjunction with ultrasonography could help determine the zero-length in each subject. Other limitations of the approach used in these studies are the skin movements and the curved path of the tendon. Previous evidence have found that considering the Achilles tendon as a straight line between gastrocnemius medialis myotendinous junction and calcaneus results in an underestimation of the tendon length and carries errors of up to 78% of the length changes. In this regard, Kharazi et al. developed a new approach for Achilles strain in vivo measurement, which considers the tendon curve-path shape using skin reflective markers.

**Imaging techniques**

Ultrasonography as a strain measurement technique has some important advantages over other methods: it is non-invasive, does not expose the volunteers to radiation and it is relatively affordable. The absence of a sensor inside the body that can hinder mobility, together with the non-use of anaesthesia, allow natural movements. Additionally, ultrasonography enables the differentiation of muscle and tendon interfaces, enabling muscle and tendon strains to be independently measured. Basically, two approaches could be used to analyse strain using imaging techniques: on the one hand, displacement measurements between the tendon origin and insertion anatomical sites (myotendinous junction), approach used in this review by Rees et al. and Chaudhry et al. The tracking of these anatomical sites is done through different methods. Initially, this task was performed through manual marking of the anatomical sites in successive ultrasound frames throughout the movement. However, this methodology was excessively laborious, so it was limited to only a few frames. For this reason, different algorithms, usually based on cross-correlation, have been developed to automate the process. In the Achilles tendon, for example, insertion is usually tracked using a marker placed on the calcaneus, while for the myotendinous junction, active marker motion analysis and ultrasound systems have been combined. On the other hand, displacement measurements between known points within the tendon midsubstance, known as speckle-tracking, can be used. The speckle-tracking technique allows unique speckle patterns of the tendon to be identified and tracked during movement. The regional strain measurement approach is an advantage over implantable sensors that only enable point-to-point strain assessment. The choice of approach is important since, taking into account that the strain distribution is not consistent throughout the tendon, the result may also be different. While the first option provides the value of the global strain across the entire length of the tendon, the second one offers a measure of a specific region. Some studies have reported that the displacement of the proximal insertion point may be a representative measurement of the total tendon elongation during contraction, but more recent works have shown the limitations of this approach. Thus, both methods may be adequate as long as they are properly reported, only being possible to compare results from the same approach. Likewise, the choice of the anatomical site used as a tracking landmark is relevant. Thus, previous studies have shown that small variations (eg, tibial tuberosity or plateau) result in significant differences in the values obtained, both in tendon strain itself and in other calculated mechanical properties (eg, tendon stiffness). Numerous limitations of imaging techniques have been widely reported. It is worth emphasising that most of these limitations are already present in measurements during isometric contractions, making progress to the measurement of dynamic exercises even more challenging. First, the ultrasound probe placement and orientation may affect the measurements, and any motion produced during the body segment movement can be a source of error. In the case of
the study of isometric contractions, researchers have tried to overcome this limitation by means of rigid fixation with straps. However, this fixation is difficult to achieve during dynamic exercises and, especially during great joint angle excursions, it is difficult to maintain a stable image of the tendon or myotendinous junction. Additionally, the fixation can interfere with the movement pattern. The type of exercises that can be evaluated is also limited by the fact that, except in the case of using wireless ultrasound probes, the subject must always be positioned a short distance from the ultrasound cart. Second, the ultrasound image has a spatial limitation directly related to the length of the ultrasound transducer, especially affecting the measurement of long tendons. This limitation could be obviated by scanning only the myotendinous junction. However, this requires assuming that the movement of the distal structures to which the tendons attach is negligible, and this does not appear to be the case even with isometric contractions. For this reason, it is recommended to scan both tendon ends, using longer transducers when necessary.

Third, another of the key limitations of ultrasonography is due to the use of 2D images to assess a tendon deformation that occurs in three dimensions. While the measurement is done through the identification and tracking of anatomical sites in planar 2D images, the reality of 3D movement means that tendon bulging, rotation or twisting can occur, and this may introduce a systematic overestimation or underestimation of tendon length. This limitation has been partially addressed with new 3D ultrasound techniques by capturing images in multiple static postures (eg, Freehand 3D). In this technique, the ultrasound transducer is moved along the tendon, and a 3D image is created by reconstruction of the captured 2D images. However, this technology requires remaining in a static position for relatively long periods of time to scan the different planes, so its use is limited to resting states or for sustained static contractions. Some strategies have been suggested to minimise these limitations as much as possible. Some of the most relevant are available in table 1 of the article by Seynnes et al.

Other techniques
During the review process, other techniques were identified. However, its current application is limited to isometric contractions, exercises such as walking, running or cycling, or controlled contractions in a laboratory setting.

Magnetic resonance imaging
Some authors have used MRI as an imaging technique to measure tendon strain. Finni et al used phase-contrast cine MRI for evaluating the patellar tendon strain during active knee extensions. In both cases, the reference zero length was identified by analysing MRI images of the tendon in a movie loop of film, noting the joint angle at which the tendon was slack. This technique allows a 3D analysis, reducing some of the limitations of ultrasonography. However, the nature of the MRI technique makes it difficult to evaluate exercises that require greater mobility.

Stretchable strain sensors
Novel stretchable strain sensors, based on soft elastomers and nanomaterials, are showing great potential for directly measuring musculoskeletal soft tissue strains in vivo. These sensors provide direct strain measurement (not force as most of the other available transducers), so they can offer very representative values of the tendon strain. However, these strain sensors share many of their limitations with other implantable devices and must be biotolerable, biocompatible and easy to implant.

Vibrational behaviour
A proof-of-concept study was identified with a novel technique for evaluating tendon force during walking, running and unilateral and bilateral heel raising. Tendon loads were measured using a vibration motor and an accelerometer placed 2 cm apart from each other on the skin superior to the Achilles tendon. The systems consist of exciting a vibration motor and collecting the signals influenced by the tendon force in the accelerometer. It is suggested that a tendon on which low force is applied responds to vibration with a steeper rising and falling edge, attributable to faster energy absorption and dissipation. However, a tendon on which high force is applied responds with a progressive rising and falling edge, attributable to slower energy absorption and dissipation.

Another novel non-invasive approach is being developed for in vivo evaluation by tracking vibrational behaviour. In this case, the direct relationship between axial stress and the speed of shear wave propagation is exploited through tensiometers consisting of a piezo-actuated tapper and two skin-mounted miniature accelerometers. Although these techniques have some limitations such as artefacts caused by noise on the skin caused by movement of the limbs, their non-invasiveness gives them an advantage over other evaluation methods.

Limitations
The main limitation of this study is the difficulty in tracking the literature because of the variety and heterogeneity of terms used. This limitation has been minimised through a search including broad terms, but some studies might still not have been identified.

CONCLUSIONS
Different evaluation methodologies are used for quantifying tendon forces and strain. However, only a minority of these techniques have been transferred to the study of dynamic rehabilitation exercises. There is a predominant use of modelling and inverse dynamics, but force...
transducers and optic fibre sensors have also been used for measuring tendon force. Ultrasound imaging is used for measuring tendon strain. Direct force or strain measurement techniques provide significant data, but their current limitations and high invasiveness reduce their application context. Indirect force estimation through inverse dynamics is not invasive but requires making controversial assumptions that may limit its accuracy. Assessing strain using imaging techniques, as long as its limitations are controlled, is a non-invasive method to assess a direct response to the loads acting on the tendon. There are other potentially applicable methods, but they have not yet been transferred to the study of dynamic rehabilitation exercises, possibly due to the difficulty of overcoming some of their limitations.

Although the methods collected in this review allow direct or indirect estimation of the forces and strain applied to the tendon during dynamic exercises, their very nature makes their applicability difficult in a clinical context. Research can use these tools to make general estimates of forces and strain in dynamic exercises, but the invasiveness of some methods and the loss of immediacy of others make it difficult to study each patient individually and provide immediate feedback to the individuals measured. The field should continue to be developed, looking for precise, direct techniques with less measurement error and less invasiveness.

Contributors All authors contributed to the study design. AE-E and AIC-V searched and screened the articles, with assistance from JC. All authors contributed to data analysis and interpretation of the data. AE-E drafted the manuscript; AIC-V and JC revised it critically, and all authors contributed to revisions and approved the final manuscript. Guarantor: AIC-V.

Funding This work is part of a government-funded project supported by the University Teaching Programme (FPU) of the Ministry of Science, Innovation and Universities of Spain. Grant number: FPU17/00161. The University of Malaga has supported this study with the contribution of funds to support its publication in open access.

Competing interests None declared.

Patient and public involvement Patients and/or the public were not involved in the design, or conduct, or reporting, or dissemination plans of this research.

Patient consent for publication Not applicable.

Ethics approval Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement No data are available. No additional data available.

Supplemental material This content has been supplied by the author(s). It has not been vetted by BMJ Publishing Group Limited (BMJ) and may not have been peer-reviewed. Any opinions or recommendations discussed are solely those of the author(s) and are not endorsed by BMJ. BMJ disclaims all liability and responsibility arising from any reliance placed on the content. Where the content includes any translated material, BMJ does not warrant the accuracy and reliability of the translations (including but not limited to local regulations, clinical guidelines, terminology, drug names and drug dosages), and is not responsible for any error and/or omissions arising from translation and adaptation or otherwise.

Open access This is an open access article distributed in accordance with the Creative Commons Attribution Non Commercial (CC BY-NC 4.0) license, which permits others to distribute, remix, adapt, build upon this work non-commercially, and license their derivative works on different terms, provided the original work is properly cited, appropriate credit is given, any changes made indicated, and the use is non-commercial. See: http://creativecommons.org/licenses/by-nc/4.0/.

REFERENCES
1 Scott A, Squier K, Alfredson H, et al. Icon 2019: scientific tendinopathy symposium consensus: clinical terminology. Br J Sports Med 2020;54:260–2.
2 Cardoso TB, Pizzari T, Kinsella R, et al. Current trends in tendinopathy management. Best Pract Res Clin Rheumatol 2019;33:122–40.
3 Docking SI, Cook J. How do tendons adapt? going beyond tissue responses to understand positive adaptation and pathology development: a narrative review. J Musculoskelet Neuronal Interact 2019;19:300–10.
4 Mellor R, Bennell K, Grimaldi A, et al. Education plus exercise versus corticosteroid injection use versus a wait and see approach on global outcome and pain from gluteal tendinopathy: prospective, pragmatic, randomized controlled trial. BMJ Open 2020;10:1.
5 Beyer R, Kongsgaard M, Hougs Kjaer B, et al. Heavy slow resistance versus eccentric training as treatment for Achilles tendinopathy: a randomized controlled trial. Am J Sports Med 2015;43:1704–11.
6 Kongsgaard M, Kovanen V, Aagaard P, et al. Corticosteroid injections, eccentric decline squat training and heavy slow resistance training in patellar tendinopathy. Scand J Med Sci Sports 2009;19:790–802.
7 Pizzolato C, Lloyd DG, Zheng MH, et al. Finding the sweet spot via personalised achilles tendon training: the future is within reach. Br J Sports Med 2019;53:11–12.
8 Wang JH-C. Mechanobiology of tendon. J Biomech 2006;39:1583–82.
9 Chiquet M, Renedo AS, Huber F, et al. How do fibroblasts translate mechanical signals into changes in extracellular matrix production? Matrix Biol 2003;22:73–80.
10 Wang T, Lin Z, Day RE, et al. Programmable mechanical stimulation influences tendon homeostasis in a bioreactor system. Biotechnol Bioeng 2013;110:656–67.
11 Arampatzis A, Karamanidis K, Albracht K. Adaptational responses to the human achilles tendon by modulation of the applied cyclic strain magnitude. J Exp Biol 2007;210:2743–53.
12 Rio E, van Ark M, Docking S, et al. Isometric contractions are more analgesic than eccentric contractions for patellar tendinopathy: an in-season randomized clinical trial. Clin J Sport Med 2017;27:253–9.
13 Alfredson H, Pietila T, Jonsson P, et al. Heavy-load eccentric calf muscle training for the treatment of chronic achilles tendinosis. Am J Sports Med 1998;26:360–6.
14 Silbernagel KG, Thomeé R, Thomée P, et al. Eccentric overload training for patients with chronic achilles tendon pain—a randomised controlled study with reliability testing of the evaluation methods. Scand J Med Sci Sports 2001;11:197–206.
15 Silbernagel KG, Thomeé R, Eriksson BI, et al. Continued sports activity, using a pain-monitoring model, during rehabilitation in patients with achilles tendinopathy: a randomized controlled study. Am J Sports Med 2007;35:897–906.
16 Malliaras P, Cook J, Purdam C, et al. Patellar tendinopathy: clinical diagnosis, load management, and advice for challenging case presentations. J Orthop Sports Phys Ther 2015;45:887–896.
17 Mascaro A, Cos Miquel Ángel, Morral A, et al. Load management in tendinopathy: clinical progression for Achilles and patellar tendinopathy. Apoints. Medicina de l’Esport 2018;53:19–27.
18 Cook J, Purdam C. Is compressive load a factor in the development of tendinopathy? Br J Sports Med 2012;46:163–8.
19 Cook J, Purdam CR. Is tendon pathology a continuum? a pathology model to explain the clinical presentation of load-induced tendinopathy. Br J Sports Med 2009;43:409–16.
20 Wang JH-C, Guo Q, UB. Tendon biomechanics and mechanobiology—a minireview of basic concepts and recent advancements. J Hand Therapy 2012;25:133–41.
21 Huang L, Korhonen RK, Turunen MJ, et al. Experimental mechanical strain measurement of tissues. PeerJ 2019;7:e6545.
22 Kannus P. Structure of the tendon connective tissue. Scand J Med Sci Sports 2000;10:312–20.
23 Fleming BC, Beynon BD. In vivo measurement of ligament/tendon strains and forces: a review. Ann Biomed Eng 2004;32:318–28.
24 Glos DL, Butler DL, Grood ES, et al. In vitro evaluation of an inextensible force transducer (IFT) in a patellar tendon model. J Biomech Eng 1993;115:335–43.

ORCID iDs
Adrian Escriche-Escuder http://orcid.org/0000-0003-4402-6483
Antonio I Cuesta-Vargas http://orcid.org/0000-0002-8880-4315
25 Dick TJM, Arnold AS, Wakeling JM. Quantifying achilles tendon force in vivo from ultrasound images. J Biomech 2016;49:3200–7.
26 Dumas R, Barré A, Moissinen F, et al. Can a reduction approach predict reliable joint contact and musculo-tendon forces? J Biomech 2015;48:1080–9.
27 Farris DJ, Buckeridge E, Trevartha G, et al. The effects of orthotic heel lifts on achilles tendon force and strain during running. J Appl Biomech 2012;28:511–9.
28 Kongsgaard M, Aagaard P, Roikjaer S, et al. Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats. Clin Biomech 2006;21:748–54.
29 Joseph CW, Bradshaw EJ, Furness TP, et al. Early changes in achilles tendon behaviour in vivo following downhill backwards walking. J Sports Sci 2016;34:1215–21.
30 Franz JR, Schulze K, Fassbender M, et al. Non-uniform in vivo deformations of the human achilles tendon during walking. Gait Posture 2015;41:192–7.
31 Lichtwark GA, Bougoulias K, Wilson AM. Muscle fascicle and serial elastic element length changes along the length of the human gastrocnemius during walking and running. J Biomech 2007;40:157–64.
32 Lichtwark GA, Wilson AM. In vivo mechanical properties of the human achilles tendon during one-legged hopping. J Exp Biol 2005;208:4715–25.
33 Zhang G, Adam NC, Hosseini Nasab SH, et al. Techniques for in vivo measurement of ligament and tendon strain; a review. Ann Biomed Eng 2021;49:7–28.
34 Bull AMJ, Reilly P, Wallace AL, et al. A novel technique to measure active tendon forces: application to the subscapularis tendon. Knee Surgery, Sports Traumatology, Arthroscopy 2000;8:145–50.
35 Zhang X, Deng L, Yang Y, et al. Acute shoe effects on achilles tendon loading in runners with habitual rearfoot strike pattern. Gait Posture 2020;82:322–8.
36 Dixon SJ, Kerwin DG. The influence of heel lift manipulation on achilles tendons loading in running. J Appl Biomech 1998;14:374–89.
37 Gregor RJ, Komi PV, Järvinen M. Achilles tendons force during cycling. Int J Sports Med 1987;8 Suppl 1:9–14.
38 Ebrahimi A, Loegering IF, Martin JA, et al. Achilles tendons loading is lower in older adults than young adults across a broad range of walking speeds. J Gerontol A Biol Sci Med Sci 2020;75:2566–72.
39 Fröberg A, Komi P, Ishikawa M, et al. Force in the achilles tendon during walking with ankle foot orthosis. Am J Sports Med 2009;37:1200–7.
40 Tricco AC, Lillie E, Zarin W, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med 2018;169:467–73.
41 Branner WM, Rethiefsen ML, Kleijnen J, et al. Optimal database combinations for literature searches in systematic reviews: a prospective exploratory study. Syst Rev 2017;6:245.
42 Khalil H, Peters M, Godfrey CM, et al. An evidence-based approach to scoping reviews. Worldviews Evid Based Nurs 2016;13:118–23.
43 Peters MDJ, Godfrey CM, Khalil H, et al. Guidance for conducting systematic scoping reviews. Int J Evid Based Healthc 2015;13:141–6.
44 Kursa K, Lattanza L, Diao E, et al. In vivo flexor tendon forces increase with finger and wrist flexion during active finger flexion and extension. J Orthop Res 2006;24:783–9.
45 Edsfield S, Rempel D, Kursa K, et al. In vivo flexor tendons force generated during different rehabilitation exercises. J Hand Surg Eur Vol 2015;40:785–10.
46 Nikanjam M, Kursa K, Lehan S, et al. Finger flexor motor control patterns during active flexion: an in vivo tendon force study. Hum Mov Sci 2007;26:1–10.
47 Kerenzke T, Gheydi N, Ragan R. Comparison of estimates of achilles tendon loading from inverse dynamics and inverse dynamics-based static optimisation during running. J Sports Sci 2017;35:2073–9.
48 Baxter JR, Corrigan P, Huliffish TJ, et al. Exercise progression to Incrementally load the achilles tendon. Med Sci Sports Exerc 2021;53:124–31.
49 Frohn A, Halvorsen K, Thorstensson A. Patellar tendon load in different types of eccentric squats. Clin Biomech 2007;22:704–11.
50 Sinclair J, Edmundson C, Atkins S, et al. The effect of front and back squat techniques on peak loads experienced by the achilles tendon. J Athl Train 2010;45:264–8.
51 Reilly DJ, Martins M. Experimental analysis of the quadriceps muscle force and patello-femoral joint reaction force for various activities. Acta Orthop Scand 1972;43:126–37.
52 Zwerver J, Bredeweg SW, Hof AL. Biomechanical analysis of the single-leg dynamic quadriceps moment. Br J Sports Med 2007;41:164–7.
53 Richards J, Seife J, Sinclair J, et al. The effect of different decline angles on the biomechanics of double limb squats and the implications to clinical and training practice. J Hum Kinet 2016;52:125–38.
54 Yeh C-H, Calder JD, Antflick J, et al. Maximum dorsiflexion increases achilles tendon force during exercise for midportion achilles tendinopathy. J Orthop Res 2017;1:1674–82.
55 Chaudhry S, Morrissey D, Woleger RC, et al. Eccentric and concentric loading of the triceps surae: an in vivo study of dynamic muscle and tendon biomechanical parameters. J Biomech 2015;31:69–78.
56 Ghedi N, Kerenzke TW, Willson JD, et al. Achilles tendon loading during weight bearing exercises. Phys Ther Sport 2018;32:260–8.
57 Revak A, Diers K, Kerenzke TW, et al. Achilles tendon loading during heel-raising and -lowering exercises. J Athl Train 2017;52:89–96.
58 Zelmier M, Kerenzke TW, Ghedi N, et al. Patellar tendon stress between two variations of the forward step lunge. J Sport Health Sci 2018;7:235–41.
59 van den Bogert AJ, Geijtenbeek T, Even-Zohar O, et al. A real-time system for biomechanical analysis of human movement and muscle function. Med Biol Eng Comput 2015;51:1069–77.
60 Seth A, Hicks JL, Uchida TK, et al. OpenSim: simulating musculoskeletal dynamics and neuromuscular control to study human and animal movement. PLoS Comput Biol 2018;14:e1006223.
61 Cleather DJ, Bull AMJ. The development of a segment-based musculoskeletal model of the lower limb: introducing freeBody. R Soc Open Sci 2015;2:140449.
62 Weinert-Aplin RA, Bull AMJ, McGregor AH. Investigating the effects of knee flexion during the eccentric heel-drop exercise. J Sports Sci Med 2015;14:149–55.
63 Schuind F, Garcia-Elias M, Cooney WP, et al. Flexor tendons force: in vivo measurements. J Hand Surg Am 1992;17:291–8.
64 Powell ES, Trail IA. Forces transmitted along human flexor tendons- the effect of extending the fingers against the resistance provided by rubber bands. J Hand Surg Eur Vol 2006;34:186–9.
65 Powell ES, Trail IA. Forces transmitted along human flexor tendons during passive and active movements of the fingers. J Hand Surg Br 2004;29:386–9.
66 Dennerlein JT, Miller JM, Mote CD, et al. A low profile human tendon force transducer: the influence of tendon thickness on calibration. J Biomech 1997;30:395–7.
67 Dillon EM, Erasmus PJ, Müller JH, et al. Differential forces within the proximal patellar tendon as an explanation for the characteristic lesion of patellar tendinopathy: an in vivo descriptive experimental study. Am J Sports Med 2008;36:2119–27.
68 Rees JD, Lichtwark GA, Wolman RL, et al. The mechanism for efficacy of eccentric loading in achilles tendon injury; an in vivo study in humans. Rheumatology 2008;47:1493–7.
69 Earp JE, Newton RJ, Cormie P, et al. Faster movement speed results in greater tendon strain during the loaded squat exercise. Front Physiol 2016;7:366.
70 Wren TA, Yerba SA, Beaufre GS, et al. Mechanical properties of the human achilles tendon. Clin Biomech 2001;16:245–51.
71 Faber H, van Soest AJ, Kistemaker DA. Inverse dynamics of mechanical multibody systems: an improved algorithm that ensures consistency between kinematics and external forces. PLoS One 2018;13:e0204575.
72 Seynnes OR, Bojsen-Moller J, Albracht K, et al. Ultrasound-based testing of tendon mechanical properties: a critical evaluation. J Appl Physiol 2015;118:133–41.
73 Tsaoopoulos DE, Baltzopoulos V, Magnanaris CN. Human patellar tendon moment arm length: measurement considerations and clinical implications for joint loading assessment. Clin Biomech 2006;21:657–67.
74 Magnanaris CN. Imaging-based estimates of moment arm length in intact human muscle-tendons. Eur J Appl Physiol 2004;91:130–9.
75 Tsaoopoulos DE, Magnanaris CN, Baltzopoulos V. Can the patellar tendon moment arm be predicted from anthropometric measurements? J Biomech 2007;40:645–51.
76 Behmann GP, Hilder J, Mirotnik MS. Fiber optic micro sensor for the measurement of tendon forces. Biomed Eng Online 2012;11:77.
77 Komi PV, Salonen M, Järvinen M, et al. In vivo registration of achilles tendons forces in man. I. methodological development. Int J Sports Med 1987;8 Suppl 1:3–8.
78 Fukashiro S, Komi PV, Järvinen M, et al. In vivo achilles tendon loading during jumping in humans. Eur J Appl Physiol Occup Physiol 1995;71:453–8.
79 Komi PV. Relevance of in vivo force measurements to human achilles tendon in vivo. Excerc Sport Sci Rev 2015;43:190–7.
November 2022. Downloaded from http://bmjopen.bmj.com/ BMJ Open: first published as 10.1136/bmjopen-2021-057605 on 25 July 2022. Protected by copyright.

81 Slane LC, Thelen DG. Non-uniform displacements within the achilles tendon observed during passive and eccentric loading. *J Biomech* 2014;47:2831–5.
82 Slane LC, Dandois F, Bogaerts S, et al. Non-uniformity in the healthy patellar tendon is greater in males and similar in different age groups. *J Biomech* 2018;80:16–22.
83 Bautry CM, Kaizawa Y, Schroeder BC, et al. A stretchable and biodegradable strain and pressure sensor for orthopaedic application. *Nat Electron* 2018;1:314–21.
84 Finiti T, Komi PV, Ljubimov I. Achilles tendon loading during walking: application of a novel optic fiber technique. *Eur J Appl Physiol Occup Physiol* 1998;77:289–91.
85 Ravary B, Pourcelot P, Bortolussi C, et al. Strain and force transducers used in human and veterinary tendon and ligament biomechanics of the studies. *Clin Biomech* 2000;15:43–47.
86 Arndt AN, Komi PV, Brüggemann G-P, et al. Individual muscle contributions to the in vivo achilles tendon force. *Clin Biomech* 1999;13:532–41.
87 Ishikawa M, Finiti T, Komi PV. Behaviour of vastus lateralis muscle-tendon during high intensity SSC exercises in vivo. *Acta Physiol Scand* 2003;178:205–13.
88 Finiti T, Komi PV, Lepola V. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump. *Eur J Appl Physiol* 2000;83:416–26.
89 Komi PV, Belli A, Huttunen V, et al. Optic fibre as a transducer of tendomuscular forces. *Eur J Appl Physiol Occup Physiol* 1996;72:278–80.
90 Arampatzis A, Mersmann F, Bohm S. Individualized Muscle-Tendon unit and training in long jump. *J Biomech* 2004;37:785–91.
91 Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Eur J Appl Physiol* 2010;102:821–32.
92 Cavanagh PR, Komi PV. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump. *Eur J Appl Physiol* 2000;83:416–26.
93 Komi PV, Belli A, Huttunen V, et al. Optic fibre as a transducer of tendomuscular forces. *Eur J Appl Physiol Occup Physiol* 1996;72:278–80.
94 Arampatzis A, Mersmann F, Bohm S. Individualized Muscle-Tendon unit and training in long jump. *J Biomech* 2004;37:785–91.
95 Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Eur J Appl Physiol* 2010;102:821–32.
96 Cavanagh PR, Komi PV. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump. *Eur J Appl Physiol* 2000;83:416–26.
97 Komi PV, Belli A, Huttunen V, et al. Optic fibre as a transducer of tendomuscular forces. *Eur J Appl Physiol Occup Physiol* 1996;72:278–80.
98 Arampatzis A, Mersmann F, Bohm S. Individualized Muscle-Tendon unit and training in long jump. *J Biomech* 2004;37:785–91.
99 Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Eur J Appl Physiol* 2010;102:821–32.
100 Cavanagh PR, Komi PV. In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump. *Eur J Appl Physiol* 2000;83:416–26.
101 Komi PV, Belli A, Huttunen V, et al. Optic fibre as a transducer of tendomuscular forces. *Eur J Appl Physiol Occup Physiol* 1996;72:278–80.
102 Kurokawa S, Fukunaga T, Kushikata S, et al. Behaviour of fascicles and tendinous structures of human gastrocnemius during vertical jumping. *J Appl Physiol* 2001;90:1349–58.
103 De Monte G, Arampatzis A, Stogiannidis S, et al. In vivo motion transmission in the active gastrocnemius medialis muscle tendon unit during ankle and knee joint rotation. *J Electromyogr Kinesiol* 2006;16:413–22.
104 Fukutani A, Hashizume S, Kusumoto K, et al. Influence of neglecting the curved path of the achilles tendon on achilles tendon length change at various muscle lengths. *Eur J Appl Physiol* 2012;114:2178–88.
105 Kharazi M, Bohm S, Theodorakis E, et al. Quantifying mechanical loading and elastic strain energy of the human achilles tendon during walking and running. *Sci Rep* 2021;11:3830.
106 Korstanje J-WH, Selles RW, Stam HJ, et al. Development and validation of ultrasound-based and electrogoniometric methods to quantify tendon displacement. *J Biomech* 2010;43:1373–9.
107 Pearson SJ, Ritchings T, Mohamed ASA. The use of normalized cross-correlation analysis for automatic tendon excursion measurement in dynamic ultrasound imaging. *J Biomech Biomed Eng* 2013:29:185–73.
108 Magnusson SP, Hansen P, Aagaard P, et al. Differential strain patterns of the human gastrocnemius aponeurosis and free tendon, in vivo. *Acta Physiol Scand* 2003;177:185–95.
109 Swenson RB, Slane LC, Magnusson SP. Ultrasound-based speckle-tracking in tendons: a critical analysis for the technician and the clinician. *J Appl Physiol Bethesda Md* 1985.
110 Mersmann F, Seynes OR, Legerlotz K, et al. Effects of tracking landmarks and trial point of resistive force application on the assessment of muscle- tendon force-displacement curves. *Eur J Appl Physiol* 2010;104:1320–8.
111 Klimstra M, Dowling J, Durkin JL, et al. The effect of ultrasound probe orientation on muscle architecture measurement. *J Electromyogr Kinesiol* 2007;17:504–14.
112 Finiti T, Haviu M, Bogaerts S, et al. Mechanical behavior of the quadriceps femoris muscle tendon unit during low-load contractions. *J Appl Physiol* 2008;104:1320–8.
113 Bolus NB, Jeong HK, Blaho BM, et al. Fit to burst: toward noninvasive estimation of achilles tendon load using burst vibrations. *IEEE Trans Biomed Eng* 2011;58:470–81.
114 Martin JA, Brandon SC, Keuler EM, et al. Gauging force by tapping tendons. *Nat Commun* 2018;9:1592.
115 Delp SL, Loan JP, Hoy MG, et al. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng* 1989:37:757–67.
116 Self BP, Paine D. Ankle biomechanics during four landing techniques. *Med Sci Sports Exerc* 2001;33:1338–44.
117 Winter DA. Three-Dimensional Kinematics and Kinetics. In: Biomechanics and Motor Control of Human Movement. John Wiley & Sons, Ltd, 2009: 176–99.
118 Visser JJ, Hoogkamer JE, Bobbert MF, et al. Length and moment arm of human leg muscles as a function of knee and hip-joint angles. *Eur J Appl Physiol Occup Physiol* 1990;61:453–60.
119 Robertson D, Caldwell G, Hamill J. Research Methods in Biomechanics. Champlain, IL: Human Kinetics, 2004.
116 Self BP, Paine D. Ankle biomechanics during four landing techniques. *Med Sci Sports Exerc* 2001;33:1338–44.
117 Winter DA. Three-Dimensional Kinematics and Kinetics. In: Biomechanics and Motor Control of Human Movement. John Wiley & Sons, Ltd, 2009: 176–99.
118 Visser JJ, Hoogkamer JE, Bobbert MF, et al. Length and moment arm of human leg muscles as a function of knee and hip-joint angles. *Eur J Appl Physiol Occup Physiol* 1990;61:453–60.
119 Robertson D, Caldwell G, Hamill J. Research Methods in Biomechanics. Champlain, IL: Human Kinetics, 2004.