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Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review

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Title: Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review

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Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review

ABSTRACT

Objective: The objective of this scoping review was to review the techniques that have been applied in vivo to directly and indirectly estimate the forces and loads transmitted to the human tendon in dynamic exercises commonly used during rehabilitation processes.

Design: Scoping review.

Data sources: Primary studies were independently identified by two reviewers in Embase, PubMed, Web of Science, and Google Scholar.

Eligibility criteria for selecting studies: Cross-sectional or longitudinal studies were included if they included humans; focused on evaluating the forces or loads of tendons in vivo using direct or indirect techniques; during dynamic exercises; and were available in English or Spanish language. They were excluded if tendon forces were used as part of the calculation of other parameters; if evaluated neuromuscular or joint forces and loads not describing being evaluating the tendon; if not evaluated dynamic exercises other than running, walking, jumping or landing; and if they were conference proceedings or book chapters.

Results: Twenty-two studies were included in the review. Fifteen studies used an indirect evaluation methodology based on inverse dynamics, 10 of them in the Achilles tendon and five in the patellar tendon. Six studies implemented force transducers for measuring tendon forces, all of them in open carpal tunnel release surgery patients. One study applied an optic fibre technique to detect forces in the patellar tendon. Two studies included a strain or differences in tendon length measurement for measuring tendon loads using ultrasound imaging techniques.

Conclusion: There is a predominant use of modelling and 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 forces in dynamic exercises, the invasiveness of some methods and the loss of immediacy of others make it still difficult to study each patient individually.

Keywords: Foot & ankle; hand & wrist; musculoskeletal disorders; rehabilitation medicine; sports medicine

Strengths and limitations of the study

- The extensive search carried out in this review in four of the main databases allows the reader to approach a wide field of knowledge.
- This review provides a snapshot of the current situation of the current situation in the study of forces and loads on the tendon during dynamic exercises.
- Grouping the assessment tools into subgroups allows an analysis of the advantages and disadvantages of each option.
- One of the limitations is the difficulty in tracking the literature due to the variety of terms used.

INTRODUCTION

Tendinopathy is the preferred term for persistent tendon pain and loss of function related to mechanical loading [1]. 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 [2].

Loading intervention through a progressive exercise programme is considered the preferred management of tendinopathies due to the vast evidence published in the last decades [3,2,4–6]. This approach focus on producing adequate stimulus that generate adaptations and increase the tolerance of the tendon to load and exercise [3]. Therefore, 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 passive support interventions for pain and symptom control [2].

Different exercise modalities and intensities have been successfully applied in tendinopathy [6–9]. Likewise, different strategies have been implemented for handling and modifying the loads [10–12]. These strategies range from a quantification of volume (series and repetitions, number of jumps, etc.) or the amount of time of physical activity, to the use of concepts such as maximum repetition (RM) or the BORG scale of perceived exertion. However, although concepts such as RM 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 reaches the tendon in these activities is usually unknown.

For both prevention and treatment of tendinopathy, proper load management would benefit from a greater understanding of direct forces and loads on the tendon during exercises. In vitro studies [13], as well as in vivo indirect calculations based on body position, joint reaction forces, and inverse dynamic models [14–16] have made it possible to approximate knowledge in this field. Additionally, as underlined by a previous review, direct evaluations using buckle-type transducers and optic fibre techniques have approximated the direct measurement of loads in tendons of the hand and the Achilles and patellar tendons [17].

Directly measurement of strains and forces in vivo in human tendons is challenging, due to the difficulties to implant biotolerable and biocompatible sensors that allow to correctly measure the forces without damaging the tissue or influencing the measurement results [17]. Likewise, some methods developed for the quantification of force and loads on the tendon have been designed to evaluate isometric contractions [18,19] or cyclic activities such as running [20,21], cycling [14,22], or walking [23,24]. Thus, there is 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 to directly and indirectly estimate the forces and loads transmitted to the human tendon in dynamic exercises commonly used during rehabilitation processes.

MATERIAL AND METHODS

This scoping review was undertaken following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines [25]. 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 [26] for biomedical reviews, four databases were searched in 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 Supplementary Appendix 1.

Eligibility criteria

All studies that met the following eligibility criteria were included:

(a) Cross-sectional studies published in scientific journals;

(b) Including humans with or without tendinopathy;

(c) Focused on evaluating the forces/loads (tendon strain evaluation was included if it was described as a way to quantify loads) of tendons in vivo using direct or indirect techniques;

(d) During dynamic exercises;

(e) Available in English or Spanish language.

Conversely, those studies meeting any of these exclusion criteria were discarded: (a) Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results; (b) studies with evaluation of neuromuscular or joint forces and loads that do not describe evaluating the tendon; (c) no dynamic exercises other than running, walking, jumping, landing, or everyday tasks; (d) conference proceedings; (e) 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 two independent authors. Finally, the same two reviewers screened the full texts of identified articles to select those that met the eligibility criteria. A third reviewer solved any disagreements.

Data extraction

Two reviewers 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; tendon forces/loads results.

In this review, they were included those studies that analysed the forces and loads 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 analysis

Current guidelines on conducting a scoping review describe the inclusion of a methodological quality analysis as not necessary [27,28]. 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 focus on analysing the forces and loads 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

Patients were not involved in this research.

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, 151 were retrieved 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, only 22 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 Supplementary Appendix 2.

[Figure 1 near here]

In total, 306 subjects were included in the analysed studies. Among these, 208 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 [29–31] (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, optic fibre sensors, and strain evaluated using imaging techniques. The tendon locations evaluated were the Achilles, 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.

Table 1. Forces and loads evaluation methodologies identified in the included studies.

Measurement methodology	Tendon	References
Inverse dynamics	Achilles	[32–41]
	Patellar	[42–46]
Force transducers (Buckle force transducer, S-shaped force transducer, load cell)	Hand	Buckle [29–31] Load cell [47,48] S-shaped [49]
Optic fibre sensors	Patellar	[50]
Strain evaluation (imaging techniques)	Achilles	[37,40]

Inverse dynamics

Fifteen studies used an indirect evaluation methodology based on inverse dynamics, 10 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 [51]. Moment arms are estimated from previous literature data or estimated specifically for each patient through imaging techniques such as magnetic resonance imaging or ultrasound.

Most of the included studies used motion capture systems for kinematics, while force plates were the most used device for obtaining kinetic data. Some studies used generic moment arms based on the published literature [32,44], other used previously described procedures and equations [36,38,41,42,46], while other estimated subject-specific moment arms based on imaging techniques [33,34]. Kinematic and kinetic data were integrated into different musculoskeletal models: three studies [35,37,43] used the Human Body Model [52], one [32] study used the OpenSim model [53], one study [33] used FreeBody model [54], while other studies [34,39,42] implemented other codes or models.

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 [29–31], s-shaped force transducer [49], and load cell [47,48].

Optic fibre sensor

Dillon et al. (2008)[50] 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 an optic fibre sensor through the entire cross section of the tendon. The optic fibre was attached to a transmitter-receiver unit for light intensity monitoring.

Strain as a load measure

Two studies [37,40] carried out additional measurements for quantifying loads on the tendon through strain or differences in tendon length, both using ultrasound imaging. Revak et al. (2017) [37] calculated the tendon strain using the average Young modulus value (819 cm) reported in previous literature [56]. Rees et al. (2008) [40] calculated the Achilles tendon length as the distance between the medial gastrocnemius muscle tendon junction (tendon origin) and the tendon insertion.

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. Eight studies including this type of exercises [32,34–37,40,39,33]. In patellar tendon disorders, different modalities of squats are commonly prescribed, as well as exercises involving knee flexion and extension. Eight [32,35,38,42,44–46,50] and two[41,50] studies analysed these types of exercises, respectively. Another exercise commonly applied for lower limb disorders such as lunge was analysed in two studies [35,43]. Three studies analysed step-up and step-down exercises or stairs climbing [32,41,50]. Finally [29–31,47–49]. Table 2 includes the type of exercises analysed in each study.

Table 2. Characteristics of the included studies.

Autor and year	Population	Tendon	Type of exercise	Evaluation methodology
Baxter et al. 2021 [32]	N= 8; Healthy; 6M, 2F; 30 ±4 years; BMI: 24.1 ±3.2	Achilles	Dynamic exercises: seated single-legged heel raise with 15 kg 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)	Inverse dynamics: Achilles tendon load was estimated as the plantarflexion moment calculated with inverse dynamic analysis divided by a plantarflexor moment arm of 5 cm and normalized tendon load by participant bodyweight. Musculoskeletal model: OpenSim. A motion analysis system and force plate data were used for the procedure.
Chaudhry et al. 2015 [34]	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	Inverse dynamics: Achilles tendon force was calculated by dividing the externally applied ankle joint moment by the moment arm and normalized across subjects by body weight. The perpendicular distance to the ankle joint center 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 (US). Data analysis: Matlab code. A motion analysis system and force plate data were used for the procedure.
Gheidi et al. 2018 [35]	N= 18; Healthy; 18M; 22.1 ±1.8 years; Weight: 74.29 ±11.3 kg; Height: 177.7 ±8.4 cm	Achilles	Dynamic exercises: unilateral and bilateral heel raising, squat, lunge	Inverse dynamics: Muscle forces were estimated from a musculoskeletal model. Moment arms were based on previous literature (graphics-based model) [55]. 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.
Kawakami et al. 2002 [36]	N= 6; Healthy; 6M; 24-45 years; Weight: 72 ±6 kg; Height: 171 ±5 cm	Achilles	Dynamic exercises: ankle plantar flexion at 40% of maximal voluntary force with and without countermovement	Inverse dynamics: The Achilles tendon force was estimated by the following equation: $Ft = Tq \times d^{-1}$, where d is the moment arm length of the Achilles' tendon and Tq the torque around the ankle joint. Torque was estimated from the force at the ball of the foot tangential to the ankle joint rotation arc multiplied by the distance from the estimated centre of ankle joint to the ball of the foot, measured for each subject. The moment arm length as a function of the ankle joint angle was derived from a previous report [56]. An electrogoniometer and force plate data were used for the procedure.
Rees et al. 2008 [40]	N= 7; Healthy; 4M, 3F; 19-41 years;	Achilles	Dynamic exercises: eccentric heel-drop and concentric heel-raises exercises	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. Differences in tendon length: The differences in the Achilles tendon length were calculated. The Achilles tendon length was calculated as the distance between the medial gastrocnemius muscle tendon junction (tendon origin) and the tendon insertion (ultrasonography).

Revak et al. 2017 [37]	N= 21; Healthy; 21M; 21.59 ±1.92 years; Weight: 75.81 ±1.24 kg; Height: 178.22 ±8.02 cm	Achilles	Dynamic exercises: seated bilateral heel raising and lowering, standing bilateral heel raising and lowering, unilateral heel raising and lowering, and bilateral heel raising and unilateral lowering.	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: Strain was calculated using the average Young modulus of 819 cm reported in previous literature [57] using ultrasonography.
Sinclair et al. 2015 [38]	N= 18; Healthy; 18M; 23.61 ±4.17 years; Weight: 75.63 ±6.54 kg; Height: 178 ±10 cm	Achilles	Dynamic exercises: back and front squat	Inverse dynamics: The Achilles tendon load (ATL) was determined by dividing the plantar flexion moment (MPF) by the estimated Achilles tendon moment arm (MA): ATL = MPF / MA. The moment arm was quantified as a function of the ankle sagittal plane angle using a procedure described in previous literature [58]. A motion analysis system and force plate data were used for the procedure.
Weinert-Aplin et al. 2015 [39]	N= 19; Healthy; 8M, 11F; M: 28 ±3 years; Weight: 73.4 ±12 kg; Height: 176 ±10 cm F: 29 ±6 years; Weight: 58.7 ±10.2 kg; Height: 163 ±5 cm	Achilles	Dynamic exercises: barefoot and in shoes eccentric heel-drop (with knee extended and flexed)	Inverse dynamics: Kinematics and kinetics were used to calculate the angles and inter-segmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics [59]. 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 al. 2021 [33]	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, 160 of %BW); seated heel drop and rise (13, 21-28, 38, 63 of %BW)	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 al. 2008 [50]	N= 7; Healthy; 7M; 26.4 ±3.9 years; BMI: 24.8 ±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	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.
Earp et al. 2016 [45]	N= 10; Healthy; 10M; 25.8 ±2.8 years; Weight: 83.8 ±9.4 kg; Height: 177 ±6 cm	Patellar	Dynamic exercises: depth back squat lifts with 60% of 1RM at three different speeds: slowfixed-tempo, volitional-speed without a pause, and maximum-speed jump)	Inverse dynamics: Patellar tendon forces were estimated by multiplying knee moment by the joint-derived moment arm length of the patella; as determined using a previously published model [60]. 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 previously published literature [61]. A motion analysis system and force plate data were used for the procedure.
Frohm et al. 2007 [44]	N_{Total}= 14; Healthy; 14M N_1: 13; 36 ±9 years; Weight: 87 ±4 kg; Height: 183 ±5 cm	Patellar	Dynamic exercises: eccentric squats holding a weight (barbell disc) of 10 kg, eccentric squat in Bromsman device	Inverse dynamics: Patellar tendon force 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 [62]. A motion analysis system and force plate data were used for the procedure.

	N_2: 11; 39 ±10 years; Weight: 87 ±5 kg; Height: 183 ±5 cm			
Reilly and Martens 1972 [41]	N= 3; Heathy; 3M; 24, 26, and 30 years	Patellar	Dynamic exercises: leg raising, stair climbing, and deep knee bends	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 parameter (strain gage instrumented force plate). Moment arm of the patellar tendon force were measured from roentgenograms. A stroboscopic photography system and force plate data were used for the procedure.
Richards et al. 2016 [46]	N= 18; Healthy; 9M, 9F; 20-46 years; Weight: 75.1 kg (58.3-100)	Patellar	Dynamic exercises: decline squats at 0°, 5°, 10°, 15°, 20° and 25°	Inverse dynamics: Patellar tendon force (PTF) was determined by dividing the extensor moment (ME) by the tendon moment arm (PTMA): PTF = ME / PTMA. The moment arm was quantified as a function of the knee flexion angle by fitting a 2nd order polynomial curve to data published in previous literature [63]. A motion analysis system and force plate data were used for the procedure.
Zellmer et al. 2019 [43]	N= 25; Healthy; 25F 22.69 ±0.74 years; Weight: 61.55 ±9.74 kg; Height: 169.39 ±6.44 cm	Patellar	Dynamic exercises: forward step lunge with knee in front of toes, forward step lunge with knee behind toes	Inverse dynamics: Muscle forces were estimated from a musculoskeletal model. The calculated muscle forces were used to quantify the total patellar tendon force by summing the muscle forces of the rectus femoris, vastus medialis, vastu 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 [42]	N= 5; Healthy; 2M, 3F; 19-24 years (mean 22); Weight: 58-84 kg (mean 72); Height: 168-200 cm (mean 180)	Patellar	Dynamic exercises: single-leg decline squats at 0°, 5°, 10°, 15°, 20°, 25° and 30° (with and without a backpack of 10 kg)	Inverse dynamics: Normalised patellar tendon forces were estimated according to the following formula: F_{tendon} = 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 [64]. A motion analysis system and force plate data were used for the procedure.
Edsfeldt et al. 2015 [30]	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	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 [29]	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)	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 [31]	N= 12; open carpal tunnel release surgery patients; 4M, 8F; 42 ±10 years	Hand	Dynamic exercises: unresisted finger flexion and extension	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.

Powell and Trail 2004 [48]	N= 33; open carpal tunnel release surgery patients; 54 (24-86) years	Hand	Dynamic exercises: unresisted finger flexion and resisted finger flexion (pulley with weights 100-500g)	Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger; FDP of the ring finger or little finger; FPL of the thumb).
Powell and Trail 2009 [47]	N= 24; open carpal tunnel release surgery patients; 12M, 12F; 57 (23-86) years	Hand	Dynamic exercises: resisted finger flexion (pulley with weights 100-500g) and resisted finger extension (rubber band)	Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger).
Schuind et al. 1992 [49]	N= 5; open carpal tunnel release surgery patients; 3M, 2F	Hand	Dynamic exercises: wrist and fingers flexion and extension	S-shaped force transducers: S-shaped force transducers were applied to the flexor pollicis longus and FDS and FDP tendons of the index finger in five patients operated on for treatment of carpal tunnel syndrome. The experiment was conducted during open carpal tunnel release surgery with local anaesthesia.

CONC: Concentric; ECC: Eccentric; FDP: Flexor digitorum profundus; FDS: Flexor digitorum superficialis; FPL: Flexor digitorum profundus longus; GRF: Ground Reaction Forces; HSR: Heavy Slow Resistance; M: Male; MRI: Magnetic Resonance Imaging; F: Female; %BW: Percentage of body weight

DISCUSSION

The aim of this study was to review the techniques that have been applied in vivo to directly and indirectly estimate the forces and loads transmitted to the human tendon in dynamic exercises commonly used during rehabilitation processes. The main finding of this review is that most studies in dynamic exercises used an indirect method such as inverse dynamics, while there is a lack of direct measurements.

Inverse dynamics

Most of the studies included in this review used inverse dynamics as indirect evaluation of tendon loads and forces. This methodology uses measured kinematics and external forces to indirectly calculate net joint torques and forces in a body segment model [65]. With this system, the problems associated with the introduction of sensors inside the tendon are avoided. However, although this method is widely used, it is suggested that the results obtained differ from the actual due to incorrect modelling assumptions and measurement errors [65]. For example, classical inverse dynamics assumes idealised pin joints and the existence of rigid body segments, and that does not match reality [65]. 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 [65]. These problems have been addressed in recent years, trying to obtain new procedures that limit the inconsistencies of the process [65].

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 [35,37,43], OpenSim [32], FreeBody [33], among others [34,39,42]. These models make more or less precise assumptions that allow us to transform the kinematics and kinetics data into net torques of body segments, with a different margin of error in each of them. Likewise, the studies that used 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 [35,37,43]. This fact could imply an additional error in the estimation. Other models included in this review estimated the tendon forces through a previous estimation of the values of the different moment arms, with some differences both in the models and in the equations used [34,39,42]. Different methods were used for estimating the moment arms. While some studies performed subject-specific calculations based on imaging techniques to minimise error [33,34], others studies used data from previously published literature (e.g. 5 cm ankle moment arm) [32,44]. Some studies used an intermediate method, based on the use of new or previously published equations together with specific data from each patient [36,38,41,42,46]. The method used is relevant because estimating anthropometric parameters for a specific subject on basis of a limited number of anthropometric characteristics combined with data of previously published studies is an additional source of potential error [65].

Despite all the above, modelling approaches have been widely employed to estimate tendon force and stress [51]. Thus, previous studies have used mathematical and modeling approaches for estimating these muscle and force loads [66–70]. The results of this review show that inverse dynamics is also the predominant option for evaluating dynamic exercises, despite being an indirect methodology.

Buckle force transducer

In the last decades, an attempt has been made to develop measurement techniques that allow the forces and loads in the tendon to be directly evaluated. In this context, 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 [22,71–73]. However, the use of this technology is limited due to the need to insert the sensors into the tendon. Thus, transducers must be biotolerable (for short-term measurements) and biocompatible (for long-term use), as well as easy to implant [17]. Devices should avoid to damage body tissues and to alter the tendon and joint mobility and neuromuscular function [17]. These requirements have limited its indications and forced the design of technology of a smaller size.

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 significantly limits the type of patients and situations in which it is applied. Furthermore, in all cases the procedure was carried out after the application of anaesthesia, which together with the surgery procedure itself could have some impact on the measurement results.

Despite the existence of the previously mentioned studies of buckle transducers evaluating dynamic movements (walking, running, cycling, jumping), none of the studies included in this review used this technology to evaluate the forces in the Achilles and patellar tendons during dynamic exercises.

The introduction of the force transducers was carried out during surgery with local anaesthesia. Three modalities of force transducers were applied: buckle force transducer [29–31], s-shaped force transducer [49], and load cell [47,48].

Buckle force transducers technique consisted of a modified version of the method described by Dennerlein et al. (1997) [74]. This device consisted of a 9 x 16 x 4.5 mm stainless steel frame and a removable fulcrum designed to fit inside the carpal canal [29–31]. In this system, each tendon lies in semi-circular arches in the device [29–31]. The S-shaped force transducer consisted of a stainless steel frame combined with four strain gauges attached on its central beam [49]. In the case of load cell, an apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements [47,48]. The central hook was connected to a load cell, recording the applied forces.

Optic fibre sensor

The use of optic fibre sensors appeared as a smaller solution compared to previous force transducers (e.g. E-form and buckle force transducers) [75]. In this way, it was intended to alleviate some existing limitations, trying to reduce the magnitude of the surgical process required for its insertion and the healing process, as well as the possible interference of the sensor during movement [75]. During the last decades, different devices based on optic fibre have been developed and applied to directly measure tendon forces in vivo in humans in isometric contractions [76] and in dynamic activities such as walking or jumping [24,75,77–79]. However, the main limitation of this measurement technique is still the invasiveness of the procedure for introducing and removing the sensor [77]. The procedure is usually performed under local anesthesia, causing a wound of several centimeters in the tissue that can interfere with movement [77]. For this reason, in some cases it is considered to keep the sensor inside the body for several weeks until the wound heals and allows normal activity [77].

In this review, only one study used optic fibre sensors to detect forces in both the anterior and the posterior regions of the proximal patellar tendon [50]. The authors inserted an optic fibre sensor, attached to a transmitter-receiver unit, through the entire cross section of the tendon.

The sensor was introduced under local anaesthesia. Then, tendon forces were registered during dynamic exercises, removing the sensor at the end of all tests [50].

Although in the included studies this was the only direct method in lower limb tendons, the existence of a single study suggests that further study of the matter is still necessary in order to limit its drawbacks.

Strain

In this review, two studies included a strain or differences in tendon length measurement for measuring tendon loads using ultrasound imaging techniques [37,40]. Rees et al. (2008) [40] assessed the differences in tendon length in heel lowering and rising exercises, differentiating between the concentric and eccentric phases of the movement. Revak et al. (2017) [37] evaluated different versions of the heel raising exercise through the tendon strain, using an average Young modulus value of 819 cm.

Several authors have reported a linear relationship between tendon forces and tendon strain using in vitro tensile tests and in vivo ultrasound techniques [19,80–82]. Thus, some studies have used tendon and tendon-aponeurosis strain as load measurement technique in different isometric and dynamic activities [19,83,84]. However, some authors suggest that tendon undergoes non-uniform deformation under in vivo loading conditions [85–87], which would be a limitation for this method.

Other ultrasound-based techniques such as the shear-wave have been used to estimate the forces in the tendon in activities such as walking [88]. However, no studies using these procedures have been identified in the dynamic exercises collected in this review.

Other techniques: Burst vibrations

During the review process, a proof-of-concept study was identified with a novel technique for evaluating forces in tendons [89]. However, the study did not meet the selection criteria. In this work, the feasibility of a technique based on burst vibrations for the evaluation of walking, running, and unilateral and bilateral heel raising was studied. Thus, 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 collect the signals influenced by the tendon tension in the accelerometer [89]. It is suggested that a tendon on which low tension is applied responds to vibration with a steeper rising and falling edge, attributable to faster energy absorption and dissipation [89]. However, a tendon on which high tension is applied responds with a progressive rising and falling edge, attributable to a slower energy absorption and dissipation [89]. Although it has some limitations such as artifacts caused by noise on the skin caused by movement of the limbs [89], its non-invasiveness gives it an advantage over other evaluation methods.

Conclusions

Different evaluation methodologies are used for quantifying forces and loads in dynamic rehabilitation exercises. There is a predominant use of modelling and inverse dynamics, but force transducers, optic fibre, and estimations from strain data are also used.

Practical applications

Although the methods collected in this review allow a direct or indirect estimation of the forces and loads 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 loads in dynamic exercises, but the invasiveness of some methods and the loss of immediacy of others make it difficult to study each patient individually. The field should continue to be developed looking for precise, direct techniques, with less measurement error and less invasiveness.

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Competing interests

None

Data availability statement

No additional data available.

Contributorship Statement

All authors contributed to the study design. AEE and AICV searched and screened the articles, with assistance from JC. All authors contributed to data analysis and interpretation of the data. AEE drafted the manuscript, AICV and JC revised it critically, and all authors contributed to revisions and approved the final manuscript.

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Figure 1. Flow diagram of the selection process.

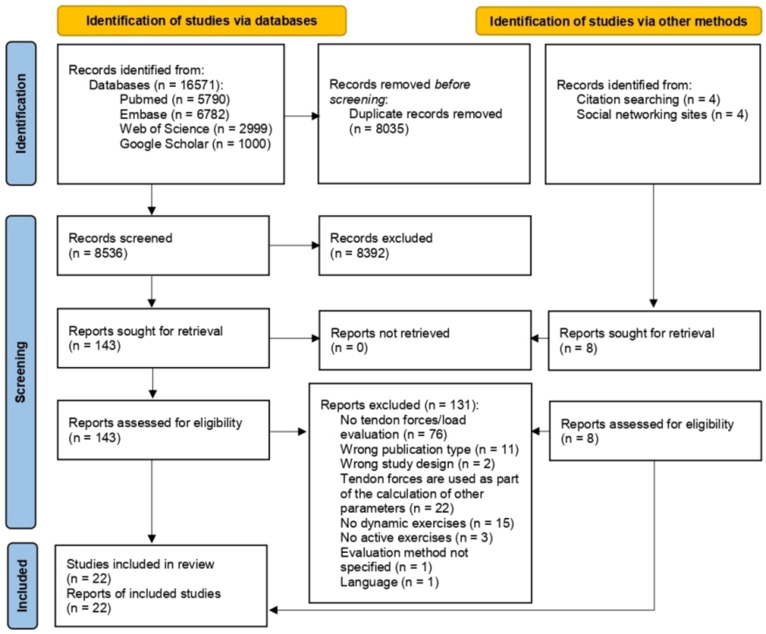

Figure 1. Flow diagram of the selection process.

210x297mm (150 x 150 DPI)

SUPPLEMENTARY FILE

BMJ OPEN

Supplement to: *Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review*

Adrian Escriche-Escuder, Antonio I. Cuesta-Vargas, José Casaña

TABLE OF CONTENTS

Supplementary Appendices

Appendix S1. Detailed information sources and search strategy

	Pubmed	EMBASE	WOS	Google Scholar (200 primeras)
Tendon AND Load	3837	4311		200
Tendon [Title] AND Load [Title]	100	183	536	
Tendon [Title] AND Force [Title]	185	202	297	
Tendon [Title] AND Biomechanics [Title]	90	111	83	
Tendon AND wave	893	1220	1282	200
Tendon [Title] AND Properties [Title]	685	755	801	
Tendon AND Force				200
Tendon AND Biomechanics				200
Tendon AND Properties				200
	5790	**6782**	**2999**	**1000**
Total	**16571**			

Appendix S2. Articles excluded with full-text with reasons

Autor and year	Title	Reasons for exclusion
Acuna et al. 2019	Achilles tendon shear wave speed tracks the dynamic modulation of standing balance	No tendon forces/load evaluation
Aita et al. 1998	The load applied to the foot in a patellar ligament-bearing cast	No tendon forces/load evaluation
Andarawis-Puri et al. 2010	Infraspinatus and supraspinatus tendon strain explained using multiple regression models.	No tendon forces/load evaluation
Ando et al. 2019	Positive relationship between passive muscle stiffness and rapid force production	No tendon forces/load evaluation
Ateş et al. 2015	Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity	No tendon forces/load evaluation
Beck et al. 2020	Cyclically producing the same average muscle-tendon force with a smaller duty increases metabolic rate	No tendon forces/load evaluation
Bobbert et al. 1986	An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping	No tendon forces/load evaluation
Bojsen-Moller et al. 2003	Measuring mechanical properties of the vastus lateralis tendon-aponeurosis complex in vivo by ultrasound imaging	No tendon forces/load evaluation
Bojsen-Møller et al. 2005	Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures	No tendon forces/load evaluation
Bolus et al. 2021	Fit to Burst: Toward Noninvasive Estimation of Achilles Tendon Load Using Burst Vibrations	Proof-of-concept study
Breda et al. 2020	The association between patellar tendon stiffness measured with shear-wave elastography and patellar tendinopathy—a case-control study	No tendon forces/load evaluation
Bruggemann 1985	Mechanical load on the Achilles-tendon during rapid dynamic sport movements	Wrong publication type (Book chapter)
Brum et al. 2013	In Vivo Achilles Tendon Elasticity Assessment using	No tendon forces/load evaluation

	Supersonic Shear Imaging: a feasibility study	
Bujalski et al. 2018	A Monte Carlo analysis of muscle force estimation sensitivity to muscle-tendon properties using a Hill-based muscle model	No tendon forces/load evaluation
Burgess et al. 2007	Plyometric vs. Isometric training influences on tendon properties and muscle output	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cao et al. 2019	A multicenter large-sample shear wave ultrasound elastographic study of the achilles tendon in chinese adults	No tendon forces/load evaluation
Cattagni et al. 2017	No Alteration of the Neuromuscular Performance of Plantar-Flexor Muscles After Achilles Tendon Vibration	No tendon forces/load evaluation
Centner et al. 2019	Low-load blood flow restriction training induces similar morphological and mechanical Achilles tendon adaptations compared with high-load resistance training	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Chang et al. 2020	Strain ratio of ultrasound elastography for the evaluation of tendon elasticity	No tendon forces/load evaluation
Cheung et al. 2006	Effect of Achilles tendon loading on plantar fascia tension in the standing foot.	No dynamic exercises (No exercises evaluated)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cruz-Montecinos et al. 2015	Estimation of tensile properties of the Achilles tendon in haemophilic arthropathy of the ankle: case study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cruz-Montecinos et al. 2019	Assessment of tensile mechanical properties of the Achilles tendon in adult patients with haemophilic arthropathy. Reproducibility study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Deforth et al. 2019	The effect of foot type on the Achilles tendon moment arm and biomechanics	No tendon forces/load evaluation

Delp et al. 2007	OpenSim: open-source software to create and analyze dynamic simulations of movement.	Wrong publication type
Dennerlein et al. 1999	In vivo finger flexor tendon force while tapping on a keyswitch	No dynamic exercises (everyday tasks)
Ebrahimi et al. 2020	Shear Wave Tensiometry Reveals an Age-Related Deficit in Triceps Surae Work at Slow and Fast Walking Speeds	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Ejeskar et al. 1982	Finger flexion force and hand grip strength after tendon repair	No tendon forces/load evaluation
Firminger et al. 2019	Effect of Shoe and Surface Stiffness on Lower Limb Tendon Strain in Jumping	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Fowler and Nicol 2000	Interphalangeal joint and tendon forces: normal model and biomechanical consequences of surgical reconstruction	No dynamic exercises (everyday tasks)
Fowler et al. 1999	Measurement of external three-dimensional interphalangeal loads applied during activities of daily living	No tendon forces/load evaluation
Friesenbichler et al. 2019	Gait and strength asymmetries in patients with insertional achilles tendinopathy	No tendon forces/load evaluation
Fröberg et al. 2020	The Effect of Ankle Foot Orthosis' Design and Degree of Dorsiflexion on Achilles Tendon Biomechanics-Tendon Displacement, Lower Leg Muscle Activation, and Plantar Pressure During Walking	No tendon forces/load evaluation
Gerus et al. 2011	A method to characterize in vivo tendon force-strain relationship by combining ultrasonography, motion capture and loading rates	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Gerus et al. 2012	Subject-Specific Tendon-Aponeurosis Definition in Hill-Type Model Predicts Higher Muscle Forces in Dynamic Tasks	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Giacomozzi et al. 2015	Does the thickening of Achilles tendon and plantar fascia	No tendon forces/load evaluation

	contribute to the alteration of diabetic foot loading?	
Gomes et al. 2020	Is there a relationship between back squat depth, ankle flexibility, and Achilles tendon stiffness?	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hager et al. 2020	Influence of joint angle on muscle fascicle dynamics and rate of torque development during isometric explosive contractions.	No tendon forces/load evaluation
Hansen et al. 2006	Mechanical properties of the human patellar tendon, in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Harding et al. 1993	Finger joint force minimization in pianists using optimization techniques	No dynamic exercises (everyday tasks)
Harlaar et al. 2020	Patellofemoral joint contact forces at different activities - effects of modeling assumptions	No tendon forces/load evaluation
Harnie et al. 2020	Acute effect of tendon vibration applied during isometric contraction at two knee angles on maximal knee extension force production	No tendon forces/load evaluation
Hashizume and Yanagiya 2016	Influences of the foot strike pattern and the running speed on the forces applied to foot	Wrong publication type (Conference proceeding)
Haufe et al. 2020	Biomechanical effects of passive hip springs during walking	No tendon forces/load evaluation
Hauraix et al. 2015	In vivo maximal fascicle-shortening velocity during plantar flexion in humans.	No tendon forces/load evaluation
Heinemeier et al. 2016	Methods of Assessing Human Tendon Metabolism and Tissue Properties in Response to Changes in Mechanical Loading	Wrong publication type (Book chapter)
Helland et al. 2013	Mechanical properties of the patellar tendon in elite volleyball players with and without patellar tendinopathy.	No tendon forces/load evaluation
Histen et al. 2017	Achilles Tendon Properties of Minimalist and Traditionally Shod Runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

Hoang et al. 2007	Passive mechanical properties of human gastrocnemius muscle-tendon units, muscle fascicles and tendons in vivo	No dynamic exercises
Hof et al. 2002	Mechanics of human triceps surae muscle in walking, running and jumping	No tendon forces/load evaluation
Holzer et al. 2020	Considerations on the human Achilles tendon moment arm for in vivo triceps surae muscle-tendon unit force estimates	Wrong study design (calculations using results from other studies)
Homayuouni et al. 2015	Modeling Implantable Passive Mechanisms for Modifying the Transmission of Forces and Movements Between Muscle and Tendons	No tendon forces/load evaluation
Hopper et al. 2015	Dance floor force reduction influences ankle loads in dancers during drop landings.	No tendon forces/load evaluation
Hu et al. 2014	Biomechanical Analysis of Force Distribution in Human Finger Extensor Mechanisms	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hullfish et al. 2020	A simple instrumented insole algorithm to estimate plantar flexion moments	No tendon forces/load evaluation
Jones et al. 1985	Effect of muscle tendon vibration on the perception of force	No tendon forces/load evaluation
Joseph et al. 2014	Achilles tendon biomechanics in response to acute intense exercise.	No dynamic exercises
Kathy Cheng et al. 2008	Finite element analysis of plantar fascia under stretch—The relative contribution of windlass mechanism and Achilles tendon force	Wrong study design (Finite element analysis)/ No tendon forces/load evaluation
Kawakami et al. 2002	Effect of series elasticity on isokinetic torque-angle relationship in humans.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Kaya and Yucesoy 2020	Muscle-tendon unit length-spastic muscle force data by combined intraoperative-musculoskeletal modelling work	No tendon forces/load evaluation
Kernozek et al. 2016	Comparing Two Methods for Estimating Achilles Tendon Loading during Running	Wrong publication type (Conference proceeding)

Kernozek et al. 2018	The effects of habitual foot strike patterns on Achilles tendon loading in female runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Kongsgaard et al. 2006	Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats	No dynamic exercises
Kouno et al. 2019	Effects of the strain rate on mechanical properties of tendon structures in knee extensors and plantar flexors in vivo	No dynamic exercises
Kruse et al. 2019	Effects of serial casting on muscle-tendon properties, muscle function and gait in a healthy child with calf muscle shortening	No tendon forces/load evaluation
Kubo et al. 1999	Influence of elastic properties of tendon structures on jump performance in humans	No tendon forces/load evaluation
Kubo et al. 2000	Elastic properties of muscle-tendon complex in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2001	Influence of static stretching on viscoelastic properties of human tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2002	Measurement of viscoelastic properties of tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2003	Gender differences in the viscoelastic properties of tendon structures	No tendon forces/load evaluation
Kubo et al. 2005	Effects of cold and hot water immersion on the mechanical properties of human muscle and tendon in vivo.	No dynamic exercises
Kubo et al. 2015	Relationship between elastic properties of tendon structures and performance in long distance runners	No tendon forces/load evaluation
Kubo et al. 2015	Relationship between Achilles tendon properties and foot strike patterns in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2020	Mechanical properties of muscle and tendon at high strain rate in sprinters	No tendon forces/load evaluation

Lee et al. 2015	Repeatability and agreement of digital image correlation (DIC) for regional strain estimates of the in-vivo human patellar tendon	No tendon forces/load evaluation
Lian et al. 1996	Characteristics of the leg extensors in male volleyball players with jumper's knee	No tendon forces/load evaluation
Lian et al. 2003	Performance characteristics of volleyball players with patellar tendinopathy	No tendon forces/load evaluation
Lichtwark et al. 2006	Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Lichtwark et al. 2011	Achilles tendon (3D): Do the mechanical properties of tendon change in response to exercise?	Wrong publication type (Conference proceeding)
Lima et al. 2017	Triceps surae elasticity modulus measured by shear wave elastography is not correlated to the plantar flexion torque	No tendon forces/load evaluation
Lu et al. 2013	Quantifying Catch-and-Release: The Extensor Tendon Force Needed to Overcome the Catching Flexors in Trigger Fingers	No dynamic exercises (everyday tasks)
Mademli et al. 2008	Age-related effect of static and cyclic loadings on the strain-force curve of the vastus lateralis tendon and aponeurosis	No dynamic exercises
Marouane et al. 2017	Changes in Knee Adduction Rotation and not Adduction Moment Influence Joint Compartmental Load Partitioning	Wrong publication type (Conference proceeding)
Martin et al. 2012	Effects of the index finger position and force production on the flexor digitorum superficialis moment arms at the metacarpophalangeal joints - a magnetic resonance imaging study.	No tendon forces/load evaluation
Martin et al. 2018	Gauging force by tapping tendons	No tendon forces/load evaluation
Matsubayashi et al. 2008	Ultrasonographic measurement of tendon displacement caused	No tendon forces/load evaluation

	by active force generation in the psoas major muscle	
McCrum et al. 2018	Loading rate and contraction duration effects on in vivo human Achilles tendon mechanical properties	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McMahon et al. 2013	The manipulation of strain, when stress is controlled, modulates in vivo tendon mechanical properties but not systemic TGF-β1 levels	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McNair et al. 2013	Biomechanical properties of the plantar flexor muscle-tendon complex 6 months post-rupture of the Achilles tendon	No tendon forces/load evaluation
Mileusnic et al. 2009	Force estimation from ensembles of Golgi tendon organs	No tendon forces/load evaluation
Mimura 1986	[The load-bearing function of a patellar tendon bearing cast]	No tendon forces/load evaluation
Monte 2021	In vivo manipulation of muscle shape and tendinous stiffness affects the human ability to generate torque rapidly	No tendon forces/load evaluation
Nicol et al. 1998	Significance of passively induced stretch reflexes on achilles tendon force enhancement	No active exercises evaluated
Nicol et al. 1999	Quantification of Achilles tendon force enhancement by passively induced dorsiflexion stretches	No active exercises evaluated
Okuyama et al. 2019	Study on fingertip force sensor based on measurement of tendon tension	Tendon forces are used as part of the calculation of other parameters
Olszewski et al. 2015	Achilles tendon moment arms: the importance of measuring at constant tendon load when using the tendon excursion method.	No dynamic exercises
Pearson et al. 2013	The use of normalized cross-correlation analysis for automatic tendon excursion measurement in dynamic ultrasound imaging.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Peltonen et al. 2013	Viscoelastic properties of the Achilles tendon in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

Perl et al. 2012	Effects of Footwear and Strike Type on Running Economy	No tendon forces/load evaluation (no data)
Petrescu et al. 2016	Evaluation of normal and pathological Achilles tendon by real-time shear wave elastography	No tendon forces/load evaluation (no data)
Rowley et al. 2000	The effect of the patellar tendon-bearing cast on loading	No tendon forces/load evaluation
Salman et al. 2019	Spatial Variations in Achilles Tendon Shear Wave Speed Using a Cost-Effective Method of Accelerometers	Wrong publication type (Conference proceeding)
Saltzman et al. 1992	The patellar tendon-bearing brace as treatment for neurotrophic arthropathy: a dynamic force monitoring study.	No tendon forces/load evaluation
Sasaki et al. 2019	Electromyographic analysis of infraspinatus and scapular muscles during external shoulder rotation with different weight loads and positions.	No tendon forces/load evaluation
Sheehan et al. 2000	Human patellar tendon strain. A noninvasive, in vivo study	No tendon forces/load evaluation
Sinsel et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation during exercises
Slane et al. 2014	Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading	No tendon forces/load evaluation
Stafilidis et al. 2007	Muscle-tendon unit mechanical and morphological properties and sprint performance	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Stanojev et al. 2018	Effects of patellar tendon strap bracing on the motor performance and biomechanics of healthy adolescent athletes	Wrong publication type (Conference proceeding)
Stegman et al. 2009	A feasibility study for measuring accurate tendon displacements using an audio-based Fourier analysis of pulsed-wave Doppler ultrasound signals.	Wrong publication type (Conference proceeding)
Sugisaki et al. 2011	Effect of muscle contraction levels on the force-length relationship of the human Achilles tendon during	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

	lengthening of the triceps surae muscle-tendon unit	
Sussmilch-Leitch et al. 2012	Effect of foot orthoses on ankle kinematics and kinetics in male runners with Achilles tendinopathy	Wrong publication type (Conference proceeding)
Taniguchi 1988	[The load bearing function of patellar tendon bearing brace--on the relation between shaft length and rate of load bearing]	No tendon forces/load evaluation
Thomeer et al. 2020	Load Distribution at the Patellofemoral Joint During Walking.	No tendon forces/load evaluation
Totorean et al. 2014	The role of plantar pressure evaluation in rehabilitation of patients with Achilles tendon ruptures	No tendon forces/load evaluation
Ullrich et al. 2010	Influence of length-restricted strength training on athlete's power-load curves of knee extensors and flexors	No tendon forces/load evaluation
Ushiyama et al. 2005	Difference in aftereffects following prolonged Achilles tendon vibration on muscle activity during maximal voluntary contraction among plantar flexor synergists	No tendon forces/load evaluation
Veeger et al. 2002	Load on the shoulder in low intensity wheelchair propulsion.	No tendon forces/load evaluation
Wearing et al. 2019	Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait?	No tendon forces/load evaluation
Wearing et al. 2020	Transmission-Mode Ultrasound for Monitoring the Instantaneous Elastic Modulus of the Achilles Tendon During Unilateral Submaximal Vertical Hopping	No tendon forces/load evaluation
Werkhausen et al. 2018	Effect of training-induced changes in achilles tendon stiffness on muscle–tendon behavior during landing	No tendon forces/load evaluation
Werkhausen et al. 2019	Distinct muscle-tendon interaction during running at different speeds and in different loading conditions.	No tendon forces/load evaluation
Westphal et al. 2013	Load-Dependent Variations in Knee Kinematics Measured with Dynamic MRI	No dynamic exercises (No exercises are used)

Woodburn et al. 2013	Achilles tendon biomechanics in psoriatic arthritis patients with ultrasound proven enthesitis	The method of evaluating tendon forces is not specified.
Wretenberg et al. 1993	Passive knee muscle moment arms measured in vivo with MRI	No active exercises
Wu et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation
Yamaguchi et al. 2002	Effect of different frequencies of skipping rope on elastic components of muscle and tendon in human triceps surae	Wrong language (Japanese)
Yamamoto et al. 2020	Effects of Varying Plantarflexion Stiffness of Ankle-Foot Orthosis on Achilles Tendon and Propulsion Force during Gait	No tendon forces/load evaluation
Yoshitake et al. 2004	Fluctuations in plantar flexion force are reduced after prolonged tendon vibration	No tendon forces/load evaluation

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	5
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	5
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	6
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	5
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	5
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	7
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	7
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	7
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	7

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SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	8
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	8
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	9
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	16
Limitations	20	Discuss the limitations of the scoping review process.	21
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	21
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	22

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.
* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.
† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).
‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.
§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Modelling and in vivo evaluation of tendon forces, stress, and strain in dynamic rehabilitation exercises: a scoping review

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Title: Modelling and in vivo evaluation of tendon forces, stress, and strain in dynamic rehabilitation exercises: a scoping review

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Modelling and in vivo evaluation of tendon forces, stress, and strain in dynamic rehabilitation exercises: a scoping review

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, stress, 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 or longitudinal studies available in English or Spanish language were included if they focused on evaluating the forces, stress, or strain of human tendons in vivo during dynamic exercises. They were excluded if did not described being evaluating the tendon; if not evaluated dynamic exercises other than running, walking, jumping or landing; 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 or tendon length using ultrasound imaging 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, the invasiveness of some methods and the loss of immediacy of others make it difficult to provide immediate feedback to the individuals measured.

Keywords: Foot & ankle; hand & wrist; musculoskeletal disorders; rehabilitation medicine; sports medicine

Strengths and limitations of the study

- The extensive search carried out in this review in four of the main databases allows the reader to approach a wide field of knowledge.
- This review provides a summary of the available literature on the study of forces, stress, and strain that act on the tendon during dynamic exercises.
- Grouping the assessment tools into subgroups allows an analysis of the advantages and disadvantages of each option.
- Some studies might not have been identified due to the difficulty in tracking the literature because of the variety of terms used.

INTRODUCTION

Tendinopathy is the preferred term for persistent tendon pain and loss of function related to mechanical loading[1]. 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[2].

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[2]. Thus, loading intervention through a progressive exercise programme is considered an essential part of the management of tendinopathies due to the vast evidence published in the last decades[3,2,4–6]. These approaches focus on producing adequate stimulus that generate adaptations and increase the tolerance of the tendon and other body tissues and systems to load and exercise[3,7]. Regarding the adaptations in the tendon, research data suggests that tenocytes respond to adequate or excessive/insufficient mechanical loading (i.e. tendon strain) by inducing anabolic and catabolic processes of matrix proteins, respectively, through a process known as mechanotransduction[7–11].

Different exercise modalities and intensities have been applied in tendinopathy with reasonably good results[6,12–14]. Likewise, different strategies have been implemented for handling and modifying the applied loads[15–17]. However, although concepts such as repetition maximum (RM) 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. For both prevention and treatment of tendinopathy, proper load management would benefit from a greater understanding of the loads that act on the tendon during exercises. Thus, this knowledge could provide direct evidence for activity selection, ensuring that the strain levels produced are within the appropriate spot to elicit the desired adaptations[7].

In the analysis of the loads that act on the tendon, it is relevant to differentiate between concepts such as force, stress and strain. Despite the relationship between the concepts of force and stress, the basic difference is that force is the external action applied to a body, while tension stress is the resistance force developed by the body to resist deformation (force on a body per unit area)[18]. Therefore, stress depends on the mechanical properties of the body and varies between different tendons and contexts for a given force. The resulting deformation can be in the form of a change in length (if tensile stress), volume (if compressional stress), and shape (if shear stress) of the affected body. In this regard, research data suggests that human tendons usually have a fracture stress of approximately 100 N/m^2[19]. This value offers a safety margin since, in practice, most tendons are not usually subject to stresses greater than 30 N/m2 (tendons such as the Achilles sometimes experience stresses of up to 70 N/m^2)[19]. Finally, if stress is related to the resistance force and is measured in N/m^2, strain refers to a measure of the extent to which a body is deformed due to this stress[18]. Thus, strain will also have a different nature depending on the stress that produces it (e.g. tensile or compressive strain). Although tendons are subjected to compression, tension, or shear forces in daily activities[20,21], it is the tensile load (and the strain it produces) that plays a leading role in the function of the tendon[22]. Therefore, the evaluation of the tensile stress and strain is especially relevant for the study of the loading programmes[23].

Regardless of the parameter evaluated, it is important to take into account a factor that makes this study difficult: tendons are not uniaxial structures but are usually made up of different bundles[24]. This causes regional variations in mechanical properties, and the distribution of forces and strains throughout the tissue is not uniform[25]. Tendon forces have been calculated through in vitro studies[26], as well as have been estimated through in vivo indirect calculations based on body position, joint reaction forces, and inverse dynamic models[27–29]. 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[25].

Medical imaging techniques such as ultrasound or magnetic resonance imaging have previously made it possible to directly measure strain during isometric contractions[30], walking[31,32], running[29,33], and hopping[34]. However, transducer position may affect ultrasound measurements significantly, and it is necessary a rigid fixation over the tissue that may alter movement patterns[35]. Therefore, its use in some dynamic activities is still limited.

Internal tendon stress cannot be directly measured non-invasively[36]. It can be evaluated in vitro or estimated from tendon forces (e.g. calculated by dividing the tendon force by the subject's cross-sectional area[37–39]) with the help of biomechanical models. However, these calculations are subject to large errors due to their dependence on the accuracy of some assumptions about the tendon's mechanical properties[36].

Some reviews have been previously published focused on the evaluation of tendon loads (especially forces and strain)[25,35]. These reviews are not specific to dynamic rehabilitation exercises and include mainly methods developed for the study of isometric contractions[30,40] or cyclic activities such as running[41,42], cycling[27,43], or walking[44,45]. 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[35]. 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 to, directly and indirectly, estimate the forces, stress, and strain that act on the human tendon in dynamic exercises commonly used during rehabilitation processes.

MATERIAL AND METHODS

This scoping review was undertaken following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines[46]. 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[47] for biomedical reviews, four databases were searched by two reviewers (A.E-E, J.C.G.) 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 Supplementary 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, stress, 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; (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 (A.E-E) to exclude clearly irrelevant articles. Finally, two reviewers (A.E-E, J.C.G.) screened the full texts of identified articles to select those that met the eligibility criteria. A third reviewer solved any disagreements (A.I.C.V).

Data extraction

Two reviewers (A.E-E, J.C.G.) 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; tendon forces/stress/strain results.

In this review, they were included those studies that analysed the forces, stress, 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 analysis

Current guidelines on conducting a scoping review describe the inclusion of a methodological quality analysis as not necessary[48,49]. 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 focus on analysing the forces, stress, 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

Patients were not involved in this research.

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, only 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 Supplementary Appendix 2.

[Figure 1 near here]

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[50–52] (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, indirect stress estimations, 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.

Table 1. Forces, stress and strain evaluation methodologies identified in the included studies.

Measurement methodology	Tendon	References
Forces		
Inverse dynamics	Achilles	[37,39,53–59]
	Patellar	[60–64]
Force transducers	Hand	Buckle [50–52]
(Buckle force transducer, S-shaped		Load cell [65,66]
force transducer, load cell)		S-shaped [67]
Optic fibre sensors	Patellar	[68]
Strain		
Ultrasound imaging	Achilles	[37,55,58]
	Quadriceps	[63]
Stress		
Indirectly (from force and cross-	Achilles	[37,39]
sectional area)	Patellar	[61]

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[38]. Moment arms are estimated from previous literature data or estimated specifically for each patient through imaging techniques such as magnetic resonance imaging or ultrasound.

Most of the included studies used motion capture systems for kinematics, while force plates were the most used device for obtaining kinetic data. Some studies used generic moment arms based on the published literature[53,62], other used previously described procedures and equations[56,59,60,64], while other estimated subject-specific moment arms based on imaging techniques[54,55]. Kinematic and kinetic data were integrated into different musculoskeletal models: three studies[37,39,61] used the Human Body Model[69], one[53] study used the OpenSim model[70], one study[54] used the FreeBody model[71], while other studies[55,57,60] 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)[53,54]. The single-leg heel raising and lowering obtained values between 3-5.12 BW for the Achilles tendon[39,53,54,57]. 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[62,64].

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[50–52], s-shaped force transducer[67], and load cell[65,66].

The buckle force transducers technique used in three of the studies[50–52] consisted of a modified version of the method described by Dennerlein et al. (1997)[72]. This device consisted of a 9 x 16 x 4.5 mm stainless steel frame and a removable fulcrum designed to fit inside the carpal canal[50–52]. In this system, each tendon lies in semi-circular arches in the device[50–52]. These studies evaluated unresisted finger flexion and extension at different wrist angles, obtaining a range of mean values between 1.3 N – 25.5 N for the flexor digitorum profundus (range -1.6 N – 74.7 N) and 1.3 N – 12.9 N (range -2.0 N – 47.53 N) for the flexor digitorum superficialis[50–52]. The S-shaped force transducer consisted of a stainless steel frame combined with four strain gauges attached on its central beam[67]. This study obtained values between 0 and 12.0 kgf (117.7 N, obtained with the active tip pinch) in the evaluation of different finger and wrist flexion and extension exercises[67]. In the case of load cell, an apparatus consisting of three vertical rods, each terminating in a ''hook' was used for the tendon force measurements[65,66]. The central hook was connected to a load cell, recording the applied forces. These studies evaluated different finger flexion and extension exercises, with and without resistance, obtaining values in a range between 1 N and 50 N (resisted finger flexion, 300 g)[65,66].

Optic fibre sensor

Dillon et al. (2008)[68] 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[68]. 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[68]. In this study the sensors were not calibrated to record forces in N. Therefore, the data is only available through the differential output of the fibre signal[68]. 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)[68].

Strain as a load measure

Four studies[37,55,58,63] carried out additional measurements for quantifying loads on the tendon through strain or elongation measurement. Rees et al. (2008)[58] and Chaudhry et al. (2015)[55] 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 al. (2008)[58] established and tracked the position of these anatomical sites in terms of 3D coordinates over time by using an active marker motion analysis system through a previously detailed methodology[34]. Chaudhry et al. (2015) implemented an algorithm that provides an intensity map of the ultrasound images, from which the 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, also known as zero-length. To do this, it is necessary to define what is the position for the zero-length, which is usually done in the neutral position of the joint. In these studies, standing eccentric heel-drop and concentric heel-raises exercises were assessed, both phases performed with bent and extended knee[55,58]. In the study by Rees et al., during eccentric heel lowering the Achilles tendon length increased (13.6mm on average) through the movement and during concentric heel rise AT length decreased (14.9mm on average)[58]. Chaudhry et al. (2015)[55] obtained different temporal strain during the eccentric phase (with approximately 8 mm of peak mean elongation) than during the concentric phase (approximately 7 mm), but these differences were equalised when plotting for the normalised position. Therefore, these findings were attributed to the dynamics of the movement[55,58]. Earp et al. (2016)[63] estimated the myotendinous unit length using previous models based on joint position and individual limb lengths. This information was used to compare different ways of performing the squat, analysing the tendon lengthening pattern during the concentric and eccentric phases[63]. Revak et al. (2017)[37] estimated the tendon strain using the average Young modulus value (819 N/mm^2) reported in previous literature[73]. First, the Achilles tendon stress was calculated by dividing the tendon force (estimated using inverse dynamics) by the cross-sectional area of each participant[37]. Then, the tendon strain was calculated by dividing the tendon stress by the Young modulus. In this case, ultrasound was used to measure the cross section of the tendon (not during exercises)[37]. The strain values obtained (expressed in %) were between 0.71±0.35 and 8.80±0.35, corresponding to the seated heel raising and lowering and the unilateral heel raising and lowering exercises, respectively[37].

Stress

The tendon stress was calculated in three of the included studies, two of them in the Achilles tendon [37,39] and one in the patellar one[61]. In all cases, the tendon stress was indirectly calculated by dividing the estimated tendon force by the specific cross-sectional area.

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 including this type of exercises[53,55,39,37,58,57,54]. In patellar tendon disorders, different modalities of squats are commonly prescribed, as well as exercises involving knee flexion and extension.

Eight[39,53,56,60,62–64,68] and two[59,68] studies analysed these types of exercises, respectively. Another exercise commonly applied for lower limb disorders such as lunge was analysed in two studies[39,61]. Three studies analysed step-up and step-down exercises or stairs climbing[53,59,68]. Finally[50–52,65–67]. Table 2 includes the type of exercises analysed in each study.

Table 2. Characteristics of the included studies.

Autor and year	Population	Tendon	Type of exercise	Evaluated parameter and evaluation methodology
Baxter et al. 2021 [53]	N= 8; Healthy; 6M, 2F; 30 ±4 years; BMI: 24.1 ±3.2	Achilles	Dynamic exercises: seated single-legged heel raise with 15 kg 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 bodyweight. Musculoskeletal model: OpenSim. A motion analysis system and force plate data were used for the procedure.
Chaudhry et al. 2015 [55]	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 center 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 code. A motion analysis system and force plate data were used for the procedure. **Strain:** Tendon length was calculated as the distance between the Achilles tendon insertion and the distal MTJ of the medial gastrocnemius (ultrasonography and active motion analysis system).
Gheidi et al. 2018 [39]	N= 18; Healthy; 18M; 22.1 ±1.8 years; Weight: 74.29 ±11.3 kg; Height: 177.7 ±8.4 cm	Achilles	Dynamic exercises: unilateral and bilateral heel raising, squat, lunge	**Force:** Inverse dynamics: Muscle forces were estimated from a musculoskeletal model. Moment arms were based on previous literature (graphics-based model) [74]. 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. **Stress:** The AT stress was calculated by dividing the AT force by the participant specific AT cross-sectional area.
Rees et al. 2008 [58]	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. **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).
Revak et al. 2017 [37]	N= 21; Healthy; 21M; 21.59 ±1.92 years; Weight: 75.81 ±1.24 kg; Height: 178.22 ±8.02 cm	Achilles	Dynamic exercises: seated bilateral heel raising and lowering, standing bilateral heel raising and lowering, unilateral heel raising and lowering, and bilateral heel raising and unilateral 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. **Stress:** tendon stress was calculated by dividing the Achilles tendon force by the individual cross-sectional area. **Strain:** Strain was indirectly calculated by dividing the tendon stress by the average Young modulus of 819 N/mm2 reported in previous literature.
Sinclair et al. 2015 [56]	N= 18; Healthy; 18M; 23.61 ±4.17 years; Weight: 75.63 ±6.54 kg; Height: 178 ±10 cm	Achilles	Dynamic exercises: back and front squat	**Force;** Inverse dynamics: The Achilles tendon load (ATL) was determined by dividing the plantar flexion moment (MPF) by the estimated Achilles tendon moment arm (MA): ATL = MPF / MA. The moment arm was quantified as a function of the ankle sagittal plane angle using a procedure described in previous literature [75]. A motion analysis system and force plate data were used for the procedure.
Weinert-Aplin et al. 2015 [57]	N= 19; Healthy; 8M, 11F; M: 28 ±3 years; Weight: 73.4 ±12 kg; Height: 176 ±10 cm F: 29 ±6 years; Weight: 58.7 ±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 inter-segmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics [76]. 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 al. 2021 [54]	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, 160 of %BW); seated heel drop and rise (13, 21-28, 38, 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 al. 2008 [68]	N= 7; Healthy; 7M; 26.4 ±3.9 years; BMI: 24.8 ±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.
Earp et al. 2016 [63]	N= 10; Healthy; 10M; 25.8 ±2.8 years; Weight: 83.8 ±9.4 kg; Height: 177 ±6 cm	Patellar	Dynamic exercises: depth back squat lifts with 60% of 1RM at three different speeds: slowfixed-tempo, volitional-speed without a pause, and maximum-speed jump)	**Force:** Inverse dynamics: Patellar tendon forces were estimated by multiplying knee moment by the joint-derived moment arm length of the patella; as determined using a previously published model [77]. 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 previously published literature [78]. A motion analysis system and force plate data were used for the procedure. **Strain:** Myotendinous unit length was estimated using previous models based on joint position and individual limb lengths. The quadriceps tendon length of the tendinous was calculated as the longitudinal length of the recorded fascicle subtracted from the myotendinous unit length.

Frohm et al. 2007 [62]	N_{Total}= 14; Healthy; 14M N_1: 13; 36 ±9 years; Weight: 87 ±4 kg; Height: 183 ±5 cm N_2: 11; 39 ±10 years; Weight: 87 ±5 kg; Height: 183 ±5 cm	Patellar	Dynamic exercises: eccentric squats holding a weight (barbell disc) of 10 kg in decline board and horizontal surface, eccentric squat in Bromsman device in decline board and horizontal surface	**Force:** Inverse dynamics: Patellar tendon force 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 [79]. A motion analysis system and force plate data were used for the procedure.
Reilly and Martens 1972 [59]	N= 3; Heathy; 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 mathematical formulation with experimentally determined parameters (strain gage instrumented force plate). Moment arm of the patellar tendon force were measured from roentgenograms. A stroboscopic photography system and force plate data were used for the procedure.
Richards et al. 2016 [64]	N= 18; Healthy; 9M, 9F; 20-46 years; Weight: 75.1 kg (58.3-100)	Patellar	Dynamic exercises: decline squats at different angles of declination (0°, 5°, 10°, 15°, 20° and 25°)	**Force:** Inverse dynamics: Patellar tendon force (PTF) was determined by dividing the extensor moment (ME) by the tendon moment arm (PTMA): PTF = ME / PTMA. The moment arm was quantified as a function of the knee flexion angle by fitting a 2nd order polynomial curve to data published in previous literature [80]. A motion analysis system and force plate data were used for the procedure.
Zellmer et al. 2019 [61]	N= 25; Healthy; 25F 22.69 ±0.74 years; Weight: 61.55 ±9.74 kg; Height: 169.39 ±6.44 cm	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 patellar tendon force 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. **<u>Stress:</u>** tendon stress was calculated by dividing the patellar tendon force by the cross-sectional area.
Zwerver et al. 2007 [60]	N= 5; Healthy; 2M, 3F; 19-24 years (mean 22); Weight: 58-84 kg (mean 72); Height: 168-200 cm (mean 180)	Patellar	Dynamic exercises: single-leg decline squats at different angles of declination (0°, 5°, 10°, 15°, 20°, 25° and 30°) with and without a backpack of 10 kg	**Force:** Inverse dynamics: Normalised patellar tendon forces were estimated according to the following formula: F_{tendon} = 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 [81]. A motion analysis system and force plate data were used for the procedure.
Edsfeldt et al. 2015 [51]	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 [50]	N= 12; open carpal tunnel release surgery patients; 4M, 8F;	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

	42 ±10 years			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 [52]	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.
Powell and Trail 2004 [66]	N= 33; open carpal tunnel release surgery patients; 54 (24-86) years	Hand	Dynamic exercises: unresisted finger flexion and resisted finger flexion (pulley with weights 100-500g)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger; FDP of the ring finger or little finger; FPL of the thumb).
Powell and Trail 2009 [65]	N= 24; open carpal tunnel release surgery patients; 12M, 12F; 57 (23-86) years	Hand	Dynamic exercises: resisted finger flexion (pulley with weights 100-500g) and resisted finger extension (rubber band)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger).
Schuind et al. 1992 [67]	N= 5; open carpal tunnel release surgery patients; 3M, 2F	Hand	Dynamic exercises: wrist and fingers flexion and extension	**Force:** S-shaped force transducer: S-shaped force transducers were applied to the flexor pollicis longus and FDS and FDP tendons of the index finger in five patients operated on for treatment of carpal tunnel syndrome. The experiment was conducted during open carpal tunnel release surgery with local anaesthesia.

CONC: Concentric; ECC: Eccentric; FDP: Flexor digitorum profundus; FDS: Flexor digitorum superficialis; FPL: Flexor digitorum profundus longus; GRF: Ground Reaction Forces; HSR: Heavy Slow Resistance; M: Male; MRI: Magnetic Resonance Imaging; MTJ: Myotendinous junction; F: Female; %BW: Percentage of body weight

DISCUSSION

The aim of this study was to review the techniques that have been applied in vivo to estimate the forces, stress, 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[82]. 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[83]. 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[82]. For example, classical inverse dynamics assumes idealised pin joints and the existence of rigid body segments, and that does not match reality[82]. 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[82].

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[37,39,61], OpenSim[53], FreeBody[54], among others[55,57,60]. 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[37,39,61]. 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[83]. 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[55,57,60]. Some studies performed subject-specific calculations based on imaging techniques to minimise error[54,55], and others studies used data from previously published literature (e.g. 5 cm ankle moment arm)[53,62]. Alternatively, some studies used an intermediate method based on the use of new or previously published equations together with specific data from each patient[56,59,60,64]. 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[83,84], and, sometimes, this value is not scaled to the rest of the anatomical structures[83,85]. 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[86]. 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[83,85]. 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°)[83,84]. Likewise, these differences could translate into up to 67% differences in the estimated values of tendon force[83,84].

Despite all the above mentioned limitations, modelling approaches have been widely employed to estimate tendon forces[38]. 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.[35] Sensors must be biotolerable (for short-term measurements) and biocompatible (for long-term use), as well as easy to implant[25]. Additionally, devices should avoid damaging body tissues and alter the tendon and joint mobility and neuromuscular function[25]. It has been suggested that these sensors should also be flexible and allow wireless data transmission to facilitate their clinical use[35]. 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[87]. Additionally, potential complications such as local pain or infections have limited the use of this methodology to a restricted research population[87].

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[43,88–90]. This kind of transducer consists of a metallic buckle with strain gages through which a tendon is

looped[25]. When a tensile force is applied to the tendon, the buckle deforms and produces a voltage output proportional to the force[25]. Due to their configuration, these buckle transducers facilitate the measurement of the entire cross-section of the tendon[25]. This is an advantage over other implantable transducers (e.g., 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[25,91–93]. However, the placement of the tendon through the buckle shortens the tendon and can alter its natural movement[25]. 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[25].

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[94]. 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 to previous force transducers[95]. 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[25,96]. Therefore, 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[25,96]. 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[25,96]. This effect can be achieved using two types of sensors: intensity-based and spectral-based optical sensors[87].

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 contractions[97] and during dynamic activities such as walking or jumping[45,87,95,98,99]. These sensors have evolved from the earliest models (approximately 500µm)[100] to modern spectral-based models incorporating fibre Bragg gratings and micro-fabricated stainless steel housings (approximately 200µm)[87]. Modern optic fibre sensors offer some advantages such as small size, high sensitivity, fast response time, large dynamic range, and insensitivity to electromagnetic interference[87]. However, the main limitation of this measurement technique is still the invasiveness of the procedure for introducing and removing the sensor[87]. The procedure is usually performed under local anaesthesia, causing a little wound in the tissue that can interfere with movement[87]. Due to its smaller size, compared to 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[25]. Also, the possible interference of the sensor during movement and changes in the natural shape of the tendon are reduced compared to other transducers, although still existing[25,95].

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[100].

Therefore, this technology may be considered an appropriate option for in vivo evaluation as long as these artefacts can be minimised[87].

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[25,91–93]. This phenomenon could be related to the relative sliding between the different tendon fascicles or because some tendons (e.g., Achilles tendon) seem to consist of independent portions with distinct mechanical properties[91,92].

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[7,101,19,23]. Thus, it has been suggested that it is the strain magnitude experienced by tendon fibres, not force or stress, that is more directly related to the positive or negative effects triggered in the tissue[7,23,101]. This may be due to the interaction of the tendon's viscoelastic properties, which cause the force or stress parameters to have a different effect on the tendon depending on the context, with strain, on the other hand, being a direct result of these phenomena. However, this evaluation is complicated by the fact that different load magnitudes and rates affect the stress-strain relationship differently for a given force because tendons are viscoelastic structures[11,63]. Thus, the measurements are specific to the parameters used and difficult to compare when these parameters are not controlled. 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)[37].

The use of imaging techniques (e.g., 2D[30,102,103] and 3D[104] ultrasound or magnetic resonance imaging[102]) has been previously reported, especially during isometric contractions, but most of these methods have not been transferred to the study of dynamic rehabilitation exercises.

Several authors have reported a relationship between tendon forces and tendon strain using in vitro tensile tests and in vivo ultrasound techniques[30,105–107]. However, it is worth emphasising that this relationship is not completely linear[83]. Actually, the tendon force-elongation relation is curvilinear, consisting of an initial toe region and a posterior linear portion[83]. As reported in previous works[83], to avoid potential errors caused by this characteristic, some research groups have focused exclusively on the linear region of the force-elongation curve[108] or used exponential functions[109]. This linear region could be above 30–50 N/mm^2 in most cases, based on data from human studies that measured voluntary contractions[83].

Regardless of the measurement technique used, it is essential to take into account that mechanical and viscoelastic properties of the tendon imply a time-dependent behaviour of the tendon when a force is applied to it. Thus, when there is a constant strain, the stress progressively decreases, and when continuous or cyclical stress is applied, the strain increases over time[105]. This phenomenon means that different results can be obtained in measurements (e.g. in tendon strain) with a given force, depending on the context. This limitation is sometimes faced through the application of conditioning contractions that allow a state of certain stability and reliability to be reached at the moment of the application of forces for its evaluation, but this is not done or at least described in most studies[110,111].

Additionally, most of the strain measurement methods have been developed for the evaluation of isometric contractions in which changes in strain more directly reflect the forces acting on the tendon. However, in dynamic movements (active or passive), myotendinous structures are subject to changes in their lengths related to joint positions[112], which can make it difficult to estimate loads through strain measurements.

In this review, four studies[37,55,58,63] included a tendon elongation measurement for assessing tendon loads. Revak et al. (2017)[37] evaluated different versions of the heel raising exercise through the tendon strain, calculating the tendon strain by dividing the tendon stress (previously obtained) by the average Young modulus reported (819 N/mm^2)[37]. 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. Differently, Rees et al. (2008)[58] and Chaudhry et al. (2015)[55] assessed the changes in tendon length in heel lowering and rising exercises, using ultrasound imaging and motion analysis. The authors calculated the Achilles tendon length as the distance between the tendon origin and the tendon insertion[58]. Thus, they tracked the position of these anatomical sites by using an active marker motion analysis system[58]. Earp et al. (2016)[63] estimated the myotendinous unit length using derived models based on joint position and individual limb lengths, a method that has been found to be valid and reliable[113,114]. Regarding the identification of the zero-length, the joint position corresponding to it is not known[25]. Thus, it is important to normalise this parameter to allow comparison between studies, for example, using a particular position of the joint[25]. 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[25]. The use of a force sensor in conjunction with ultrasonography could help determine the zero-length in each subject[25].

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[35]. The absence of a sensor inside the body that can hinder mobility, together with the non-use of anaesthesia, allow natural movements[25]. Additionally, ultrasonography enables the differentiation of muscle and tendon interfaces, enabling muscle and tendon strains to be independently measured[35]. 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. (2008)[58] and Chaudhry et al. (2015)[55]. 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[55]. However, this methodology was excessively laborious, so it was limited to only a few frames[55]. For this reason, different algorithms, usually based on cross-correlation, have been developed to automate the process[55,115–117]. 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[55,58]. On the other hand, displacement measurements between known points within the tendon mid-substance, known as speckle-tracking[35]. The speckle-tracking technique allows unique speckle patterns of the tendon to be identified and tracked during movement[118]. 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[83]. Thus, both methods may be adequate as long as they are properly reported, only being possible to compare results from the same approach[25]. Likewise, the choice of the anatomical site used as a tracking landmark is relevant. Thus, previous studies have shown that small variations (e.g., tibial tuberosity or plateau) result in significant differences in the values obtained, both in tendon strain itself and in other calculated mechanical properties (e.g., tendon stiffness)[119].Numerous limitations of imaging techniques have been widely reported[25,35,83]. It is worth emphasizing 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[35,83,120]. 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 can interfere with the movement pattern[35]. 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[35,83]. Second, the ultrasound image has a spatial limitation directly related to the length of the ultrasound transducer, especially affecting the measurement of long tendons[83]. This limitation could be obviated by scanning only the myotendinous junction[83]. 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[83]. For this reason, it is recommended to scan both tendon ends, using longer transducers when necessary[83]. 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[35,83]. While the measurement is done through the identification and tracking of anatomical sites in planar 2D images, the reality of three-dimensional movement means that tendon bulging, rotation, or twisting can occur, and this fact may introduce a systematic over- or underestimation of tendon length[35,83]. This limitation has been partially addressed with new 3D ultrasound techniques by capturing images in multiple static postures (e.g., Freehand 3D[104]). 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[35,83]. 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. (2015)[83]. Additional issues can be found in each specific tendon location. For example, previous evidence shows 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[121]. In this regard, Kharazi et al. (2021)[122] developed a new approach for Achilles strain in vivo measurement, which considers the tendon curve-path shape using skin reflective markers. These new solutions could also be useful in the study of dynamic rehabilitation exercises.

Similar to the case of traditional ultrasonography, elastography can use speckle patterns within to measure tendon displacement or strain. This technique uses ultrasound radiofrequency data to track the displacement of speckle patterns along the ultrasound beam [92,123].

Stress

As described in the introduction, in vivo measurement of tendon stress is practically impossible[36]. Thus, the four included studies calculated the tendon stress by dividing the estimated tendon force by the specific cross-sectional area[37,39,61,63]. This indirect calculation carries all measurement errors of the methods used to estimate the tendon forces.

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. (2008)[124] in knee extension-flexion cycles against calibrated resistance. Sheehan and Drace (2020)[102] 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[102,124]. This technique allows a three-dimensional 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[35]. 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. On the other hand, these strain sensors share many of their limitations with other implantable devices and must be biotolerable, biocompatible, and easy to implant[35].

Vibrational behaviour

A proof-of-concept study was identified with a novel technique for evaluating tendon tension during walking, running, and unilateral and bilateral heel raising[125]. 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 tension in the accelerometer[125]. It is suggested that a tendon on which low tension is applied responds to vibration with a steeper rising and falling edge, attributable to faster energy absorption and dissipation[125]. However, a tendon on which high tension is applied responds with a progressive rising and falling edge, attributable to slower energy absorption and dissipation[125].

Another novel non-invasive approach is being developed for in vivo evaluation by tracking vibrational behaviour[126]. 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[126].

Although these techniques have some limitations such as artefacts caused by noise on the skin caused by movement of the limbs[125], 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, stress, 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.

Practical applications

Although the methods collected in this review allow direct or indirect estimation of the forces, stress, 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, stress, 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.

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Competing interests

None

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All authors contributed to the study design. AEE and AICV searched and screened the articles, with assistance from JC. All authors contributed to data analysis and interpretation of the data. AEE drafted the manuscript, AICV and JC revised it critically, and all authors contributed to revisions and approved the final manuscript.

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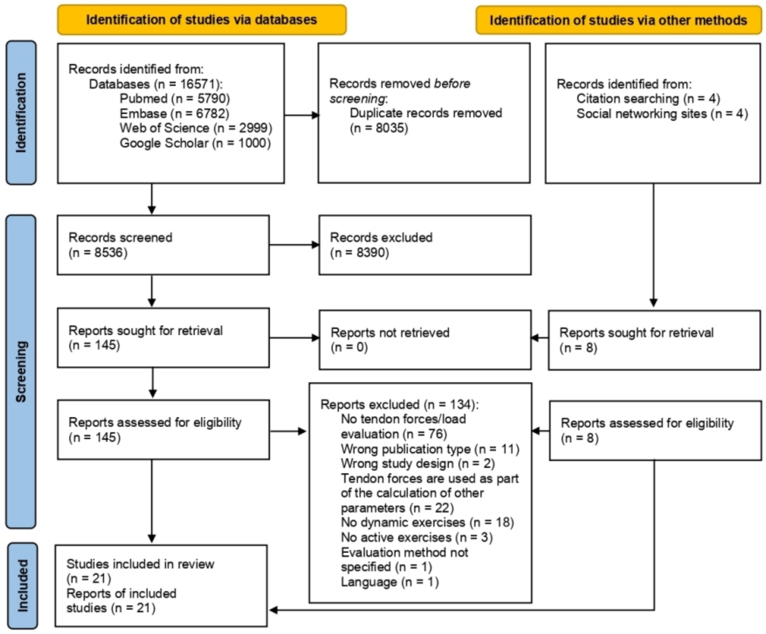

Figure 1. Flow diagram of the selection process.

210x297mm (150 x 150 DPI)

SUPPLEMENTARY FILE

BMJ OPEN

Supplement to: *Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review*

Adrian Escriche-Escuder, Antonio I. Cuesta-Vargas, José Casaña

TABLE OF CONTENTS

Supplementary Appendices

Appendix S1. Detailed information sources and search strategy

	Pubmed	EMBASE	WOS	Google Scholar (200 primeras)
Tendon AND Load	3837	4311		200
Tendon [Title] AND Load [Title]	100	183	536	
Tendon [Title] AND Force [Title]	185	202	297	
Tendon [Title] AND Biomechanics [Title]	90	111	83	
Tendon AND wave	893	1220	1282	200
Tendon [Title] AND Properties [Title]	685	755	801	
Tendon AND Force				200
Tendon AND Biomechanics				200
Tendon AND Properties				200
	5790	**6782**	**2999**	**1000**
Total	**16571**			

Appendix S2. Articles excluded with full-text with reasons

Autor and year	Title	Reasons for exclusion
Acuna et al. 2019	Achilles tendon shear wave speed tracks the dynamic modulation of standing balance	No tendon forces/load evaluation
Aita et al. 1998	The load applied to the foot in a patellar ligament-bearing cast	No tendon forces/load evaluation
Andarawis-Puri et al. 2010	Infraspinatus and supraspinatus tendon strain explained using multiple regression models.	No tendon forces/load evaluation
Ando et al. 2019	Positive relationship between passive muscle stiffness and rapid force production	No tendon forces/load evaluation
Ateş et al. 2015	Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity	No tendon forces/load evaluation
Beck et al. 2020	Cyclically producing the same average muscle-tendon force with a smaller duty increases metabolic rate	No tendon forces/load evaluation
Bobbert et al. 1986	An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping	No tendon forces/load evaluation
Bojsen-Moller et al. 2003	Measuring mechanical properties of the vastus lateralis tendon-aponeurosis complex in vivo by ultrasound imaging	No tendon forces/load evaluation
Bojsen-Møller et al. 2005	Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures	No tendon forces/load evaluation
Bolus et al. 2021	Fit to Burst: Toward Noninvasive Estimation of Achilles Tendon Load Using Burst Vibrations	Proof-of-concept study
Breda et al. 2020	The association between patellar tendon stiffness measured with shear-wave elastography and patellar tendinopathy—a case-control study	No tendon forces/load evaluation
Bruggemann 1985	Mechanical load on the Achilles-tendon during rapid dynamic sport movements	Wrong publication type (Book chapter)
Brum et al. 2013	In Vivo Achilles Tendon Elasticity Assessment using	No tendon forces/load evaluation

	Supersonic Shear Imaging: a feasibility study	
Bujalski et al. 2018	A Monte Carlo analysis of muscle force estimation sensitivity to muscle-tendon properties using a Hill-based muscle model	No tendon forces/load evaluation
Burgess et al. 2007	Plyometric vs. Isometric training influences on tendon properties and muscle output	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cao et al. 2019	A multicenter large-sample shear wave ultrasound elastographic study of the achilles tendon in chinese adults	No tendon forces/load evaluation
Cattagni et al. 2017	No Alteration of the Neuromuscular Performance of Plantar-Flexor Muscles After Achilles Tendon Vibration	No tendon forces/load evaluation
Centner et al. 2019	Low-load blood flow restriction training induces similar morphological and mechanical Achilles tendon adaptations compared with high-load resistance training	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Chang et al. 2020	Strain ratio of ultrasound elastography for the evaluation of tendon elasticity	No tendon forces/load evaluation
Cheung et al. 2006	Effect of Achilles tendon loading on plantar fascia tension in the standing foot.	No dynamic exercises (No exercises evaluated)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cruz-Montecinos et al. 2015	Estimation of tensile properties of the Achilles tendon in haemophilic arthropathy of the ankle: case study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cruz-Montecinos et al. 2019	Assessment of tensile mechanical properties of the Achilles tendon in adult patients with haemophilic arthropathy. Reproducibility study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Deforth et al. 2019	The effect of foot type on the Achilles tendon moment arm and biomechanics	No tendon forces/load evaluation

Delp et al. 2007	OpenSim: open-source software to create and analyze dynamic simulations of movement.	Wrong publication type
Dennerlein et al. 1999	In vivo finger flexor tendon force while tapping on a keyswitch	No dynamic exercises (everyday tasks)
Ebrahimi et al. 2020	Shear Wave Tensiometry Reveals an Age-Related Deficit in Triceps Surae Work at Slow and Fast Walking Speeds	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Ejeskar et al. 1982	Finger flexion force and hand grip strength after tendon repair	No tendon forces/load evaluation
Farris et al. 2013	Differential strain patterns of the human Achilles tendon determined in vivo with freehand three-dimensional ultrasound imaging	No dynamic exercises (isometric)
Finni et al. 2008	Mechanical behavior of the quadriceps femoris muscle tendon unit during low-load contractions	No dynamic exercises (laboratory setting)
Firminger et al. 2019	Effect of Shoe and Surface Stiffness on Lower Limb Tendon Strain in Jumping	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Fowler and Nicol 2000	Interphalangeal joint and tendon forces: normal model and biomechanical consequences of surgical reconstruction	No dynamic exercises (everyday tasks)
Fowler et al. 1999	Measurement of external three-dimensional interphalangeal loads applied during activities of daily living	No tendon forces/load evaluation
Friesenbichler et al. 2019	Gait and strength asymmetries in patients with insertional achilles tendinopathy	No tendon forces/load evaluation
Fröberg et al. 2020	The Effect of Ankle Foot Orthosis' Design and Degree of Dorsiflexion on Achilles Tendon Biomechanics-Tendon Displacement, Lower Leg Muscle Activation, and Plantar Pressure During Walking	No tendon forces/load evaluation
Gerus et al. 2011	A method to characterize in vivo tendon force-strain relationship by combining ultrasonography,	Tendon forces are used as part of the calculation of other parameters and not

	motion capture and loading rates	reported as evaluation results
Gerus et al. 2012	Subject-Specific Tendon-Aponeurosis Definition in Hill-Type Model Predicts Higher Muscle Forces in Dynamic Tasks	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Giacomozzi et al. 2015	Does the thickening of Achilles tendon and plantar fascia contribute to the alteration of diabetic foot loading?	No tendon forces/load evaluation
Gomes et al. 2020	Is there a relationship between back squat depth, ankle flexibility, and Achilles tendon stiffness?	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hager et al. 2020	Influence of joint angle on muscle fascicle dynamics and rate of torque development during isometric explosive contractions.	No tendon forces/load evaluation
Hansen et al. 2006	Mechanical properties of the human patellar tendon, in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Harding et al. 1993	Finger joint force minimization in pianists using optimization techniques	No dynamic exercises (everyday tasks)
Harlaar et al. 2020	Patellofemoral joint contact forces at different activities - effects of modeling assumptions	No tendon forces/load evaluation
Harnie et al. 2020	Acute effect of tendon vibration applied during isometric contraction at two knee angles on maximal knee extension force production	No tendon forces/load evaluation
Hashizume and Yanagiya 2016	Influences of the foot strike pattern and the running speed on the forces applied to foot	Wrong publication type (Conference proceeding)
Haufe et al. 2020	Biomechanical effects of passive hip springs during walking	No tendon forces/load evaluation
Hauraix et al. 2015	In vivo maximal fascicle-shortening velocity during plantar flexion in humans.	No tendon forces/load evaluation
Heinemeier et al. 2016	Methods of Assessing Human Tendon Metabolism and Tissue Properties in Response to Changes in Mechanical Loading	Wrong publication type (Book chapter)

Helland et al. 2013	Mechanical properties of the patellar tendon in elite volleyball players with and without patellar tendinopathy.	No tendon forces/load evaluation
Histen et al. 2017	Achilles Tendon Properties of Minimalist and Traditionally Shod Runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hoang et al. 2007	Passive mechanical properties of human gastrocnemius muscle-tendon units, muscle fascicles and tendons in vivo	No dynamic exercises
Hof et al. 2002	Mechanics of human triceps surae muscle in walking, running and jumping	No tendon forces/load evaluation
Holzer et al. 2020	Considerations on the human Achilles tendon moment arm for in vivo triceps surae muscle-tendon unit force estimates	Wrong study design (calculations using results from other studies)
Homayuouni et al. 2015	Modeling Implantable Passive Mechanisms for Modifying the Transmission of Forces and Movements Between Muscle and Tendons	No tendon forces/load evaluation
Hopper et al. 2015	Dance floor force reduction influences ankle loads in dancers during drop landings.	No tendon forces/load evaluation
Hu et al. 2014	Biomechanical Analysis of Force Distribution in Human Finger Extensor Mechanisms	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hullfish et al. 2020	A simple instrumented insole algorithm to estimate plantar flexion moments	No tendon forces/load evaluation
Jones et al. 1985	Effect of muscle tendon vibration on the perception of force	No tendon forces/load evaluation
Joseph et al. 2014	Achilles tendon biomechanics in response to acute intense exercise.	No dynamic exercises
Kathy Cheng et al. 2008	Finite element analysis of plantar fascia under stretch—The relative contribution of windlass mechanism and Achilles tendon force	Wrong study design (Finite element analysis)/ No tendon forces/load evaluation
Kawakami et al. 2002	Effect of series elasticity on isokinetic torque-angle relationship in humans.	Tendon forces are used as part of the calculation of other parameters and not

		reported as evaluation results
Kawakami et al. 2002	In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity	No dynamic exercises (laboratory setting)
Kaya and Yucesoy 2020	Muscle-tendon unit length-spastic muscle force data by combined intraoperative-musculoskeletal modelling work	No tendon forces/load evaluation
Kernozek et al. 2016	Comparing Two Methods for Estimating Achilles Tendon Loading during Running	Wrong publication type (Conference proceeding)
Kernozek et al. 2018	The effects of habitual foot strike patterns on Achilles tendon loading in female runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Kongsgaard et al. 2006	Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats	No dynamic exercises
Kouno et al. 2019	Effects of the strain rate on mechanical properties of tendon structures in knee extensors and plantar flexors in vivo	No dynamic exercises
Kruse et al. 2019	Effects of serial casting on muscle-tendon properties, muscle function and gait in a healthy child with calf muscle shortening	No tendon forces/load evaluation
Kubo et al. 1999	Influence of elastic properties of tendon structures on jump performance in humans	No tendon forces/load evaluation
Kubo et al. 2000	Elastic properties of muscle-tendon complex in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2001	Influence of static stretching on viscoelastic properties of human tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2002	Measurement of viscoelastic properties of tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2003	Gender differences in the viscoelastic properties of tendon structures	No tendon forces/load evaluation
Kubo et al. 2005	Effects of cold and hot water immersion on the mechanical	No dynamic exercises

	properties of human muscle and tendon in vivo.	
Kubo et al. 2015	Relationship between elastic properties of tendon structures and performance in long distance runners	No tendon forces/load evaluation
Kubo et al. 2015	Relationship between Achilles tendon properties and foot strike patterns in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2020	Mechanical properties of muscle and tendon at high strain rate in sprinters	No tendon forces/load evaluation
Lee et al. 2015	Repeatability and agreement of digital image correlation (DIC) for regional strain estimates of the in-vivo human patellar tendon	No tendon forces/load evaluation
Lian et al. 1996	Characteristics of the leg extensors in male volleyball players with jumper's knee	No tendon forces/load evaluation
Lian et al. 2003	Performance characteristics of volleyball players with patellar tendinopathy	No tendon forces/load evaluation
Lichtwark et al. 2006	Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Lichtwark et al. 2011	Achilles tendon (3D): Do the mechanical properties of tendon change in response to exercise?	Wrong publication type (Conference proceeding)
Lima et al. 2017	Triceps surae elasticity modulus measured by shear wave elastography is not correlated to the plantar flexion torque	No tendon forces/load evaluation
Lu et al. 2013	Quantifying Catch-and-Release: The Extensor Tendon Force Needed to Overcome the Catching Flexors in Trigger Fingers	No dynamic exercises (everyday tasks)
Mademli et al. 2008	Age-related effect of static and cyclic loadings on the strain-force curve of the vastus lateralis tendon and aponeurosis	No dynamic exercises
Marouane et al. 2017	Changes in Knee Adduction Rotation and not Adduction Moment Influence Joint	Wrong publication type (Conference proceeding)

	Compartmental Load Partitioning	
Martin et al. 2012	Effects of the index finger position and force production on the flexor digitorum superficialis moment arms at the metacarpophalangeal joints - a magnetic resonance imaging study.	No tendon forces/load evaluation
Martin et al. 2018	Gauging force by tapping tendons	No tendon forces/load evaluation
Matsubayashi et al. 2008	Ultrasonographic measurement of tendon displacement caused by active force generation in the psoas major muscle	No tendon forces/load evaluation
McCrum et al. 2018	Loading rate and contraction duration effects on in vivo human Achilles tendon mechanical properties	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McMahon et al. 2013	The manipulation of strain, when stress is controlled, modulates in vivo tendon mechanical properties but not systemic TGF-β1 levels	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McNair et al. 2013	Biomechanical properties of the plantar flexor muscle-tendon complex 6 months post-rupture of the Achilles tendon	No tendon forces/load evaluation
Mileusnic et al. 2009	Force estimation from ensembles of Golgi tendon organs	No tendon forces/load evaluation
Mimura 1986	[The load-bearing function of a patellar tendon bearing cast]	No tendon forces/load evaluation
Monte 2021	In vivo manipulation of muscle shape and tendinous stiffness affects the human ability to generate torque rapidly	No tendon forces/load evaluation
Nicol et al. 1998	Significance of passively induced stretch reflexes on achilles tendon force enhancement	No active exercises evaluated
Nicol et al. 1999	Quantification of Achilles tendon force enhancement by passively induced dorsiflexion stretches	No active exercises evaluated
Okuyama et al. 2019	Study on fingertip force sensor based on measurement of tendon tension	Tendon forces are used as part of the calculation of other parameters
Olszewski et al. 2015	Achilles tendon moment arms: the importance of measuring at	No dynamic exercises

	constant tendon load when using the tendon excursion method.	
Pearson et al. 2013	The use of normalized cross-correlation analysis for automatic tendon excursion measurement in dynamic ultrasound imaging.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Peltonen et al. 2013	Viscoelastic properties of the Achilles tendon in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Perl et al. 2012	Effects of Footwear and Strike Type on Running Economy	No tendon forces/load evaluation (no data)
Petrescu et al. 2016	Evaluation of normal and pathological Achilles tendon by real-time shear wave elastography	No tendon forces/load evaluation (no data)
Rowley et al. 2000	The effect of the patellar tendon-bearing cast on loading	No tendon forces/load evaluation
Salman et al. 2019	Spatial Variations in Achilles Tendon Shear Wave Speed Using a Cost-Effective Method of Accelerometers	Wrong publication type (Conference proceeding)
Saltzman et al. 1992	The patellar tendon-bearing brace as treatment for neurotrophic arthropathy: a dynamic force monitoring study.	No tendon forces/load evaluation
Sasaki et al. 2019	Electromyographic analysis of infraspinatus and scapular muscles during external shoulder rotation with different weight loads and positions.	No tendon forces/load evaluation
Sheehan et al. 2000	Human patellar tendon strain. A noninvasive, in vivo study	No tendon forces/load evaluation
Sinsel et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation during exercises
Slane et al. 2014	Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading	No tendon forces/load evaluation
Stafilidis et al. 2007	Muscle-tendon unit mechanical and morphological properties and sprint performance	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

Stanojev et al. 2018	Effects of patellar tendon strap bracing on the motor performance and biomechanics of healthy adolescent athletes	Wrong publication type (Conference proceeding)
Stegman et al. 2009	A feasibility study for measuring accurate tendon displacements using an audio-based Fourier analysis of pulsed-wave Doppler ultrasound signals.	Wrong publication type (Conference proceeding)
Sugisaki et al. 2011	Effect of muscle contraction levels on the force-length relationship of the human Achilles tendon during lengthening of the triceps surae muscle-tendon unit	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Sussmilch-Leitch et al. 2012	Effect of foot orthoses on ankle kinematics and kinetics in male runners with Achilles tendinopathy	Wrong publication type (Conference proceeding)
Taniguchi 1988	[The load bearing function of patellar tendon bearing brace--on the relation between shaft length and rate of load bearing]	No tendon forces/load evaluation
Thomeer et al. 2020	Load Distribution at the Patellofemoral Joint During Walking.	No tendon forces/load evaluation
Totorean et al. 2014	The role of plantar pressure evaluation in rehabilitation of patients with Achilles tendon ruptures	No tendon forces/load evaluation
Ullrich et al. 2010	Influence of length-restricted strength training on athlete's power-load curves of knee extensors and flexors	No tendon forces/load evaluation
Ushiyama et al. 2005	Difference in aftereffects following prolonged Achilles tendon vibration on muscle activity during maximal voluntary contraction among plantar flexor synergists	No tendon forces/load evaluation
Veeger et al. 2002	Load on the shoulder in low intensity wheelchair propulsion.	No tendon forces/load evaluation
Wearing et al. 2019	Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait?	No tendon forces/load evaluation
Wearing et al. 2020	Transmission-Mode Ultrasound for Monitoring the Instantaneous Elastic Modulus of the Achilles Tendon During	No tendon forces/load evaluation

	Unilateral Submaximal Vertical Hopping	
Werkhausen et al. 2018	Effect of training-induced changes in achilles tendon stiffness on muscle–tendon behavior during landing	No tendon forces/load evaluation
Werkhausen et al. 2019	Distinct muscle-tendon interaction during running at different speeds and in different loading conditions.	No tendon forces/load evaluation
Westphal et al. 2013	Load-Dependent Variations in Knee Kinematics Measured with Dynamic MRI	No dynamic exercises (No exercises are used)
Woodburn et al. 2013	Achilles tendon biomechanics in psoriatic arthritis patients with ultrasound proven enthesitis	The method of evaluating tendon forces is not specified.
Wretenberg et al. 1993	Passive knee muscle moment arms measured in vivo with MRI	No active exercises
Wu et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation
Yamaguchi et al. 2002	Effect of different frequencies of skipping rope on elastic components of muscle and tendon in human triceps surae	Wrong language (Japanese)
Yamamoto et al. 2020	Effects of Varying Plantarflexion Stiffness of Ankle-Foot Orthosis on Achilles Tendon and Propulsion Force during Gait	No tendon forces/load evaluation
Yoshitake et al. 2004	Fluctuations in plantar flexion force are reduced after prolonged tendon vibration	No tendon forces/load evaluation

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	6
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	7
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	7
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	7
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	8
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	8
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	8
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	9

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SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	10
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	10
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	10
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	10
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	21
Limitations	20	Discuss the limitations of the scoping review process.	34
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	34
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	35

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

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Modelling and in vivo evaluation of tendon forces and strain in dynamic rehabilitation exercises: a scoping review

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Title: Modelling and in vivo evaluation of tendon forces and strain in dynamic rehabilitation exercises: a scoping review

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Modelling and in vivo evaluation of tendon forces and strain in dynamic rehabilitation exercises: a scoping review

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 or longitudinal 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.

Keywords: Foot & ankle; hand & wrist; musculoskeletal disorders; rehabilitation medicine; sports medicine

Strengths and limitations of this study

- The extensive search carried out in this review in four of the main databases allows the reader to approach a wide field of knowledge.
- This review provides a summary of the available literature on the study of forces and strain that act on the tendon during dynamic exercises.
- Grouping the assessment tools into subgroups allows an analysis of the advantages and disadvantages of each option.
- Some studies might not have been identified due to the difficulty in tracking the literature because of the variety of terms used.

INTRODUCTION

Tendinopathy is the preferred term for persistent tendon pain and loss of function related to mechanical loading[1]. 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[2].

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[2]. 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[3,2,4–6]. These approaches focus on producing an adequate stimulus for tendon adaptations and aim to increase the patients' loading capacity [3,7]. Regarding the adaptations in the tendon, research data suggests that tenocytes respond to mechanical loading by inducing anabolic and catabolic processes of matrix proteins, respectively, through a process known as mechanotransduction[7–11]. 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[6,12–14]. Likewise, different strategies have been implemented for handling and modifying the applied loads[15–17]. However, although concepts such as repetition maximum (RM) 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[7].

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 have a different nature depending on the force that produces it. Thus, tendons are subjected to compression, tension, or shear forces in daily activities[18,19], but it is the tensile load (and the strain it produces) that plays a leading role in the function of the tendon[20]. Therefore, the evaluation of the tensile strain is especially relevant for the study of the loading programmes[21].

Regardless of the parameter evaluated, it is important to take into account a factor that makes this study difficult: tendons are not uniaxial structures but are usually made up of different bundles[22]. This causes regional variations in mechanical properties, and the distribution of forces and strains throughout the tissue is not uniform[23]. Tendon forces have been calculated through in vitro studies[24], as well as have been estimated through in vivo indirect calculations based on body position, joint reaction forces, and inverse dynamic models[25–27]. 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[23].

Medical imaging techniques such as ultrasound or magnetic resonance imaging have previously made it possible to directly measure strain during isometric contractions[28], walking[29,30], running[27,31], and hopping[32]. However, transducer position may affect ultrasound measurements significantly, and it is necessary a rigid fixation over the tissue that may alter movement patterns[33]. Therefore, its use in some dynamic activities is still limited.

Some reviews have been previously published focused on the evaluation of tendon loads[23,33]. These reviews are not specific to dynamic rehabilitation exercises and include mainly methods developed for the study of isometric contractions[28,34] or cyclic activities such as running[35,36], cycling[25,37], or walking[38,39]. 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[33]. 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 to, 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 PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines[40]. 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[41] for biomedical reviews, four databases were searched by two reviewers (A.E-E, J.C.G.) 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 Supplementary 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; (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 (A.E-E) to exclude clearly irrelevant articles. Finally, two reviewers (A.E-E, J.C.G.) screened the full texts of identified articles to select those that met the eligibility criteria. A third reviewer solved any disagreements (A.I.C.V).

Data extraction

Two reviewers (A.E-E, J.C.G.) 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; 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 analysis

Current guidelines on conducting a scoping review describe the inclusion of a methodological quality analysis as not necessary[42,43]. 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 focus 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

Patients were not involved in this research.

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 Supplementary Appendix 2.

[Figure 1 near here]

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[44–46] (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.

Table 1. Forces and strain evaluation methodologies identified in the included studies.

Measurement methodology	Tendon	References
Forces		
Inverse dynamics	Achilles	[47–55]
	Patellar	[56–60]
Force transducers (Buckle force transducer, S-shaped force transducer, load cell)	Hand	Buckle [44–46] Load cell [61,62] S-shaped [63]
Optic fibre sensors	Patellar	[64]
Strain		
Ultrasound imaging	Achilles	[49,51,54]
	Quadriceps	[59]

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[65]. Moment arms are estimated from previous literature data or estimated specifically for each patient through imaging techniques such as magnetic resonance imaging or ultrasound.

Most of the included studies used motion capture systems for kinematics, while force plates were the most used device for obtaining kinetic data. Some studies used generic moment arms based on the published literature[47,58], other used previously described procedures and equations[52,55,56,60], while other estimated subject-specific moment arms based on imaging techniques[48,49]. Kinematic and kinetic data were integrated into different musculoskeletal models: three studies[50,51,57] used the Human Body Model[66], one[47] study used the OpenSim model[67], one study[48] used the FreeBody model[68], while other studies[49,53,56] 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)[47,48]. The single-leg heel raising and lowering obtained values between 3-5.12 BW for the Achilles tendon[47,48,50,53]. 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[58,60].

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 transducer[63], and load cell[61,62].

The buckle force transducers technique used in three of the studies[44–46] consisted of a modified version of the method described by Dennerlein et al. (1997)[69]. This device consisted of a 9 x 16 x 4.5 mm stainless steel frame and a removable fulcrum designed to fit inside the carpal canal[44–46]. In this system, each tendon lies in semi-circular arches in the device[44–46]. These studies evaluated unresisted finger flexion and extension at different wrist angles, obtaining a range of mean values between 1.3 N – 25.5 N for the flexor digitorum profundus (range -1.6 N – 74.7 N) and 1.3 N – 12.9 N (range -2.0 N – 47.53 N) for the flexor digitorum superficialis[44–46]. The S-shaped force transducer consisted of a stainless steel frame combined with four strain gauges attached on its central beam[63]. This study obtained values between 0 and 12.0 kgf (117.7 N, obtained with the active tip pinch) in the evaluation of different finger and wrist flexion and extension exercises[63]. In the case of load cell, an apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements[61,62]. The central hook was connected to a load cell, recording the applied forces. These studies evaluated different finger flexion and extension exercises, with and without resistance, obtaining values in a range between 1 N and 50 N (resisted finger flexion, 300 g)[61,62].

Optic fibre sensor

Dillon et al. (2008)[64] 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[64]. 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[64]. In this study the sensors were not calibrated to record forces in N. Therefore, the data is only available through the differential output of the fibre signal[64]. 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)[64].

Strain as a load measure

Four studies[49,51,54,59] carried out additional measurements for quantifying loads on the tendon through strain or elongation measurement. Rees et al. (2008)[54] and Chaudhry et al. (2015)[49] 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 al. (2008)[54] established and tracked the position of these anatomical sites in terms of 3D coordinates over time by using an active marker motion analysis system through a previously detailed methodology[32]. Chaudhry et al. (2015) implemented an algorithm that provides an intensity map of the ultrasound images, from which the 2D position and angular orientation of the most intense points can be established[49]. Thus, the authors used this mechanism to locate and track the myotendinous junction[49]. 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 assessed, both phases performed with bent and extended knee[49,54]. In the study by Rees et al., the authors found that the elongation of the tendon during the eccentric and concentric part of the exercise is similar (13.6mm and 14.9mm on average for eccentric and concentric phase, respectively)[54]. Chaudhry et al. (2015)[49] also obtained similar elongation of the tendon during the eccentric (approximately 8 mm of peak mean elongation) and concentric phase (approximately 7 mm), [49]. Earp et al. (2016)[59] estimated the myotendinous unit length of the distal vastus lateralis using previous models based on joint position and individual limb lengths. This information was used to compare different ways of performing the squat, analysing the tendon lengthening pattern during the concentric and eccentric phases[59]. Revak et al. (2017)[51] estimated the tendon strain using the average Young modulus value (819 N/mm^2) reported in previous literature[70]. First, the Achilles tendon stress (magnitude that quantifies the load per unit area of the tendon) was calculated by dividing the tendon force (estimated using inverse dynamics) by the cross-sectional area of each participant[51]. Then, the tendon strain was calculated by dividing the tendon stress by the Young modulus. In this case, ultrasound was used to measure the cross section of the tendon (not during exercises)[51]. The strain values obtained (expressed in %) were between 0.71±0.35 and 8.80±0.35, corresponding to the seated heel raising and lowering and the unilateral heel raising and lowering exercises, respectively[51].

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 including this type of exercises[47,49–51,54,53,48]. In patellar tendon disorders, different modalities of squats are commonly prescribed, as well as exercises involving knee flexion and extension. Eight[47,50,52,56,58–60,64] and two[55,64] studies analysed these types of exercises, respectively. Another exercise commonly applied for lower limb disorders such as lunge was analysed in two studies[50,57]. Three studies analysed step-up and step-down exercises or stairs climbing[47,55,64]. Finally[44–46,61–63]. Table 2 includes the type of exercises analysed in each study.

Table 2. Characteristics of the included studies.

Autor and year	Population	Tendon	Type of exercise	Evaluated parameter and evaluation methodology
Baxter et al. 2021 [47]	N= 8; Healthy; 6M, 2F; 30 ±4 years; BMI: 24.1 ±3.2	Achilles	Dynamic exercises: seated single-legged heel raise with 15 kg 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 bodyweight. Musculoskeletal model: OpenSim. A motion analysis system and force plate data were used for the procedure.
Chaudhry et al. 2015 [49]	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 center 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 code. A motion analysis system and force plate data were used for the procedure. **Strain:** Tendon length was calculated as the distance between the Achilles tendon insertion and the distal MTJ of the medial gastrocnemius (ultrasonography and active motion analysis system).
Gheidi et al. 2018 [50]	N= 18; Healthy; 18M; 22.1 ±1.8 years; Weight: 74.29 ±11.3 kg; Height: 177.7 ±8.4 cm	Achilles	Dynamic exercises: unilateral and bilateral heel raising, squat, lunge	**Force:** Inverse dynamics: Muscle forces were estimated from a musculoskeletal model. Moment arms were based on previous literature (graphics-based model) [71]. 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 al. 2008 [54]	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. **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).
Revak et al. 2017 [51]	N= 21; Healthy; 21M; 21.59 ±1.92 years; Weight: 75.81 ±1.24 kg; Height: 178.22 ±8.02 cm	Achilles	Dynamic exercises: seated bilateral heel raising and lowering, standing bilateral heel raising and lowering, unilateral heel raising and lowering, and bilateral heel raising and unilateral 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:** Strain was indirectly calculated by dividing the tendon stress by the average Young modulus of 819 N/mm reported in previous literature.
Sinclair et al. 2015 [52]	N= 18; Healthy; 18M; 23.61 ±4.17 years; Weight: 75.63 ±6.54 kg; Height: 178 ±10 cm	Achilles	Dynamic exercises: back and front squat	**Force;** Inverse dynamics: The Achilles tendon load (ATL) was determined by dividing the plantar flexion moment (MPF) by the estimated Achilles tendon moment arm (MA): ATL = MPF / MA. The moment arm was quantified as a function of the ankle sagittal plane angle using a procedure described in previous literature [72]. A motion analysis system and force plate data were used for the procedure.
Weinert-Aplin et al. 2015 [53]	N= 19; Healthy; 8M, 11F; M: 28 ±3 years; Weight: 73.4 ±12 kg; Height: 176 ±10 cm F: 29 ±6 years; Weight: 58.7 ±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 inter-segmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics [73]. 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 al. 2021 [48]	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, 160 of %BW); seated heel drop and rise (13, 21-28, 38, 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 al. 2008 [64]	N= 7; Healthy; 7M; 26.4 ±3.9 years; BMI: 24.8 ±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.
Earp et al. 2016 [59]	N= 10; Healthy; 10M; 25.8 ±2.8 years; Weight: 83.8 ±9.4 kg; Height: 177 ±6 cm	Patellar	Dynamic exercises: depth back squat lifts with 60% of 1RM at three different speeds: slowfixed-tempo, volitional-speed without a pause, and maximum-speed jump)	**Force:** Inverse dynamics: Patellar tendon forces were estimated by multiplying knee moment by the joint-derived moment arm length of the patella; as determined using a previously published model [74]. 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 previously published literature [75]. A motion analysis system and force plate data were used for the procedure. **Strain:** Myotendinous unit length was estimated using previous models based on joint position and individual limb lengths. The quadriceps tendon length of the tendinous was calculated as the longitudinal length of the recorded fascicle subtracted from the myotendinous unit length.
Frohm et al. 2007 [58]	N_{Total}= 14; Healthy; 14M N_1: 13; 36 ±9 years; Weight: 87 ±4 kg;	Patellar	Dynamic exercises: eccentric squats holding a weight (barbell disc) of 10 kg in decline board and horizontal surface, eccentric squat in	**Force:** Inverse dynamics: Patellar tendon force 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

	Height: 183 ±5 cm N_2: 11; 39 ±10 years; Weight: 87 ±5 kg; Height: 183 ±5 cm		Bromsman device in decline board and horizontal surface	previous literature [76]. A motion analysis system and force plate data were used for the procedure.
Reilly and Martens 1972 [55]	N= 3; Heathy; 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 gage instrumented force plate). Moment arm of the patellar tendon force were measured from roentgenograms. A stroboscopic photography system and force plate data were used for the procedure.
Richards et al. 2016 [60]	N= 18; Healthy; 9M, 9F; 20-46 years; Weight: 75.1 kg (58.3-100)	Patellar	Dynamic exercises: decline squats at different angles of declination (0°, 5°, 10°, 15°, 20° and 25°)	**Force:** Inverse dynamics: Patellar tendon force (PTF) was determined by dividing the extensor moment (ME) by the tendon moment arm (PTMA): PTF = ME / PTMA. The moment arm was quantified as a function of the knee flexion angle by fitting a 2nd order polynomial curve to data published in previous literature [77]. A motion analysis system and force plate data were used for the procedure.
Zellmer et al. 2019 [57]	N= 25; Healthy; 25F 22.69 ±0.74 years; Weight: 61.55 ±9.74 kg; Height: 169.39 ±6.44 cm	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 patellar tendon force 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 [56]	N= 5; Healthy; 2M, 3F; 19-24 years (mean 22); Weight: 58-84 kg (mean 72); Height: 168-200 cm (mean 180)	Patellar	Dynamic exercises: single-leg decline squats at different angles of declination (0°, 5°, 10°, 15°, 20°, 25° and 30°) with and without a backpack of 10 kg	**Force:** Inverse dynamics: Normalised patellar tendon forces were estimated according to the following formula: F_{tendon} = 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 [78]. A motion analysis system and force plate data were used for the procedure.
Edsfeldt et al. 2015 [45]	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 [44]	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 [46]	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.

Powell and Trail 2004 [62]	N= 33; open carpal tunnel release surgery patients; 54 (24-86) years	Hand	Dynamic exercises: unresisted finger flexion and resisted finger flexion (pulley with weights 100-500g)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger; FDP of the ring finger or little finger; FPL of the thumb).
Powell and Trail 2009 [61]	N= 24; open carpal tunnel release surgery patients; 12M, 12F; 57 (23-86) years	Hand	Dynamic exercises: resisted finger flexion (pulley with weights 100-500g) and resisted finger extension (rubber band)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger).
Schuind et al. 1992 [63]	N= 5; open carpal tunnel release surgery patients; 3M, 2F	Hand	Dynamic exercises: wrist and fingers flexion and extension	**Force:** S-shaped force transducer: S-shaped force transducers were applied to the flexor pollicis longus and FDS and FDP tendons of the index finger in five patients operated on for treatment of carpal tunnel syndrome. The experiment was conducted during open carpal tunnel release surgery with local anaesthesia.

CONC: Concentric; ECC: Eccentric; FDP: Flexor digitorum profundus; FDS: Flexor digitorum superficialis; FPL: Flexor digitorum profundus longus; GRF: Ground Reaction Forces; HSR: Heavy Slow Resistance; M: Male; MRI: Magnetic Resonance Imaging; MTJ: Myotendinous junction; F: Female; %BW: Percentage of body weight

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[79]. 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[80]. 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[79]. For example, classical inverse dynamics assumes idealised pin joints and the existence of rigid body segments, and that does not match reality[79]. 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[79].

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[50,51,57], OpenSim[47], FreeBody[48], among others[49,53,56]. 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[50,51,57]. 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[80]. 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[49,53,56]. Some studies performed subject-specific calculations based on imaging techniques to minimise error[48,49], and others studies used data from previously published literature (e.g. 5 cm ankle moment arm)[47,58]. Alternatively, some studies used an intermediate method based on the use of new or previously published equations together with specific data from each patient[52,55,56,60]. 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[80,81], and, sometimes, this value is not scaled to the rest of the anatomical structures[80,82]. 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[83]. 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[80,82]. 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°)[80,81]. Likewise, these differences could translate into up to 67% differences in the estimated values of tendon force[80,81].

Despite all the above mentioned limitations, modelling approaches have been widely employed to estimate tendon forces[65]. 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.[33] Sensors must be biotolerable (for short-term measurements) and biocompatible (for long-term use), as well as easy to implant[23]. Additionally, devices should avoid damaging body tissues and alter the tendon and joint mobility and neuromuscular function[23]. It has been suggested that these sensors should also be flexible and allow wireless data transmission to facilitate their clinical use[33]. 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[84]. Additionally, potential complications such as local pain or infections have limited the use of this methodology to a restricted research population[84].

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[37,85–87]. This kind of transducer consists of a metallic buckle with strain gages through which a tendon is

looped[23]. When a tensile force is applied to the tendon, the buckle deforms and produces a voltage output proportional to the force[23]. Due to their configuration, these buckle transducers enable the measurement of force of the entire cross-section of the tendon[23]. This is an advantage over other implantable transducers (e.g., 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[23,88–90]. However, the placement of the tendon through the buckle shortens the tendon and can alter its natural movement[23]. 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[91]. 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 to previous force transducers[92]. 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[23,93]. 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[23,93]. 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[23,93]. This effect can be achieved using two types of sensors: intensity-based and spectral-based optical sensors[84].

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 contractions[94] and during dynamic activities such as walking or jumping[39,84,92,95,96]. These sensors have evolved from the earliest models (approximately 500µm)[97] to modern spectral-based models incorporating fibre Bragg gratings and micro-fabricated stainless steel housings (approximately 200µm)[84]. Modern optic fibre sensors offer some advantages such as small size, high sensitivity, fast response time, large dynamic range, and insensitivity to electromagnetic interference[84]. However, the main limitation of this measurement technique is still the invasiveness of the procedure for introducing and removing the sensor[84]. The procedure is usually performed under local anaesthesia, causing a little wound in the tissue that can interfere with movement[84]. Due to its smaller size, compared to 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 to other transducers, although still existing[23,92].

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[97].

Therefore, this technology may be considered an appropriate option for in vivo evaluation as long as these artefacts can be minimised[84].

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[23,88–90]. This phenomenon could be related to the relative sliding between the different tendon fascicles[88,89].

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[7,98,99,21]. 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[7,21,98]. 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)[51].

The use of imaging techniques (e.g., 2D[28,100,101] and 3D[102] ultrasound or magnetic resonance imaging[100]) 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[11,59]. However, the hysteresis of tendons has been reported to be approximately 10%[103], and the loading rate effect does not seem to be decisive in the range of loading rates applied during physical activities[104,105]. 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[106]. 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[107,108]. However, this is not done or at least described in most studies.

In this review, four studies[49,51,54,59] included a tendon elongation measurement for assessing tendon loads. Revak et al. (2017)[51] calculated the tendon strain by dividing the tendon stress (previously obtained) by the average Young modulus reported (819 N/mm^2)[51]. 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. (2016)[59] estimated the myotendinous unit length of the distal vastus lateralis using derived models based on joint position and individual limb lengths, a method that has been found to be reliable[109,110]. Differently, Rees et al. (2008)[54] and Chaudhry et al. (2015)[49] calculated the Achilles tendon length as the distance between the tendon origin and the tendon insertion[54]. Thus, they tracked the position of these anatomical sites by using an active marker motion analysis system[54]. 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[49], 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°)[111]. Thus, the joint position corresponding to the zero-length it is not always precisely known[23]. It is important to normalise this parameter to allow comparison between studies, for example, using a standardised position of the joint[23]. 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[23]. The use of a force sensor in conjunction with ultrasonography could help determine the zero-length in each subject[23]. 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[112]. In this regard, Kharazi et al. (2021)[113] 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[33]. The absence of a sensor inside the body that can hinder mobility, together with the non-use of anaesthesia, allow natural movements[23]. Additionally, ultrasonography enables the differentiation of muscle and tendon interfaces, enabling muscle and tendon strains to be independently measured[33]. 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. (2008)[54] and Chaudhry et al. (2015)[49]. 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[49]. However, this methodology was excessively laborious, so it was limited to only a few frames[49]. For this reason, different algorithms, usually based on cross-correlation, have been developed to automate the process[49,114–116]. 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[49,54]. On the other hand, displacement measurements between known points within the tendon mid-substance, known as speckle-tracking, can be used[33]. The speckle-tracking technique allows unique speckle patterns of the tendon to be identified and tracked during movement[117]. 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[80]. Thus, both methods may be adequate as long as they are properly reported, only being possible to compare results from the same approach[23]. Likewise, the choice of the anatomical site used as a tracking landmark is relevant. Thus, previous studies have shown that small variations (e.g., tibial tuberosity or plateau) result in significant differences in the values obtained, both in tendon strain itself and in other calculated mechanical properties (e.g., tendon stiffness)[118]. Numerous limitations of imaging techniques have been widely reported[23,33,80]. 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[33,80,119]. 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[33]. 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[33,80]. Second, the ultrasound image has a spatial limitation directly related to the length of the ultrasound transducer, especially affecting the measurement of long tendons[80]. This limitation could be obviated by scanning only the myotendinous junction[80]. 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[80]. For this reason, it is recommended to scan both tendon ends, using longer transducers when necessary[80]. 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[33,80]. While the measurement is done through the identification and tracking of anatomical sites in planar 2D images, the reality of three-dimensional movement means that tendon bulging, rotation, or twisting can occur, and this fact may introduce a systematic over- or underestimation of tendon length[33,80]. This limitation has been partially addressed with new 3D ultrasound techniques by capturing images in multiple static postures (e.g., Freehand 3D[102]). 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[33,80]. 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. (2015)[80].

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. (2008)[120] in knee extension-flexion cycles against calibrated resistance. Sheehan and Drace (2020)[100] 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[100,120]. This technique allows a three-dimensional 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[33]. 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. On the other hand, these strain sensors share many of their limitations with other implantable devices and must be biotolerable, biocompatible, and easy to implant[33].

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[121]. 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[121]. 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[121]. However, a tendon on which high force is applied responds with a progressive rising and falling edge, attributable to slower energy absorption and dissipation[121].

Another novel non-invasive approach is being developed for in vivo evaluation by tracking vibrational behaviour[122]. 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[122].

Although these techniques have some limitations such as artefacts caused by noise on the skin caused by movement of the limbs[121], 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.

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Competing interests

None

Data availability statement

No additional data available.

Contributors

All authors contributed to the study design. AEE and AICV searched and screened the articles, with assistance from JC. All authors contributed to data analysis and interpretation of the data. AEE drafted the manuscript, AICV and JC revised it critically, and all authors contributed to revisions and approved the final manuscript.

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FIGURE LEGENDS

Figure 1. Flow diagram of the selection process.

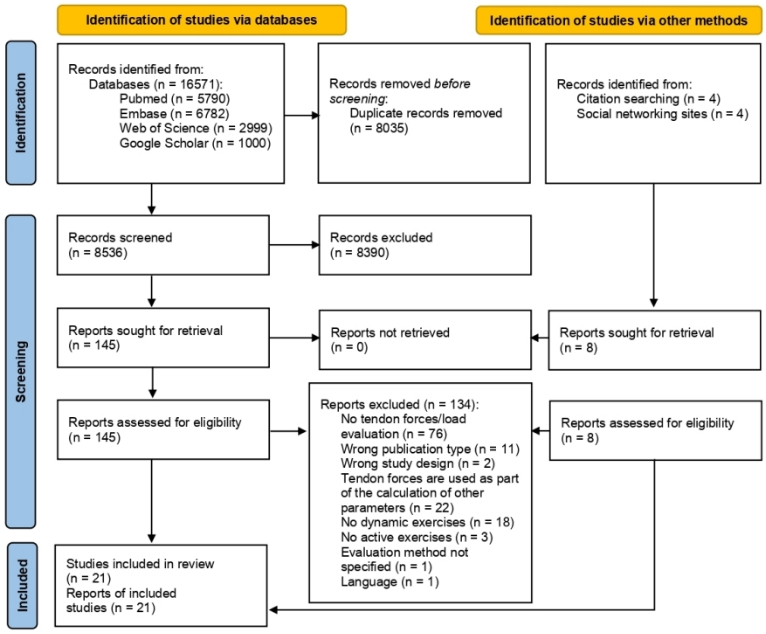

Figure 1. Flow diagram of the selection process.

210x297mm (150 x 150 DPI)

SUPPLEMENTARY FILE

BMJ OPEN

Supplement to: *Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review*

Adrian Escriche-Escuder, Antonio I. Cuesta-Vargas, José Casaña

TABLE OF CONTENTS

Supplementary Appendices

Appendix S1. Detailed information sources and search strategy

	Pubmed	EMBASE	WOS	Google Scholar (200 primeras)
Tendon AND Load	3837	4311		200
Tendon [Title] AND Load [Title]	100	183	536	
Tendon [Title] AND Force [Title]	185	202	297	
Tendon [Title] AND Biomechanics [Title]	90	111	83	
Tendon AND wave	893	1220	1282	200
Tendon [Title] AND Properties [Title]	685	755	801	
Tendon AND Force				200
Tendon AND Biomechanics				200
Tendon AND Properties				200
	5790	**6782**	**2999**	**1000**
Total	**16571**			

Appendix S2. Articles excluded with full-text with reasons

Autor and year	Title	Reasons for exclusion
Acuna et al. 2019	Achilles tendon shear wave speed tracks the dynamic modulation of standing balance	No tendon forces/load evaluation
Aita et al. 1998	The load applied to the foot in a patellar ligament-bearing cast	No tendon forces/load evaluation
Andarawis-Puri et al. 2010	Infraspinatus and supraspinatus tendon strain explained using multiple regression models.	No tendon forces/load evaluation
Ando et al. 2019	Positive relationship between passive muscle stiffness and rapid force production	No tendon forces/load evaluation
Ateş et al. 2015	Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity	No tendon forces/load evaluation
Beck et al. 2020	Cyclically producing the same average muscle-tendon force with a smaller duty increases metabolic rate	No tendon forces/load evaluation
Bobbert et al. 1986	An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping	No tendon forces/load evaluation
Bojsen-Moller et al. 2003	Measuring mechanical properties of the vastus lateralis tendon-aponeurosis complex in vivo by ultrasound imaging	No tendon forces/load evaluation
Bojsen-Møller et al. 2005	Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures	No tendon forces/load evaluation
Bolus et al. 2021	Fit to Burst: Toward Noninvasive Estimation of Achilles Tendon Load Using Burst Vibrations	Proof-of-concept study
Breda et al. 2020	The association between patellar tendon stiffness measured with shear-wave elastography and patellar tendinopathy—a case-control study	No tendon forces/load evaluation
Bruggemann 1985	Mechanical load on the Achilles-tendon during rapid dynamic sport movements	Wrong publication type (Book chapter)
Brum et al. 2013	In Vivo Achilles Tendon Elasticity Assessment using	No tendon forces/load evaluation

	Supersonic Shear Imaging: a feasibility study	
Bujalski et al. 2018	A Monte Carlo analysis of muscle force estimation sensitivity to muscle-tendon properties using a Hill-based muscle model	No tendon forces/load evaluation
Burgess et al. 2007	Plyometric vs. Isometric training influences on tendon properties and muscle output	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cao et al. 2019	A multicenter large-sample shear wave ultrasound elastographic study of the achilles tendon in chinese adults	No tendon forces/load evaluation
Cattagni et al. 2017	No Alteration of the Neuromuscular Performance of Plantar-Flexor Muscles After Achilles Tendon Vibration	No tendon forces/load evaluation
Centner et al. 2019	Low-load blood flow restriction training induces similar morphological and mechanical Achilles tendon adaptations compared with high-load resistance training	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Chang et al. 2020	Strain ratio of ultrasound elastography for the evaluation of tendon elasticity	No tendon forces/load evaluation
Cheung et al. 2006	Effect of Achilles tendon loading on plantar fascia tension in the standing foot.	No dynamic exercises (No exercises evaluated)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cruz-Montecinos et al. 2015	Estimation of tensile properties of the Achilles tendon in haemophilic arthropathy of the ankle: case study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cruz-Montecinos et al. 2019	Assessment of tensile mechanical properties of the Achilles tendon in adult patients with haemophilic arthropathy. Reproducibility study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Deforth et al. 2019	The effect of foot type on the Achilles tendon moment arm and biomechanics	No tendon forces/load evaluation

Delp et al. 2007	OpenSim: open-source software to create and analyze dynamic simulations of movement.	Wrong publication type
Dennerlein et al. 1999	In vivo finger flexor tendon force while tapping on a keyswitch	No dynamic exercises (everyday tasks)
Ebrahimi et al. 2020	Shear Wave Tensiometry Reveals an Age-Related Deficit in Triceps Surae Work at Slow and Fast Walking Speeds	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Ejeskar et al. 1982	Finger flexion force and hand grip strength after tendon repair	No tendon forces/load evaluation
Farris et al. 2013	Differential strain patterns of the human Achilles tendon determined in vivo with freehand three-dimensional ultrasound imaging	No dynamic exercises (isometric)
Finni et al. 2008	Mechanical behavior of the quadriceps femoris muscle tendon unit during low-load contractions	No dynamic exercises (laboratory setting)
Firminger et al. 2019	Effect of Shoe and Surface Stiffness on Lower Limb Tendon Strain in Jumping	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Fowler and Nicol 2000	Interphalangeal joint and tendon forces: normal model and biomechanical consequences of surgical reconstruction	No dynamic exercises (everyday tasks)
Fowler et al. 1999	Measurement of external three-dimensional interphalangeal loads applied during activities of daily living	No tendon forces/load evaluation
Friesenbichler et al. 2019	Gait and strength asymmetries in patients with insertional achilles tendinopathy	No tendon forces/load evaluation
Fröberg et al. 2020	The Effect of Ankle Foot Orthosis' Design and Degree of Dorsiflexion on Achilles Tendon Biomechanics-Tendon Displacement, Lower Leg Muscle Activation, and Plantar Pressure During Walking	No tendon forces/load evaluation
Gerus et al. 2011	A method to characterize in vivo tendon force-strain relationship by combining ultrasonography,	Tendon forces are used as part of the calculation of other parameters and not

	motion capture and loading rates	reported as evaluation results
Gerus et al. 2012	Subject-Specific Tendon-Aponeurosis Definition in Hill-Type Model Predicts Higher Muscle Forces in Dynamic Tasks	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Giacomozzi et al. 2015	Does the thickening of Achilles tendon and plantar fascia contribute to the alteration of diabetic foot loading?	No tendon forces/load evaluation
Gomes et al. 2020	Is there a relationship between back squat depth, ankle flexibility, and Achilles tendon stiffness?	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hager et al. 2020	Influence of joint angle on muscle fascicle dynamics and rate of torque development during isometric explosive contractions.	No tendon forces/load evaluation
Hansen et al. 2006	Mechanical properties of the human patellar tendon, in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Harding et al. 1993	Finger joint force minimization in pianists using optimization techniques	No dynamic exercises (everyday tasks)
Harlaar et al. 2020	Patellofemoral joint contact forces at different activities - effects of modeling assumptions	No tendon forces/load evaluation
Harnie et al. 2020	Acute effect of tendon vibration applied during isometric contraction at two knee angles on maximal knee extension force production	No tendon forces/load evaluation
Hashizume and Yanagiya 2016	Influences of the foot strike pattern and the running speed on the forces applied to foot	Wrong publication type (Conference proceeding)
Haufe et al. 2020	Biomechanical effects of passive hip springs during walking	No tendon forces/load evaluation
Hauraix et al. 2015	In vivo maximal fascicle-shortening velocity during plantar flexion in humans.	No tendon forces/load evaluation
Heinemeier et al. 2016	Methods of Assessing Human Tendon Metabolism and Tissue Properties in Response to Changes in Mechanical Loading	Wrong publication type (Book chapter)

Helland et al. 2013	Mechanical properties of the patellar tendon in elite volleyball players with and without patellar tendinopathy.	No tendon forces/load evaluation
Histen et al. 2017	Achilles Tendon Properties of Minimalist and Traditionally Shod Runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hoang et al. 2007	Passive mechanical properties of human gastrocnemius muscle-tendon units, muscle fascicles and tendons in vivo	No dynamic exercises
Hof et al. 2002	Mechanics of human triceps surae muscle in walking, running and jumping	No tendon forces/load evaluation
Holzer et al. 2020	Considerations on the human Achilles tendon moment arm for in vivo triceps surae muscle-tendon unit force estimates	Wrong study design (calculations using results from other studies)
Homayuouni et al. 2015	Modeling Implantable Passive Mechanisms for Modifying the Transmission of Forces and Movements Between Muscle and Tendons	No tendon forces/load evaluation
Hopper et al. 2015	Dance floor force reduction influences ankle loads in dancers during drop landings.	No tendon forces/load evaluation
Hu et al. 2014	Biomechanical Analysis of Force Distribution in Human Finger Extensor Mechanisms	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hullfish et al. 2020	A simple instrumented insole algorithm to estimate plantar flexion moments	No tendon forces/load evaluation
Jones et al. 1985	Effect of muscle tendon vibration on the perception of force	No tendon forces/load evaluation
Joseph et al. 2014	Achilles tendon biomechanics in response to acute intense exercise.	No dynamic exercises
Kathy Cheng et al. 2008	Finite element analysis of plantar fascia under stretch—The relative contribution of windlass mechanism and Achilles tendon force	Wrong study design (Finite element analysis)/ No tendon forces/load evaluation
Kawakami et al. 2002	Effect of series elasticity on isokinetic torque-angle relationship in humans.	Tendon forces are used as part of the calculation of other parameters and not

		reported as evaluation results
Kawakami et al. 2002	In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity	No dynamic exercises (laboratory setting)
Kaya and Yucesoy 2020	Muscle-tendon unit length-spastic muscle force data by combined intraoperative-musculoskeletal modelling work	No tendon forces/load evaluation
Kernozek et al. 2016	Comparing Two Methods for Estimating Achilles Tendon Loading during Running	Wrong publication type (Conference proceeding)
Kernozek et al. 2018	The effects of habitual foot strike patterns on Achilles tendon loading in female runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Kongsgaard et al. 2006	Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats	No dynamic exercises
Kouno et al. 2019	Effects of the strain rate on mechanical properties of tendon structures in knee extensors and plantar flexors in vivo	No dynamic exercises
Kruse et al. 2019	Effects of serial casting on muscle-tendon properties, muscle function and gait in a healthy child with calf muscle shortening	No tendon forces/load evaluation
Kubo et al. 1999	Influence of elastic properties of tendon structures on jump performance in humans	No tendon forces/load evaluation
Kubo et al. 2000	Elastic properties of muscle-tendon complex in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2001	Influence of static stretching on viscoelastic properties of human tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2002	Measurement of viscoelastic properties of tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2003	Gender differences in the viscoelastic properties of tendon structures	No tendon forces/load evaluation
Kubo et al. 2005	Effects of cold and hot water immersion on the mechanical	No dynamic exercises

	properties of human muscle and tendon in vivo.	
Kubo et al. 2015	Relationship between elastic properties of tendon structures and performance in long distance runners	No tendon forces/load evaluation
Kubo et al. 2015	Relationship between Achilles tendon properties and foot strike patterns in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2020	Mechanical properties of muscle and tendon at high strain rate in sprinters	No tendon forces/load evaluation
Lee et al. 2015	Repeatability and agreement of digital image correlation (DIC) for regional strain estimates of the in-vivo human patellar tendon	No tendon forces/load evaluation
Lian et al. 1996	Characteristics of the leg extensors in male volleyball players with jumper's knee	No tendon forces/load evaluation
Lian et al. 2003	Performance characteristics of volleyball players with patellar tendinopathy	No tendon forces/load evaluation
Lichtwark et al. 2006	Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Lichtwark et al. 2011	Achilles tendon (3D): Do the mechanical properties of tendon change in response to exercise?	Wrong publication type (Conference proceeding)
Lima et al. 2017	Triceps surae elasticity modulus measured by shear wave elastography is not correlated to the plantar flexion torque	No tendon forces/load evaluation
Lu et al. 2013	Quantifying Catch-and-Release: The Extensor Tendon Force Needed to Overcome the Catching Flexors in Trigger Fingers	No dynamic exercises (everyday tasks)
Mademli et al. 2008	Age-related effect of static and cyclic loadings on the strain-force curve of the vastus lateralis tendon and aponeurosis	No dynamic exercises
Marouane et al. 2017	Changes in Knee Adduction Rotation and not Adduction Moment Influence Joint	Wrong publication type (Conference proceeding)

	Compartmental Load Partitioning	
Martin et al. 2012	Effects of the index finger position and force production on the flexor digitorum superficialis moment arms at the metacarpophalangeal joints - a magnetic resonance imaging study.	No tendon forces/load evaluation
Martin et al. 2018	Gauging force by tapping tendons	No tendon forces/load evaluation
Matsubayashi et al. 2008	Ultrasonographic measurement of tendon displacement caused by active force generation in the psoas major muscle	No tendon forces/load evaluation
McCrum et al. 2018	Loading rate and contraction duration effects on in vivo human Achilles tendon mechanical properties	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McMahon et al. 2013	The manipulation of strain, when stress is controlled, modulates in vivo tendon mechanical properties but not systemic TGF-β1 levels	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McNair et al. 2013	Biomechanical properties of the plantar flexor muscle-tendon complex 6 months post-rupture of the Achilles tendon	No tendon forces/load evaluation
Mileusnic et al. 2009	Force estimation from ensembles of Golgi tendon organs	No tendon forces/load evaluation
Mimura 1986	[The load-bearing function of a patellar tendon bearing cast]	No tendon forces/load evaluation
Monte 2021	In vivo manipulation of muscle shape and tendinous stiffness affects the human ability to generate torque rapidly	No tendon forces/load evaluation
Nicol et al. 1998	Significance of passively induced stretch reflexes on achilles tendon force enhancement	No active exercises evaluated
Nicol et al. 1999	Quantification of Achilles tendon force enhancement by passively induced dorsiflexion stretches	No active exercises evaluated
Okuyama et al. 2019	Study on fingertip force sensor based on measurement of tendon tension	Tendon forces are used as part of the calculation of other parameters
Olszewski et al. 2015	Achilles tendon moment arms: the importance of measuring at	No dynamic exercises

	constant tendon load when using the tendon excursion method.	
Pearson et al. 2013	The use of normalized cross-correlation analysis for automatic tendon excursion measurement in dynamic ultrasound imaging.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Peltonen et al. 2013	Viscoelastic properties of the Achilles tendon in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Perl et al. 2012	Effects of Footwear and Strike Type on Running Economy	No tendon forces/load evaluation (no data)
Petrescu et al. 2016	Evaluation of normal and pathological Achilles tendon by real-time shear wave elastography	No tendon forces/load evaluation (no data)
Rowley et al. 2000	The effect of the patellar tendon-bearing cast on loading	No tendon forces/load evaluation
Salman et al. 2019	Spatial Variations in Achilles Tendon Shear Wave Speed Using a Cost-Effective Method of Accelerometers	Wrong publication type (Conference proceeding)
Saltzman et al. 1992	The patellar tendon-bearing brace as treatment for neurotrophic arthropathy: a dynamic force monitoring study.	No tendon forces/load evaluation
Sasaki et al. 2019	Electromyographic analysis of infraspinatus and scapular muscles during external shoulder rotation with different weight loads and positions.	No tendon forces/load evaluation
Sheehan et al. 2000	Human patellar tendon strain. A noninvasive, in vivo study	No tendon forces/load evaluation
Sinsel et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation during exercises
Slane et al. 2014	Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading	No tendon forces/load evaluation
Stafilidis et al. 2007	Muscle-tendon unit mechanical and morphological properties and sprint performance	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

Stanojev et al. 2018	Effects of patellar tendon strap bracing on the motor performance and biomechanics of healthy adolescent athletes	Wrong publication type (Conference proceeding)
Stegman et al. 2009	A feasibility study for measuring accurate tendon displacements using an audio-based Fourier analysis of pulsed-wave Doppler ultrasound signals.	Wrong publication type (Conference proceeding)
Sugisaki et al. 2011	Effect of muscle contraction levels on the force-length relationship of the human Achilles tendon during lengthening of the triceps surae muscle-tendon unit	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Sussmilch-Leitch et al. 2012	Effect of foot orthoses on ankle kinematics and kinetics in male runners with Achilles tendinopathy	Wrong publication type (Conference proceeding)
Taniguchi 1988	[The load bearing function of patellar tendon bearing brace--on the relation between shaft length and rate of load bearing]	No tendon forces/load evaluation
Thomeer et al. 2020	Load Distribution at the Patellofemoral Joint During Walking.	No tendon forces/load evaluation
Totorean et al. 2014	The role of plantar pressure evaluation in rehabilitation of patients with Achilles tendon ruptures	No tendon forces/load evaluation
Ullrich et al. 2010	Influence of length-restricted strength training on athlete's power-load curves of knee extensors and flexors	No tendon forces/load evaluation
Ushiyama et al. 2005	Difference in aftereffects following prolonged Achilles tendon vibration on muscle activity during maximal voluntary contraction among plantar flexor synergists	No tendon forces/load evaluation
Veeger et al. 2002	Load on the shoulder in low intensity wheelchair propulsion.	No tendon forces/load evaluation
Wearing et al. 2019	Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait?	No tendon forces/load evaluation
Wearing et al. 2020	Transmission-Mode Ultrasound for Monitoring the Instantaneous Elastic Modulus of the Achilles Tendon During	No tendon forces/load evaluation

	Unilateral Submaximal Vertical Hopping	
Werkhausen et al. 2018	Effect of training-induced changes in achilles tendon stiffness on muscle–tendon behavior during landing	No tendon forces/load evaluation
Werkhausen et al. 2019	Distinct muscle-tendon interaction during running at different speeds and in different loading conditions.	No tendon forces/load evaluation
Westphal et al. 2013	Load-Dependent Variations in Knee Kinematics Measured with Dynamic MRI	No dynamic exercises (No exercises are used)
Woodburn et al. 2013	Achilles tendon biomechanics in psoriatic arthritis patients with ultrasound proven enthesitis	The method of evaluating tendon forces is not specified.
Wretenberg et al. 1993	Passive knee muscle moment arms measured in vivo with MRI	No active exercises
Wu et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation
Yamaguchi et al. 2002	Effect of different frequencies of skipping rope on elastic components of muscle and tendon in human triceps surae	Wrong language (Japanese)
Yamamoto et al. 2020	Effects of Varying Plantarflexion Stiffness of Ankle-Foot Orthosis on Achilles Tendon and Propulsion Force during Gait	No tendon forces/load evaluation
Yoshitake et al. 2004	Fluctuations in plantar flexion force are reduced after prolonged tendon vibration	No tendon forces/load evaluation

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	6
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	6
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	7
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	6
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	6
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	7
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	8
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	8
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	8

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SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	9
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	9
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	10
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	10
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	20
Limitations	20	Discuss the limitations of the scoping review process.	31
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	32
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	33

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.

* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi: 10.7326/M18-0850.

Modelling and in vivo evaluation of tendon forces and strain in dynamic rehabilitation exercises: a scoping review

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Modelling and in vivo evaluation of tendon forces and strain in dynamic rehabilitation exercises: a scoping review

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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 or longitudinal 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.

Keywords: Foot & ankle; hand & wrist; musculoskeletal disorders; rehabilitation medicine; sports medicine

Strengths and limitations of this study

- The extensive search carried out in this review in four of the main databases allows the reader to approach a wide field of knowledge.
- This review provides a summary of the available literature on the study of forces and strain that act on the tendon during dynamic exercises.
- Grouping the assessment tools into subgroups allows an analysis of the advantages and disadvantages of each option.
- Some studies might not have been identified due to the difficulty in tracking the literature because of the variety of terms used.

INTRODUCTION

Tendinopathy is the preferred term for persistent tendon pain and loss of function related to mechanical loading[1]. 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[2].

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[2]. 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[3,2,4–6]. These approaches focus on producing an adequate stimulus for tendon adaptations and aim to increase the patients' loading capacity [3,7]. Regarding the adaptations in the tendon, research data suggests that tenocytes respond to mechanical loading by inducing anabolic and catabolic processes of matrix proteins, respectively, through a process known as mechanotransduction[7–11]. 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[6,12–14]. Likewise, different strategies have been implemented for handling and modifying the applied loads[15–17]. However, although concepts such as repetition maximum (RM) 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[7].

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 have a different nature depending on the force that produces it. Thus, tendons are subjected to compression, tension, or shear forces in daily activities[18,19], but it is the tensile load (and the strain it produces) that plays a leading role in the function of the tendon[20]. Therefore, the evaluation of the tensile strain is especially relevant for the study of the loading programmes[21].

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[22]. This causes regional variations in mechanical properties, and the distribution of forces and strains throughout the tissue is not uniform[23]. Tendon forces have been calculated through in vitro studies[24], as well as have been estimated through in vivo indirect calculations based on body position, joint reaction forces, and inverse dynamic models[25–27]. 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[23].

Medical imaging techniques such as ultrasound or magnetic resonance imaging have previously made it possible to directly measure strain during isometric contractions[28], walking[29,30], running[27,31], and hopping[32]. 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[33]. Therefore, its use in some dynamic activities is still limited.

Some reviews have been previously published focused on the evaluation of tendon loads[23,33]. These reviews are not specific to dynamic rehabilitation exercises and include mainly methods developed for the study of isometric contractions[28,34] or cyclic activities such as running[35,36], cycling[25,37], or walking[38,39]. 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[33]. 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 to, 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 PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines[40]. 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[41] for biomedical reviews, four databases were searched by two reviewers (A.E-E, J.C.G.) 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 Supplementary 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; (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 (A.E-E) to exclude clearly irrelevant articles. Finally, two reviewers (A.E-E, J.C.G.) screened the full texts of identified articles to select those that met the eligibility criteria. A third reviewer solved any disagreements (A.I.C.V).

Data extraction

Two reviewers (A.E-E, J.C.G.) 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; 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[42,43]. 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 focus 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 Supplementary Appendix 2.

[Figure 1 near here]

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[44–46] (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.

Table 1. Forces and strain evaluation methodologies identified in the included studies

Measurement methodology	Tendon	References
Forces		
Inverse dynamics	Achilles	[47–55]
	Patellar	[56–60]
Force transducers (Buckle force transducer, S-shaped force transducer, load cell)	Hand	Buckle [44–46] Load cell [61,62] S-shaped [63]
Optic fibre sensors	Patellar	[64]
Strain		
Ultrasound imaging	Achilles	[49,51,54]
	Quadriceps	[59]

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[65]. Moment arms are estimated from previous literature data or estimated specifically for each patient through imaging techniques such as magnetic resonance imaging or ultrasound.

Most of the included studies used motion capture systems for kinematics, while force plates were the most used device for obtaining kinetic data. Some studies used generic moment arms based on the published literature[47,58], other used previously described procedures and equations[52,55,56,60], while other estimated subject-specific moment arms based on imaging techniques[48,49]. Kinematic and kinetic data were integrated into different musculoskeletal models: three studies[50,51,57] used the Human Body Model[66], one[47] study used the OpenSim model[67], one study[48] used the FreeBody model[68], while other studies[49,53,56] 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)[47,48]. The single-leg heel raising and lowering obtained values between 3-5.12 BW for the Achilles tendon[47,48,50,53]. 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[58,60].

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 transducer[63], and load cell[61,62].

The buckle force transducers technique used in three of the studies[44–46] consisted of a modified version of the method described by Dennerlein et al. (1997)[69]. This device consisted of a 9 x 16 x 4.5 mm stainless steel frame and a removable fulcrum designed to fit inside the carpal canal[44–46]. In this system, each tendon lies in semi-circular arches in the device[44–46]. These studies evaluated unresisted finger flexion and extension at different wrist angles, obtaining a range of mean values between 1.3 N – 25.5 N for the flexor digitorum profundus (range -1.6 N – 74.7 N) and 1.3 N – 12.9 N (range -2.0 N – 47.53 N) for the flexor digitorum superficialis[44–46]. The S-shaped force transducer consisted of a stainless steel frame combined with four strain gauges attached on its central beam[63]. This study obtained values between 0 and 12.0 kgf (117.7 N, obtained with the active tip pinch) in the evaluation of different finger and wrist flexion and extension exercises[63]. In the case of load cell, an apparatus consisting of three vertical rods, each terminating in a ‘‘hook’ was used for the tendon force measurements[61,62]. The central hook was connected to a load cell, recording the applied forces. These studies evaluated different finger flexion and extension exercises, with and without resistance, obtaining values in a range between 1 N and 50 N (resisted finger flexion, 300 g)[61,62].

Optic fibre sensor

Dillon et al. (2008)[64] 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[64]. 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[64]. In this study the sensors were not calibrated to record forces in N. Therefore, the data is only available through the differential output of the fibre signal[64]. 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)[64].

Strain as a load measure

Four studies[49,51,54,59] carried out additional measurements for quantifying loads on the tendon through strain or elongation measurement. Rees et al. (2008)[54] and Chaudhry et al. (2015)[49] 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 al. (2008)[54] established and tracked the position of these anatomical sites in terms of 3D coordinates over time by using an active marker motion analysis system through a previously detailed methodology[32]. Chaudhry et al. (2015) implemented an algorithm that provides an intensity map of the ultrasound images, from which the 2D position and angular orientation of the most intense points can be established[49]. Thus, the authors used this mechanism to locate and track the myotendinous junction[49]. 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 assessed, both phases performed with bent and extended knee[49,54]. In the study by Rees et al., the authors found that the elongation of the tendon during the eccentric and concentric part of the exercise is similar (13.6mm and 14.9mm on average for eccentric and concentric phase, respectively)[54]. Chaudhry et al. (2015)[49] also obtained similar elongation of the tendon during the eccentric (approximately 8 mm of peak mean elongation) and concentric phase (approximately 7 mm), [49]. Earp et al. (2016)[59] estimated the myotendinous unit length of the distal vastus lateralis using previous models based on joint position and individual limb lengths. This information was used to compare different ways of performing the squat, analysing the tendon lengthening pattern during the concentric and eccentric phases based on the muscle fascicle behaviour[59]. Revak et al. (2017)[51] estimated the tendon strain using the average Young modulus value (819 N/mm^2) reported in previous literature[70]. First, the Achilles tendon stress (magnitude that quantifies the load per unit area of the tendon) was calculated by dividing the tendon force (estimated using inverse dynamics) by the cross-sectional area of each participant[51]. Then, the tendon strain was calculated by dividing the tendon stress by the Young modulus. In this case, ultrasound was used to measure the cross section of the tendon (not during exercises)[51]. The strain values obtained (expressed in %) were between 0.71±0.35 and 8.80±0.35, corresponding to the seated heel raising and lowering and the unilateral heel raising and lowering exercises, respectively[51].

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 including this type of exercises[47,49–51,54,53,48]. In patellar tendon disorders, different modalities of squats are commonly prescribed, as well as exercises involving knee flexion and extension. Eight[47,50,52,56,58–60,64] and two[55,64] studies analysed these types of exercises, respectively. Another exercise commonly applied for lower limb disorders such as lunge was analysed in two studies[50,57]. Three studies analysed step-up and step-down exercises or stairs climbing[47,55,64]. Finally[44–46,61–63]. Table 2 includes the type of exercises analysed in each study.

Table 2. Characteristics of the included studies

Autor and year	Population	Tendon	Type of exercise	Evaluated parameter and evaluation methodology
Baxter et al. 2021 [47]	N= 8; Healthy; 6M, 2F; 30 ±4 years; BMI: 24.1 ±3.2	Achilles	Dynamic exercises: seated single-legged heel raise with 15 kg 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 bodyweight. Musculoskeletal model: OpenSim. A motion analysis system and force plate data were used for the procedure.
Chaudhry et al. 2015 [49]	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 center 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 code. A motion analysis system and force plate data were used for the procedure. **Strain:** Tendon length was calculated as the distance between the Achilles tendon insertion and the distal MTJ of the medial gastrocnemius (ultrasonography and active motion analysis system).
Gheidi et al. 2018 [50]	N= 18; Healthy; 18M; 22.1 ±1.8 years; Weight: 74.29 ±11.3 kg; Height: 177.7 ±8.4 cm	Achilles	Dynamic exercises: unilateral and bilateral heel raising, squat, lunge	**Force:** Inverse dynamics: Muscle forces were estimated from a musculoskeletal model. Moment arms were based on previous literature (graphics-based model) [71]. 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 al. 2008 [54]	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. **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).
Revak et al. 2017 [51]	N= 21; Healthy; 21M; 21.59 ±1.92 years; Weight: 75.81 ±1.24 kg; Height: 178.22 ±8.02 cm	Achilles	Dynamic exercises: seated bilateral heel raising and lowering, standing bilateral heel raising and lowering, unilateral heel raising and lowering, and bilateral heel raising and unilateral 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:** Strain was indirectly calculated by dividing the tendon stress by the average Young modulus of 819 N/mm^2 reported in previous literature.
Sinclair et al. 2015 [52]	N= 18; Healthy; 18M; 23.61 ±4.17 years; Weight: 75.63 ±6.54 kg; Height: 178 ±10 cm	Achilles	Dynamic exercises: back and front squat	**Force;** Inverse dynamics: The Achilles tendon load (ATL) was determined by dividing the plantar flexion moment (MPF) by the estimated Achilles tendon moment arm (MA): ATL = MPF / MA. The moment arm was quantified as a function of the ankle sagittal plane angle using a procedure described in previous literature [72]. A motion analysis system and force plate data were used for the procedure.
Weinert-Aplin et al. 2015 [53]	N= 19; Healthy; 8M, 11F; M: 28 ±3 years; Weight: 73.4 ±12 kg; Height: 176 ±10 cm F: 29 ±6 years; Weight: 58.7 ±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 inter-segmental moments at the ankle, knee and hip joints following established inverse dynamics utilising Newton-Euler equations of motion and segment dynamics [73]. 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 al. 2021 [48]	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, 160 of %BW); seated heel drop and rise (13, 21-28, 38, 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 al. 2008 [64]	N= 7; Healthy; 7M; 26.4 ±3.9 years; BMI: 24.8 ±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.
Earp et al. 2016 [59]	N= 10; Healthy; 10M; 25.8 ±2.8 years; Weight: 83.8 ±9.4 kg; Height: 177 ±6 cm	Patellar	Dynamic exercises: depth back squat lifts with 60% of 1RM at three different speeds: slowfixed-tempo, volitional-speed without a pause, and maximum-speed jump)	**Force:** Inverse dynamics: Patellar tendon forces were estimated by multiplying knee moment by the joint-derived moment arm length of the patella; as determined using a previously published model [74]. 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 previously published literature [75]. A motion analysis system and force plate data were used for the procedure. **Strain:** Myotendinous unit length was estimated using previous models based on joint position and individual limb lengths. The quadriceps tendon length of the tendinous was calculated as the longitudinal length of the recorded fascicle subtracted from the myotendinous unit length.
Frohm et al. 2007 [58]	N_{Total}= 14; Healthy; 14M N_1: 13; 36 ±9 years; Weight: 87 ±4 kg;	Patellar	Dynamic exercises: eccentric squats holding a weight (barbell disc) of 10 kg in decline board and horizontal surface, eccentric squat in	**Force:** Inverse dynamics: Patellar tendon force 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

	Height: 183 ±5 cm N_2: 11; 39 ±10 years; Weight: 87 ±5 kg; Height: 183 ±5 cm		Bromsman device in decline board and horizontal surface	previous literature [76]. A motion analysis system and force plate data were used for the procedure.
Reilly and Martens 1972 [55]	N= 3; Heathy; 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 mathematical formulation with experimentally determined parameters (strain gage instrumented force plate). Moment arm of the patellar tendon force were measured from roentgenograms. A stroboscopic photography system and force plate data were used for the procedure.
Richards et al. 2016 [60]	N= 18; Healthy; 9M, 9F; 20-46 years; Weight: 75.1 kg (58.3-100)	Patellar	Dynamic exercises: decline squats at different angles of declination (0°, 5°, 10°, 15°, 20° and 25°)	**Force:** Inverse dynamics: Patellar tendon force (PTF) was determined by dividing the extensor moment (ME) by the tendon moment arm (PTMA): PTF = ME / PTMA. The moment arm was quantified as a function of the knee flexion angle by fitting a 2nd order polynomial curve to data published in previous literature [77]. A motion analysis system and force plate data were used for the procedure.
Zellmer et al. 2019 [57]	N= 25; Healthy; 25F 22.69 ±0.74 years; Weight: 61.55 ±9.74 kg; Height: 169.39 ±6.44 cm	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 patellar tendon force 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 [56]	N= 5; Healthy; 2M, 3F; 19-24 years (mean 22); Weight: 58-84 kg (mean 72); Height: 168-200 cm (mean 180)	Patellar	Dynamic exercises: single-leg decline squats at different angles of declination (0°, 5°, 10°, 15°, 20°, 25° and 30°) with and without a backpack of 10 kg	**Force:** Inverse dynamics: Normalised patellar tendon forces were estimated according to the following formula: $F_{tendon} = M/d$, 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 [78]. A motion analysis system and force plate data were used for the procedure.
Edsfeldt et al. 2015 [45]	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 [44]	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 [46]	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.

Powell and Trail 2004 [62]	N= 33; open carpal tunnel release surgery patients; 54 (24-86) years	Hand	Dynamic exercises: unresisted finger flexion and resisted finger flexion (pulley with weights 100-500g)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ''hook' was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger; FDP of the ring finger or little finger; FPL of the thumb).
Powell and Trail 2009 [61]	N= 24; open carpal tunnel release surgery patients; 12M, 12F; 57 (23-86) years	Hand	Dynamic exercises: resisted finger flexion (pulley with weights 100-500g) and resisted finger extension (rubber band)	**Force:** Load cell: An apparatus consisting of three vertical rods, each terminating in a ''hook' was used for the tendon force measurements. The central hook is connected to a load cell. During routine carpal tunnel decompression under local anaesthetic infiltration, tendon force measurements were carried out on each exposed tendon (FDS of the ring finger, middle finger or index finger).
Schuind et al. 1992 [63]	N= 5; open carpal tunnel release surgery patients; 3M, 2F	Hand	Dynamic exercises: wrist and fingers flexion and extension	**Force:** S-shaped force transducer: S-shaped force transducers were applied to the flexor pollicis longus and FDS and FDP tendons of the index finger in five patients operated on for treatment of carpal tunnel syndrome. The experiment was conducted during open carpal tunnel release surgery with local anaesthesia.

CONC: Concentric; ECC: Eccentric; FDP: Flexor digitorum profundus; FDS: Flexor digitorum superficialis; FPL: Flexor digitorum profundus longus; GRF: Ground Reaction Forces; HSR: Heavy Slow Resistance; M: Male; MRI: Magnetic Resonance Imaging; MTJ: Myotendinous junction; F: Female; %BW: Percentage of body weight

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[79]. 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[80]. 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[79]. For example, classical inverse dynamics assumes idealised pin joints and the existence of rigid body segments, and that does not match reality[79]. 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[79].

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[50,51,57], OpenSim[47], FreeBody[48], among others[49,53,56]. 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[50,51,57]. 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[80]. 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[49,53,56]. Some studies performed subject-specific calculations based on imaging techniques to minimise error[48,49], and others studies used data from previously published literature (e.g. 5 cm ankle moment arm)[47,58]. Alternatively, some studies used an intermediate method based on the use of new or previously published equations together with specific data from each patient[52,55,56,60]. 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[80,81], and, sometimes, this value is not scaled to the rest of the anatomical structures[80,82]. 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[83]. 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[80,82]. 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°)[80,81]. Likewise, these differences could translate into up to 67% differences in the estimated values of tendon force[80,81].

Despite all the above mentioned limitations, modelling approaches have been widely employed to estimate tendon forces[65]. 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.[33] Sensors must be biotolerable (for short-term measurements) and biocompatible (for long-term use), as well as easy to implant[23]. Additionally, devices should avoid damaging body tissues and alter the tendon and joint mobility and neuromuscular function[23]. It has been suggested that these sensors should also be flexible and allow wireless data transmission to facilitate their clinical use[33]. 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[84]. Additionally, potential complications such as local pain or infections have limited the use of this methodology to a restricted research population[84].

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[37,85–87]. This kind of transducer consists of a metallic buckle with strain gages through which a tendon is

looped[23]. When a tensile force is applied to the tendon, the buckle deforms and produces a voltage output proportional to the force[23]. Due to their configuration, these buckle transducers enable the measurement of force of the entire cross-section of the tendon[23]. This is an advantage over other implantable transducers (e.g., 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[23,88–90]. However, the placement of the tendon through the buckle shortens the tendon and can alter its natural movement[23]. 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[91]. 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 to previous force transducers[92]. 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[23,93]. 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[23,93]. 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[23,93]. This effect can be achieved using two types of sensors: intensity-based and spectral-based optical sensors[84].

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 contractions[94] and during dynamic activities such as walking or jumping[39,84,92,95,96]. These sensors have evolved from the earliest models (approximately 500µm)[97] to modern spectral-based models incorporating fibre Bragg gratings and micro-fabricated stainless steel housings (approximately 200µm)[84]. Modern optic fibre sensors offer some advantages such as small size, high sensitivity, fast response time, large dynamic range, and insensitivity to electromagnetic interference[84]. However, the main limitation of this measurement technique is still the invasiveness of the procedure for introducing and removing the sensor[84]. The procedure is usually performed under local anaesthesia, causing a little wound in the tissue that can interfere with movement[84]. Due to its smaller size, compared to 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 to other transducers, although still existing[23,92].

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[97].

Therefore, this technology may be considered an appropriate option for in vivo evaluation as long as these artefacts can be minimised[84].

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[23,88–90]. This phenomenon could be related to the relative sliding between the different tendon fascicles[88,89].

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[7,98,99,21]. 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[7,21,98]. 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)[51].

The use of imaging techniques (e.g., 2D[28,100,101] and 3D[102] ultrasound or magnetic resonance imaging[100]) 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[11,59]. However, the hysteresis of tendons has been reported to be approximately 10%[103], and the loading rate effect does not seem to be decisive in the range of loading rates applied during physical activities[104,105]. 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[106]. 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[107,108]. However, this is not done or at least described in most studies.

In this review, four studies[49,51,54,59] included a tendon elongation measurement for assessing tendon loads. Revak et al. (2017)[51] calculated the tendon strain by dividing the tendon stress (previously obtained) by the average Young modulus reported (819 N/mm^2)[51]. 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. (2016)[59] 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[109,110]. Differently, Rees et al. (2008)[54] and Chaudhry et al. (2015)[49] calculated the Achilles tendon length as the distance between the tendon origin and the tendon insertion[54]. Thus, they tracked the position of these anatomical sites by using an active marker motion analysis system[54]. 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[49], 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°)[111]. Thus, the joint position corresponding to the zero-length it is not always precisely known[23]. It is important to normalise this parameter to allow comparison between studies, for example, using a standardised position of the joint[23]. 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[23]. The use of a force sensor in conjunction with ultrasonography could help determine the zero-length in each subject[23]. 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[112]. In this regard, Kharazi et al. (2021)[113] 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[33]. The absence of a sensor inside the body that can hinder mobility, together with the non-use of anaesthesia, allow natural movements[23]. Additionally, ultrasonography enables the differentiation of muscle and tendon interfaces, enabling muscle and tendon strains to be independently measured[33]. 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. (2008)[54] and Chaudhry et al. (2015)[49]. 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[49]. However, this methodology was excessively laborious, so it was limited to only a few frames[49]. For this reason, different algorithms, usually based on cross-correlation, have been developed to automate the process[49,114–116]. 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[49,54]. On the other hand, displacement measurements between known points within the tendon mid-substance, known as speckle-tracking, can be used[33]. The speckle-tracking technique allows unique speckle patterns of the tendon to be identified and tracked during movement[117]. 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[80]. Thus, both methods may be adequate as long as they are properly reported, only being possible to compare results from the same approach[23]. Likewise, the choice of the anatomical site used as a tracking landmark is relevant. Thus, previous studies have shown that small variations (e.g., tibial tuberosity or plateau) result in significant differences in the values obtained, both in tendon strain itself and in other calculated mechanical properties (e.g., tendon stiffness)[118]. Numerous limitations of imaging techniques have been widely reported[23,33,80]. 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[33,80,119]. 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[33]. 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[33,80]. Second, the ultrasound image has a spatial limitation directly related to the length of the ultrasound transducer, especially affecting the measurement of long tendons[80]. This limitation could be obviated by scanning only the myotendinous junction[80]. 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[80]. For this reason, it is recommended to scan both tendon ends, using longer transducers when necessary[80]. 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[33,80]. While the measurement is done through the identification and tracking of anatomical sites in planar 2D images, the reality of three-dimensional movement means that tendon bulging, rotation, or twisting can occur, and this fact may introduce a systematic over- or underestimation of tendon length[33,80]. This limitation has been partially addressed with new 3D ultrasound techniques by capturing images in multiple static postures (e.g., Freehand 3D[102]). 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[33,80]. 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. (2015)[80].

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. (2008)[120] in knee extension-flexion cycles against calibrated resistance. Sheehan and Drace (2020)[100] 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[100,120]. This technique allows a three-dimensional 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[33]. 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. On the other hand, these strain sensors share many of their limitations with other implantable devices and must be biotolerable, biocompatible, and easy to implant[33].

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[121]. 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[121]. 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[121]. However, a tendon on which high force is applied responds with a progressive rising and falling edge, attributable to slower energy absorption and dissipation[121].

Another novel non-invasive approach is being developed for in vivo evaluation by tracking vibrational behaviour[122]. 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[122].

Although these techniques have some limitations such as artefacts caused by noise on the skin caused by movement of the limbs[121], 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. AEE and AICV searched and screened the articles, with assistance from JC. All authors contributed to data analysis and interpretation of the data. AEE drafted the manuscript, AICV and JC revised it critically, and all authors contributed to revisions and approved the final manuscript.

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Competing interests

None.

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Data availability statement

No additional data available.

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FIGURE TITLES

Figure 1. Flow diagram of the selection process

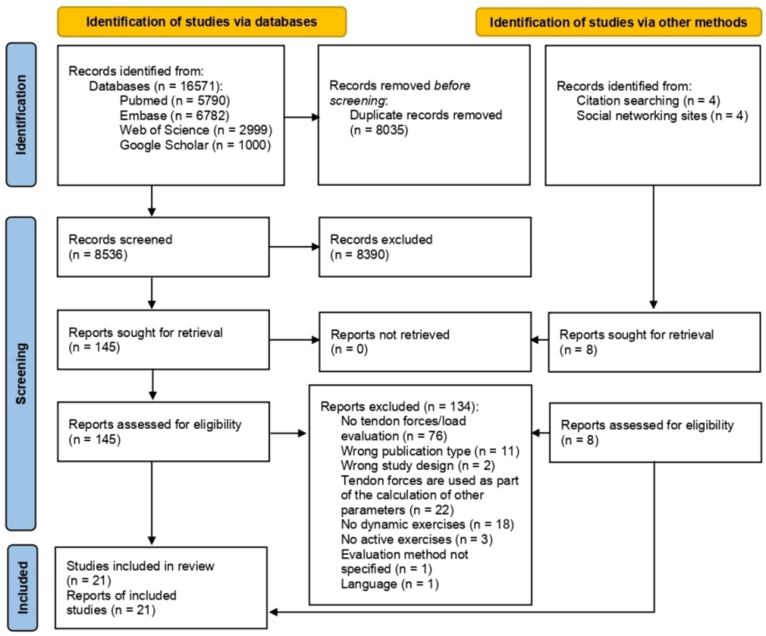

Figure 1. Flow diagram of the selection process.

210x297mm (150 x 150 DPI)

SUPPLEMENTARY FILE

BMJ OPEN

Supplement to: *Modelling and in vivo evaluation of tendon forces and loads in dynamic rehabilitation exercises: a scoping review*

Adrian Escriche-Escuder, Antonio I. Cuesta-Vargas, José Casaña

TABLE OF CONTENTS

Supplementary Appendices

Appendix S1. Detailed information sources and search strategy

	Pubmed	EMBASE	WOS	Google Scholar (200 primeras)
Tendon AND Load	3837	4311		200
Tendon [Title] AND Load [Title]	100	183	536	
Tendon [Title] AND Force [Title]	185	202	297	
Tendon [Title] AND Biomechanics [Title]	90	111	83	
Tendon AND wave	893	1220	1282	200
Tendon [Title] AND Properties [Title]	685	755	801	
Tendon AND Force				200
Tendon AND Biomechanics				200
Tendon AND Properties				200
	5790	**6782**	**2999**	**1000**
Total	**16571**			

Appendix S2. Articles excluded with full-text with reasons

Autor and year	Title	Reasons for exclusion
Acuna et al. 2019	Achilles tendon shear wave speed tracks the dynamic modulation of standing balance	No tendon forces/load evaluation
Aita et al. 1998	The load applied to the foot in a patellar ligament-bearing cast	No tendon forces/load evaluation
Andarawis-Puri et al. 2010	Infraspinatus and supraspinatus tendon strain explained using multiple regression models.	No tendon forces/load evaluation
Ando et al. 2019	Positive relationship between passive muscle stiffness and rapid force production	No tendon forces/load evaluation
Ateş et al. 2015	Muscle shear elastic modulus is linearly related to muscle torque over the entire range of isometric contraction intensity	No tendon forces/load evaluation
Beck et al. 2020	Cyclically producing the same average muscle-tendon force with a smaller duty increases metabolic rate	No tendon forces/load evaluation
Bobbert et al. 1986	An estimation of power output and work done by the human triceps surae musle-tendon complex in jumping	No tendon forces/load evaluation
Bojsen-Moller et al. 2003	Measuring mechanical properties of the vastus lateralis tendon-aponeurosis complex in vivo by ultrasound imaging	No tendon forces/load evaluation
Bojsen-Møller et al. 2005	Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures	No tendon forces/load evaluation
Bolus et al. 2021	Fit to Burst: Toward Noninvasive Estimation of Achilles Tendon Load Using Burst Vibrations	Proof-of-concept study
Breda et al. 2020	The association between patellar tendon stiffness measured with shear-wave elastography and patellar tendinopathy—a case-control study	No tendon forces/load evaluation
Bruggemann 1985	Mechanical load on the Achilles-tendon during rapid dynamic sport movements	Wrong publication type (Book chapter)
Brum et al. 2013	In Vivo Achilles Tendon Elasticity Assessment using	No tendon forces/load evaluation

	Supersonic Shear Imaging: a feasibility study	
Bujalski et al. 2018	A Monte Carlo analysis of muscle force estimation sensitivity to muscle-tendon properties using a Hill-based muscle model	No tendon forces/load evaluation
Burgess et al. 2007	Plyometric vs. Isometric training influences on tendon properties and muscle output	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cao et al. 2019	A multicenter large-sample shear wave ultrasound elastographic study of the achilles tendon in chinese adults	No tendon forces/load evaluation
Cattagni et al. 2017	No Alteration of the Neuromuscular Performance of Plantar-Flexor Muscles After Achilles Tendon Vibration	No tendon forces/load evaluation
Centner et al. 2019	Low-load blood flow restriction training induces similar morphological and mechanical Achilles tendon adaptations compared with high-load resistance training	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Chang et al. 2020	Strain ratio of ultrasound elastography for the evaluation of tendon elasticity	No tendon forces/load evaluation
Cheung et al. 2006	Effect of Achilles tendon loading on plantar fascia tension in the standing foot.	No dynamic exercises (No exercises evaluated)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cordo et al. 1993	Force and displacement-controlled tendon vibration in humans	No dynamic exercises (No exercises are used)
Cruz-Montecinos et al. 2015	Estimation of tensile properties of the Achilles tendon in haemophilic arthropathy of the ankle: case study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Cruz-Montecinos et al. 2019	Assessment of tensile mechanical properties of the Achilles tendon in adult patients with haemophilic arthropathy. Reproducibility study	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Deforth et al. 2019	The effect of foot type on the Achilles tendon moment arm and biomechanics	No tendon forces/load evaluation

Delp et al. 2007	OpenSim: open-source software to create and analyze dynamic simulations of movement.	Wrong publication type
Dennerlein et al. 1999	In vivo finger flexor tendon force while tapping on a keyswitch	No dynamic exercises (everyday tasks)
Ebrahimi et al. 2020	Shear Wave Tensiometry Reveals an Age-Related Deficit in Triceps Surae Work at Slow and Fast Walking Speeds	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Ejeskar et al. 1982	Finger flexion force and hand grip strength after tendon repair	No tendon forces/load evaluation
Farris et al. 2013	Differential strain patterns of the human Achilles tendon determined in vivo with freehand three-dimensional ultrasound imaging	No dynamic exercises (isometric)
Finni et al. 2008	Mechanical behavior of the quadriceps femoris muscle tendon unit during low-load contractions	No dynamic exercises (laboratory setting)
Firminger et al. 2019	Effect of Shoe and Surface Stiffness on Lower Limb Tendon Strain in Jumping	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Fowler and Nicol 2000	Interphalangeal joint and tendon forces: normal model and biomechanical consequences of surgical reconstruction	No dynamic exercises (everyday tasks)
Fowler et al. 1999	Measurement of external three-dimensional interphalangeal loads applied during activities of daily living	No tendon forces/load evaluation
Friesenbichler et al. 2019	Gait and strength asymmetries in patients with insertional achilles tendinopathy	No tendon forces/load evaluation
Fröberg et al. 2020	The Effect of Ankle Foot Orthosis' Design and Degree of Dorsiflexion on Achilles Tendon Biomechanics-Tendon Displacement, Lower Leg Muscle Activation, and Plantar Pressure During Walking	No tendon forces/load evaluation
Gerus et al. 2011	A method to characterize in vivo tendon force-strain relationship by combining ultrasonography,	Tendon forces are used as part of the calculation of other parameters and not

	motion capture and loading rates	reported as evaluation results
Gerus et al. 2012	Subject-Specific Tendon-Aponeurosis Definition in Hill-Type Model Predicts Higher Muscle Forces in Dynamic Tasks	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Giacomozzi et al. 2015	Does the thickening of Achilles tendon and plantar fascia contribute to the alteration of diabetic foot loading?	No tendon forces/load evaluation
Gomes et al. 2020	Is there a relationship between back squat depth, ankle flexibility, and Achilles tendon stiffness?	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hager et al. 2020	Influence of joint angle on muscle fascicle dynamics and rate of torque development during isometric explosive contractions.	No tendon forces/load evaluation
Hansen et al. 2006	Mechanical properties of the human patellar tendon, in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Harding et al. 1993	Finger joint force minimization in pianists using optimization techniques	No dynamic exercises (everyday tasks)
Harlaar et al. 2020	Patellofemoral joint contact forces at different activities - effects of modeling assumptions	No tendon forces/load evaluation
Harnie et al. 2020	Acute effect of tendon vibration applied during isometric contraction at two knee angles on maximal knee extension force production	No tendon forces/load evaluation
Hashizume and Yanagiya 2016	Influences of the foot strike pattern and the running speed on the forces applied to foot	Wrong publication type (Conference proceeding)
Haufe et al. 2020	Biomechanical effects of passive hip springs during walking	No tendon forces/load evaluation
Hauraix et al. 2015	In vivo maximal fascicle-shortening velocity during plantar flexion in humans.	No tendon forces/load evaluation
Heinemeier et al. 2016	Methods of Assessing Human Tendon Metabolism and Tissue Properties in Response to Changes in Mechanical Loading	Wrong publication type (Book chapter)

Helland et al. 2013	Mechanical properties of the patellar tendon in elite volleyball players with and without patellar tendinopathy.	No tendon forces/load evaluation
Histen et al. 2017	Achilles Tendon Properties of Minimalist and Traditionally Shod Runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hoang et al. 2007	Passive mechanical properties of human gastrocnemius muscle-tendon units, muscle fascicles and tendons in vivo	No dynamic exercises
Hof et al. 2002	Mechanics of human triceps surae muscle in walking, running and jumping	No tendon forces/load evaluation
Holzer et al. 2020	Considerations on the human Achilles tendon moment arm for in vivo triceps surae muscle-tendon unit force estimates	Wrong study design (calculations using results from other studies)
Homayuouni et al. 2015	Modeling Implantable Passive Mechanisms for Modifying the Transmission of Forces and Movements Between Muscle and Tendons	No tendon forces/load evaluation
Hopper et al. 2015	Dance floor force reduction influences ankle loads in dancers during drop landings.	No tendon forces/load evaluation
Hu et al. 2014	Biomechanical Analysis of Force Distribution in Human Finger Extensor Mechanisms	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Hullfish et al. 2020	A simple instrumented insole algorithm to estimate plantar flexion moments	No tendon forces/load evaluation
Jones et al. 1985	Effect of muscle tendon vibration on the perception of force	No tendon forces/load evaluation
Joseph et al. 2014	Achilles tendon biomechanics in response to acute intense exercise.	No dynamic exercises
Kathy Cheng et al. 2008	Finite element analysis of plantar fascia under stretch—The relative contribution of windlass mechanism and Achilles tendon force	Wrong study design (Finite element analysis)/ No tendon forces/load evaluation
Kawakami et al. 2002	Effect of series elasticity on isokinetic torque-angle relationship in humans.	Tendon forces are used as part of the calculation of other parameters and not

		reported as evaluation results
Kawakami et al. 2002	In vivo muscle fibre behaviour during counter-movement exercise in humans reveals a significant role for tendon elasticity	No dynamic exercises (laboratory setting)
Kaya and Yucesoy 2020	Muscle-tendon unit length-spastic muscle force data by combined intraoperative-musculoskeletal modelling work	No tendon forces/load evaluation
Kernozek et al. 2016	Comparing Two Methods for Estimating Achilles Tendon Loading during Running	Wrong publication type (Conference proceeding)
Kernozek et al. 2018	The effects of habitual foot strike patterns on Achilles tendon loading in female runners	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Kongsgaard et al. 2006	Decline eccentric squats increases patellar tendon loading compared to standard eccentric squats	No dynamic exercises
Kouno et al. 2019	Effects of the strain rate on mechanical properties of tendon structures in knee extensors and plantar flexors in vivo	No dynamic exercises
Kruse et al. 2019	Effects of serial casting on muscle-tendon properties, muscle function and gait in a healthy child with calf muscle shortening	No tendon forces/load evaluation
Kubo et al. 1999	Influence of elastic properties of tendon structures on jump performance in humans	No tendon forces/load evaluation
Kubo et al. 2000	Elastic properties of muscle-tendon complex in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2001	Influence of static stretching on viscoelastic properties of human tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2002	Measurement of viscoelastic properties of tendon structures in vivo	No tendon forces/load evaluation
Kubo et al. 2003	Gender differences in the viscoelastic properties of tendon structures	No tendon forces/load evaluation
Kubo et al. 2005	Effects of cold and hot water immersion on the mechanical	No dynamic exercises

	properties of human muscle and tendon in vivo.	
Kubo et al. 2015	Relationship between elastic properties of tendon structures and performance in long distance runners	No tendon forces/load evaluation
Kubo et al. 2015	Relationship between Achilles tendon properties and foot strike patterns in long-distance runners	No tendon forces/load evaluation
Kubo et al. 2020	Mechanical properties of muscle and tendon at high strain rate in sprinters	No tendon forces/load evaluation
Lee et al. 2015	Repeatability and agreement of digital image correlation (DIC) for regional strain estimates of the in-vivo human patellar tendon	No tendon forces/load evaluation
Lian et al. 1996	Characteristics of the leg extensors in male volleyball players with jumper's knee	No tendon forces/load evaluation
Lian et al. 2003	Performance characteristics of volleyball players with patellar tendinopathy	No tendon forces/load evaluation
Lichtwark et al. 2006	Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Lichtwark et al. 2011	Achilles tendon (3D): Do the mechanical properties of tendon change in response to exercise?	Wrong publication type (Conference proceeding)
Lima et al. 2017	Triceps surae elasticity modulus measured by shear wave elastography is not correlated to the plantar flexion torque	No tendon forces/load evaluation
Lu et al. 2013	Quantifying Catch-and-Release: The Extensor Tendon Force Needed to Overcome the Catching Flexors in Trigger Fingers	No dynamic exercises (everyday tasks)
Mademli et al. 2008	Age-related effect of static and cyclic loadings on the strain-force curve of the vastus lateralis tendon and aponeurosis	No dynamic exercises
Marouane et al. 2017	Changes in Knee Adduction Rotation and not Adduction Moment Influence Joint	Wrong publication type (Conference proceeding)

	Compartmental Load Partitioning	
Martin et al. 2012	Effects of the index finger position and force production on the flexor digitorum superficialis moment arms at the metacarpophalangeal joints - a magnetic resonance imaging study.	No tendon forces/load evaluation
Martin et al. 2018	Gauging force by tapping tendons	No tendon forces/load evaluation
Matsubayashi et al. 2008	Ultrasonographic measurement of tendon displacement caused by active force generation in the psoas major muscle	No tendon forces/load evaluation
McCrum et al. 2018	Loading rate and contraction duration effects on in vivo human Achilles tendon mechanical properties	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McMahon et al. 2013	The manipulation of strain, when stress is controlled, modulates in vivo tendon mechanical properties but not systemic TGF-β1 levels	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
McNair et al. 2013	Biomechanical properties of the plantar flexor muscle-tendon complex 6 months post-rupture of the Achilles tendon	No tendon forces/load evaluation
Mileusnic et al. 2009	Force estimation from ensembles of Golgi tendon organs	No tendon forces/load evaluation
Mimura 1986	[The load-bearing function of a patellar tendon bearing cast]	No tendon forces/load evaluation
Monte 2021	In vivo manipulation of muscle shape and tendinous stiffness affects the human ability to generate torque rapidly	No tendon forces/load evaluation
Nicol et al. 1998	Significance of passively induced stretch reflexes on achilles tendon force enhancement	No active exercises evaluated
Nicol et al. 1999	Quantification of Achilles tendon force enhancement by passively induced dorsiflexion stretches	No active exercises evaluated
Okuyama et al. 2019	Study on fingertip force sensor based on measurement of tendon tension	Tendon forces are used as part of the calculation of other parameters
Olszewski et al. 2015	Achilles tendon moment arms: the importance of measuring at	No dynamic exercises

	constant tendon load when using the tendon excursion method.	
Pearson et al. 2013	The use of normalized cross-correlation analysis for automatic tendon excursion measurement in dynamic ultrasound imaging.	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Peltonen et al. 2013	Viscoelastic properties of the Achilles tendon in vivo	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Perl et al. 2012	Effects of Footwear and Strike Type on Running Economy	No tendon forces/load evaluation (no data)
Petrescu et al. 2016	Evaluation of normal and pathological Achilles tendon by real-time shear wave elastography	No tendon forces/load evaluation (no data)
Rowley et al. 2000	The effect of the patellar tendon-bearing cast on loading	No tendon forces/load evaluation
Salman et al. 2019	Spatial Variations in Achilles Tendon Shear Wave Speed Using a Cost-Effective Method of Accelerometers	Wrong publication type (Conference proceeding)
Saltzman et al. 1992	The patellar tendon-bearing brace as treatment for neurotrophic arthropathy: a dynamic force monitoring study.	No tendon forces/load evaluation
Sasaki et al. 2019	Electromyographic analysis of infraspinatus and scapular muscles during external shoulder rotation with different weight loads and positions.	No tendon forces/load evaluation
Sheehan et al. 2000	Human patellar tendon strain. A noninvasive, in vivo study	No tendon forces/load evaluation
Sinsel et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation during exercises
Slane et al. 2014	Non-uniform displacements within the Achilles tendon observed during passive and eccentric loading	No tendon forces/load evaluation
Stafilidis et al. 2007	Muscle-tendon unit mechanical and morphological properties and sprint performance	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results

Stanojev et al. 2018	Effects of patellar tendon strap bracing on the motor performance and biomechanics of healthy adolescent athletes	Wrong publication type (Conference proceeding)
Stegman et al. 2009	A feasibility study for measuring accurate tendon displacements using an audio-based Fourier analysis of pulsed-wave Doppler ultrasound signals.	Wrong publication type (Conference proceeding)
Sugisaki et al. 2011	Effect of muscle contraction levels on the force-length relationship of the human Achilles tendon during lengthening of the triceps surae muscle-tendon unit	Tendon forces are used as part of the calculation of other parameters and not reported as evaluation results
Sussmilch-Leitch et al. 2012	Effect of foot orthoses on ankle kinematics and kinetics in male runners with Achilles tendinopathy	Wrong publication type (Conference proceeding)
Taniguchi 1988	[The load bearing function of patellar tendon bearing brace--on the relation between shaft length and rate of load bearing]	No tendon forces/load evaluation
Thomeer et al. 2020	Load Distribution at the Patellofemoral Joint During Walking.	No tendon forces/load evaluation
Totorean et al. 2014	The role of plantar pressure evaluation in rehabilitation of patients with Achilles tendon ruptures	No tendon forces/load evaluation
Ullrich et al. 2010	Influence of length-restricted strength training on athlete's power-load curves of knee extensors and flexors	No tendon forces/load evaluation
Ushiyama et al. 2005	Difference in aftereffects following prolonged Achilles tendon vibration on muscle activity during maximal voluntary contraction among plantar flexor synergists	No tendon forces/load evaluation
Veeger et al. 2002	Load on the shoulder in low intensity wheelchair propulsion.	No tendon forces/load evaluation
Wearing et al. 2019	Do habitual foot-strike patterns in running influence functional Achilles tendon properties during gait?	No tendon forces/load evaluation
Wearing et al. 2020	Transmission-Mode Ultrasound for Monitoring the Instantaneous Elastic Modulus of the Achilles Tendon During	No tendon forces/load evaluation

	Unilateral Submaximal Vertical Hopping	
Werkhausen et al. 2018	Effect of training-induced changes in achilles tendon stiffness on muscle–tendon behavior during landing	No tendon forces/load evaluation
Werkhausen et al. 2019	Distinct muscle-tendon interaction during running at different speeds and in different loading conditions.	No tendon forces/load evaluation
Westphal et al. 2013	Load-Dependent Variations in Knee Kinematics Measured with Dynamic MRI	No dynamic exercises (No exercises are used)
Woodburn et al. 2013	Achilles tendon biomechanics in psoriatic arthritis patients with ultrasound proven enthesitis	The method of evaluating tendon forces is not specified.
Wretenberg et al. 1993	Passive knee muscle moment arms measured in vivo with MRI	No active exercises
Wu et al. 2013	The musculoskeletal loading profile of the thumb during pipetting based on tendon displacement	No tendon forces/load evaluation
Yamaguchi et al. 2002	Effect of different frequencies of skipping rope on elastic components of muscle and tendon in human triceps surae	Wrong language (Japanese)
Yamamoto et al. 2020	Effects of Varying Plantarflexion Stiffness of Ankle-Foot Orthosis on Achilles Tendon and Propulsion Force during Gait	No tendon forces/load evaluation
Yoshitake et al. 2004	Fluctuations in plantar flexion force are reduced after prolonged tendon vibration	No tendon forces/load evaluation

Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
TITLE			
Title	1	Identify the report as a scoping review.	1
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	4
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	6
METHODS			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	6
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	7
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	6
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	6
Selection of sources of evidence†	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	7
Data charting process‡	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	8
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	8
Critical appraisal of individual sources of evidence§	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	8

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SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE #
RESULTS			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	9
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	9
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	10
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	10
DISCUSSION			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	20
Limitations	20	Discuss the limitations of the scoping review process.	31
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	32
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	33

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews.
* Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.
† A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).
‡ The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.
§ The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

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