Categorize the existing clamps used for tensile test of human graft– a systematic review

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Abstract

Background: The use of tendon allografts for orthopedic repair has gained wide acceptance in recent years, most notably in anterior cruciate tendon reconstruction. Multiple studies support the use of tendon allografts and the benefits of its use are well accepted and understood. One of the important criteria of the use of tendon allografts is statistically similar histological and biomechanical properties to autographs. The aim of this systematic literature review is to investigate and categorize existing clamps used in the determination of the biomechanical properties of tendons such as maximum load, maximum strength, modulus of elasticity, ultimate strain, and stiffness. A variety of clamps for use during the endurance test of tendons were categorized according to the temperature used during the measurement. The clamps are divided into three groups: room temperature, cooled and heated clamps. The second goal of our review is to overview of clamps on the following aspects: name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters, and summarize in Table 3, as a comprehensive catalogue.

Methods: This systematic review was carried out in keeping with the PRISMA 2020 E&E and the PRISMA-S guidelines and checklists. A search was conducted for publications dating between 1991 and February 28th 2022 through three electronic databases (Web of Science, Scopus, and PubMed). We used Critical Appraisal Skills Program checklist to check the quality of included articles.

Results: The database search and additional sources resulted in 1725 records. 1635 records eliminated during the screening for various reasons (case report, other languages, book chapter, unavailable text/conference abstract, unrelated topic). The number of articles used in the final synthesis was 90. A variety of clamps for use during the endurance test of tendons were identified and categorized according to the temperature used during the measurement. Based on this, the clamps are divided into three groups: room temperature, cooled or heated clamps.

Conclusions: On the basis of the systematic literature review, mechanical parameters determined by usage with cooled clamps proved to be more reliable than with those at room temperature and with heated clamps. The collected information from the articles included name of clamp, author and date, type of clamps, type of endurance
Introduction
The use of tendon allografts for orthopedic repair has gained wide acceptance in recent years, most notably in anterior cruciate tendon reconstruction [1–3]. Multiple studies support the use of tendon allografts and the benefits of its use are well accepted and understood [2, 4–7]. Specifically, these benefits include decreased surgical time, decreased surgical morbidity and unaltered mechanics secondary to harvesting. Furthermore, animal and human studies have shown that soft tissue allografts are statistically similar to autografts on a histological and biomechanical basis [8–10].

Anterior cruciate ligament (ACL) reconstruction is a common procedure in orthopedic practice. One of the most important decisions for the surgeon to make is the right choice of graft. Although autografts have proven to be capable and showed good clinical outcomes, graft harvest can cause persistent pain at the harvest site and a limited range of motion [11–14]. Therefore, allograft use has significantly increased in the last decades. Since it eliminates donor-site morbidity, and albeit its use is associated with higher costs, it remains a viable option, especially in revision cases. In order to ensure that there is a minimal biomechanical difference between the ACL and the graft, the biomechanical properties need to be tested so that we can choose which tendons can be good substitutes [7, 15].

The purpose of a clamp is a proper fixation technique for allograft endurance tests, and adapt it to be compatible for the loading machine [10, 19]. The main problem with tendon clamps is that it is hard to maintain the high pressure needed to provide enough friction force between the tendon and the clamp to resist a large tensile load, and at the same time to reduce the cutting effect of the clamp, reducing slippage danger [7, 20–24].

Various clamps have been developed for the assessment of the endurance test. These clamps are usually specific for measurement methods, thus, the results of the measurement methods are difficult to compare [1, 8, 11–15, 25, 26].

Aim of study
The literature of the effect of the sterilization method on the material properties of the tendon is well researched and discussed [27–31]. Nevertheless, there are no systematic reviews on the subject that would provide guidance on the clamps used for the measurements. The aim of this systematic literature review is to investigate and categorize existing clamps used in the determination of the biomechanical properties of tendons such as maximum load, maximum strength, modulus of elasticity, ultimate strain, and stiffness. A variety of clamps for use during the endurance test of tendons were categorized according to the temperature used during the measurement. The clamps are divided into three groups: room temperature, cooled and heated clamps. The second goal of our review is to overview of clamps on the following aspects: name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters, and summarize in Table 1, as a comprehensive catalogue.

Table 1  Inclusion and exclusion criteria

| Viewpoints                              | Inclusion                                                                 | Exclusion                                                                 |
|-----------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Tendon and endurance test and clamp     | Studies which included tendon and endurance test and clamp in their experimental procedures. | Studies which only included a tendon measurement method without any type of clamp. |
| Description of tendon and endurance test and clamp | Studies with detailed descriptions of the tendon and endurance test and clamp and the experimental process that was followed. | Studies without detail or incomplete descriptions of the clamp and endurance test and the experimental process that was followed. |
| Assessment of results                   | Studies with objective result assessment based on measurable parameters.   | Studies with subjective scoring/assessment of results, not (entirely) based on measurable parameters. |
Materials and methods
Data sources and search strategy
This systematic review was carried out in keeping with the PRISMA 2020 E&E and the PRISMA-S guidelines and checklists [32, 33]. A search was conducted for publications dating between 1991 and February 28th 2022 through three electronic databases (Web of Science, Scopus, and PubMed). The searches were conducted on March 1st 2022.

The electronic search for the Web of Science database is shown below. These terms were added into the Advanced search option, using the 'All fields' option: ALL=((allograft tendon OR allograft tendon* OR (allograft* AND tendon*)) AND (biomechanical pull-out test* OR stiffness OR strength OR mechanical properties OR modulus OR endurance test* OR clamp OR clamps OR clamp*)). The search was limited to journal publications. Publication date limits were set to from 1991, with the search performed on February 28th, 2022. The search of the Web of Science database yielded 670 records.

The Scopus database was searched as follows. Were used the basic search, in 'Search within' were used 'All fields' option. In 'Search documents' were used the follow search strategy: (allograft OR tendon) AND (biomechanical AND pull-out AND test OR stiffness OR strength OR mechanical AND properties OR modulus OR endurance AND test* OR clamp OR clamps). The search of the Scopus database yielded 599 records.

The PubMed database was searched as follows. These terms were added into the 'Advanced' option, using 'All fields' option: ALL=((allograft tendon"[tw] OR "allograft tendons"[tw] OR (allograft* AND tendon*)) AND ("biomechanical pull-out test"[tw] OR "stiffness"[tw] OR "strength"[tw] OR "mechanical properties"[tw] OR "modulus"[tw] OR "endurance test"[tw] OR "clamp"[tw] OR clamps[tw] OR clamp*[tw])). The search of the PubMed database yielded 456 records.

Key search terms were identified and agreed upon by DF and RMK; electronic search and downloading of results were conducted by DF. Screening, eligibility check of materials and date extraction were carried out by DF and BK [34]. The reviewers worked independently and no automation tools were used at each stage of screening. Our search strategy excludes examinees based on a reference list. Screening materials.

Screening materials
After removing the duplicates, the identified publications were screened based on their title and their abstracts. Publications of exclusively theoretical work or with topics deviating from the aim of study were excluded.

Inclusion and exclusion criteria
In order to confirm eligibility for the study, the reviewers defined the inclusion and exclusion criteria. The publications had to meet each inclusion criterion to be incorporated in the final synthesis (Table 2). If a study failed to meet any inclusion criteria, or met an exclusion criterion, it was excluded. The criteria were carefully chosen to ensure a quality assessment of the material to a certain extent, i.e., the methods used had to be well communicated and the evaluation of measurement results had to be objective.

Data extraction and analysis
In accordance with the focus of this review, the final synthesis of the collected types of clamps included extracted relevant information on the evaluation of mechanical properties. The collected information from the articles included: name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters.

Study quality, risk of Bias
Articles were evaluated using the Critical Appraisal Skills Program (CASP) quality assessment tool [112]. CASP contains several checklists, one of which is the CASP Qualitative Studies Checklist of 10 questions that we used. This checklist has several items that allow authors to rate articles for “low”, “medium” and “high” quality assessment. This review is by two authors (DF and RMK) and active discussion until consensus was reached in the case of rating discrepancies. We did not undertake a risk of bias assessment because the included studies were not randomized controlled studies and because our evidence synthesis method is outside of systematic reviews.

Results
The search of the database source gave 1725 results (Prisma 2020 Flow Diagram). Removing duplications 1361 literatures remained. When screening the titles and the abstracts, an additional 657 records were excluded, due to not fitting the scope. The remaining 704 articles have been read in their entirety. Of these studies, 567 were excluded with justifications of not meeting the eligibility criteria (without any type of clamp, incomplete description, subjective results). These review articles had a different scope from our current study. The number of articles included in the final synthesis was 90 (n=90).
| Study                  | Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | Was the research design appropriate to address the aims of the research? | Was the recruitment strategy appropriate to the aims of the research? | Was the data collected in a way that addressed the research issue? | Has the relationship between researcher and participants been adequately considered? | Have ethical issues been taken into consideration? | Was the data analysis sufficiently rigorous? | Is there a clear statement of findings? | How valuable is the research? | Overall quality assessment |
|------------------------|----------------------------------------------------------|-------------------------------------------|--------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|----------------------------------------------|-------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Aeberhard 2019 [35]    | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Aguila 2016 [36]       | 1                                                        | 1                                         | 1                                                                        | 2                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Athwal 2020 [37]       | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Awogni 2014 [38]       | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Aynardi 2017 [39]      | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Azar 2009 [40]         | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Bachmaier 2020 [41]    | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Baer 2007 [6]          | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Baldini 2014 [42]      | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Balsly 2008 [43]       | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Barros 2021 [44]       | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Bartolo 2021 [45]      | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Basso 2002 [46]        | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Bechtold 1994 [47]     | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Berlet 2014 [48]       | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Bernstein 2022 [49]    | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Bi 2018 [50]           | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Braunstein 2015 [51]   | 1                                                        | 1                                         | 1                                                                        | 1                                                                      | 1                                                                      | 1                                                                            | 1                                                                            | 1                                                                        | 1                                                                            | 1                                                  | high                                    |
| Study                      | Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | Was the research design appropriate to address the aims of the research? | Was the recruitment strategy appropriate to the aims of the research? | Was the data collected in a way that addressed the research issue? | Has the relationship between researcher and participants been adequately considered? | Have ethical issues been taken into consideration? | Was the data analysis sufficiently rigorous? | Is there a clear statement of findings? | How valuable is the research? | Overall quality assessment |
|---------------------------|----------------------------------------------------------|-------------------------------------------|--------------------------------------------------------------------------|-------------------------------------------------------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------|
| Chivot 2017 [52]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Chizari 2011 [53]         | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Colaco 2017 [54]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Coledige 2004 [55]        | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Conrad 2012 [10]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Curran 2004 [56]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Delgado 2014 [27]         | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Dibartola 2016 [30]       | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Dorna 2018 [57]           | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Dziedzic-Goclawiska 2005 [58] | 1                         | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Edwards 2016 [59]         | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Ehrensberger 2013 [60]    | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Elmes 2014 [61]           | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Erivan 2018 [62]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Farago 2020 [63]          | 1                                                        | 1                                         | 1                          | 1                                                                                                                   | 1                                                                                     | 1                                                                                                                                  | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | 1                                                                                                             | high                                                                            |
| Study                          | Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | Was the research design appropriate to address the aims of the research? | Was the recruitment strategy appropriate to the aims of the research? | Was the data collected in a way that addressed the research issue? | Has the relationship between researcher and participants been adequately considered? | Have ethical issues been taken into consideration? | Was the data analysis sufficiently rigorous? | Is there a clear statement of findings? | How valuable is the research? | Overall quality assessment |
|-------------------------------|---------------------------------------------------------|-----------------------------------------|--------------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| Gaines 2017 [64]              | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Gardner 2013 [65]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Giannini 2008 [66]            | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Gibbons 1991 [67]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Goh 2014 [19]                 | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Gokler 2021 [68]              | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Greaves 2008 [69]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Guerraoudj 2007 [70]          | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Gut 2015 [71]                 | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Halewood 2011 [72]            | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hangody 2016 [73]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hangody 2017 [74]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hashemi 2005 [75]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Herbert 2017 [76]             | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hoburg 2010 [77]              | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hoburg 2011 [78]              | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Hoburg 2014 [79]              | 1                                                       | 1                                       | 1                                                                               | 1                                                                      | 1                                                                      | 1                                                              | 1                                        | 1                                        | 1                                        | 1                                        | high                                    |
| Study                          | Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | How was the recruitment strategy designed? | Has the relationship between the researcher and participants been adequately considered? | Was the data analysis sufficiently rigorous? | Was the data collected in a way that addressed the research issue? | Was the research design appropriate to address the aims of the research? | Was ethical issues been taken into consideration? | Has the data analysis been sufficiently rigorous? |
|-------------------------------|---------------------------------------------------------|------------------------------------------|-------------------------------------------|--------------------------------------------------------------------------------------|---------------------------------------------|---------------------------------------------------------------------|-------------------------------|------------------------------------------------|---------------------------------------------|
| Höher 2013                    | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Huang 2013                    | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Irani 2018                    | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Jones 2007                    | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Jung 2011 [84]                | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Kemper 2010                   | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Kranjec 2020                  | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Lansdown 2017 [86]            | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Lenkovich 2014 [87]           | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Mac 2003 [8]                  | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Mahiragullari 2007 [9]        | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| McGilvary 2010 [88]           | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Miller 2017                   | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Mook 2017                     | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Ng 2012 [91]                  | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Ninomiya 2011 [92]            | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Oswald 2017                   | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Pailte 2015                   | high                                                   | high                                     | high                                      | high                                                                                  | high                                        | high                                                                                | high                           | high                                                           | high                                                        |
| Reference | Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | Was the research design appropriate to address the aims of the research? | Was the recruitment strategy appropriate to the aims of the research? | Was the data collected in a way that addressed the research issue? | Has the relationship between researcher and participants been adequately considered? | Have ethical issues been taken into consideration? | Was the data analysis sufficiently rigorous? | Is there a clear statement of findings? | How valuable is the research? | Overall quality assessment |
|-----------|---------------------------------------------------------|---------------------------------------------|------------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Penn 2009 [95] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Proberaj 2020 [96] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Rasmussen 1994 [97] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Ren 2012 [98] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Roberson 2017 [31] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Rudy 2017 [99] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Salehpour 1995 [100] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Samsell 2011 [14] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Schimizzi 2007 [101] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Schmidt 2012 [102] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Schmidt 2016 [13] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Schmidt 2019 [103] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Seto 2012 [104] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Smith 1996 [105] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Sobel 2012 [106] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Suhodolcan 2012 [107] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Swank 2014 [108] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
| Tse 2012 [109] | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | high |
Table 2 (continued)

| Was there a clear statement of the aims of the research? | Is a qualitative methodology appropriate? | Was the research design appropriate to address the aims of the research? | Was the recruitment strategy appropriate to the aims of the research? | Was the data collected in a way that addressed the research issue? | Has the relationship between researcher and participants been adequately considered? | Have ethical issues been taken into consideration? | Was the data analysis sufficiently rigorous? | Is there a clear statement of findings? | How valuable is the research? | Overall quality assessment |
|---------------------------------------------------------|------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|--------------------------------------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Weber 2018 [110]                                         | 1                                        | 1                                                                   | 1                                                                   | 1                                                                   | 1                                                                        | 1                                                             | 1                                                             | 1                                                             | 1                                                             | high                                          |
| Yanke 2013 [100]                                         | 1                                        | 1                                                                   | 1                                                                   | 1                                                                   | 1                                                                        | 1                                                             | 1                                                             | 1                                                             | 1                                                             | high                                          |
| Yanke 2013-2 [111]                                       | 1                                        | 1                                                                   | 1                                                                   | 1                                                                   | 1                                                                        | 1                                                             | 1                                                             | 1                                                             | 1                                                             | high                                          |
The flow diagram describing the process has uploaded as a Supplementary file\textsuperscript{1}.

Table 3 summarizes the results of the quality assessment for each included article. One articles \cite{113} had an inadequate recruitment strategy. All other articles were rated “high” in all respects.

**Type of clamps**

The systematic review aimed at creating a comprehensive catalogue of existing clamps used in the determination of biomechanical properties. These studies evaluated what kind of impact the type of clamp had on the measurement \cite{35–39, 41, 44–46, 48, 49, 51–53, 55–57, 59, 62, 64, 70, 72, 75, 77–80, 84, 85, 87, 89, 90, 92–94, 96, 98, 99, 101–103, 109–111, 115–117}, cooled clamps (under room temperature with ice, cooled air, dry ice or liquid nitrogen) \cite{36, 42, 43, 60, 63, 65, 66, 68, 69, 73, 74, 76, 82, 95, 108} and heated clamps (over room temperature with heated air, heated fluids) \cite{50, 81, 104, 113, 114}. All three groups are factory-made and custom-designed clamps.

**Room temperature clamps**

Measuring at room temperature is a quick test because it requires the least amount of preparation as there is no need for dry ice, liquid nitrogen, heating, etc. Sufficient force is applied during the measurement to prevent tendon slippage, but no transverse tension is created during the capture of the tissues, which yields invalid results.

One of the room temperature clamps is the U-shaped frame (Fig. 1), which can be used for the measurement of the following parameters:

- Failure stress, failure strain, normalized stiffness, energy to failure
- Ultimate elongation, ultimate stress, ultimate stiffness
- Maximum stress, maximum strain, modulus
- Failure load, stiffness
- Failure load, stiffness, strain
- Linear stiffness, ultimate tensile force, tensile modulus, ultimate tensile strength, ultimate tensile strain
- Failure load, failure stress, stiffness
- Young’s modulus of elasticity, maximum load, strain at tensile strength, strain at break
- Tensile strength, tensile modulus
- Stiffness, maximum load
- Ultimate tensile stress, elastic modulus, toughness

| Name of clamp | References | Type of clamp | Type of endurance test | Pre-loading type | Type of tendon | Measured and calculated parameters |
|---------------|------------|---------------|------------------------|-----------------|---------------|-----------------------------------|
| Metal U-shaped frames | 47, 50 | room temperature | static | dynamic | sheep patellar tendon | failure stress, failure strain, normalized stiffness, energy to failure |
| Custom designed clamps | 67 | room temperature | static | static | canine patella-ligament-tibia | failure load, stiffness |
| Factory clamps | 36 | room temperature | dynamic | dynamic | human patellar tendon | ultimate elongation, ultimate stress, ultimate stiffness |
| Wedge shaped factory-clamps | 42 | room temperature | dynamic | static | achilles | maximum stress, maximum strain, modulus |
| Wedge-grip clamps | 34, 38 | room temperature | dynamic | dynamic | human patellar tendon | failure load, stiffness |
| Aluminum grips with polymer liners | 40, 59, 60 | room temperature | dynamic | dynamic | human patellar tendon | failure load, stiffness, strain |
| Testing configuration for single-strand and double-strand | 32, 69 | cooled temperature | static and dynamic | dynamic | tibialis anterior and posterior | linear stiffness, ultimate tensile force, tensile modulus, ultimate tensile strength, ultimate tensile strain |
| Custom designed clamps with dry ice chamber | 28 | cooled temperature | dynamic | dynamic | anterior and posterior tibialis | failure load, failure stress, stiffness |
| Factory clamps with dry ice chamber | 56 | cooled temperature | dynamic | dynamic | achilles, quadriceps, semitendinosus-4-gracilis, tibialis anterior, peroneus longus | Young’s modulus of elasticity, maximum load, strain at tensile strength, strain at break |
| Clamp with thermo-couple | 37 | heated temperature | dynamic | dynamic | bilateral patellar tendon | tensile strength, tensile modulus |
| Custom clamp in testing chamber | 57 | heated temperature | static and dynamic | static and dynamic | human patellar tendon | stiffness, maximum load |
| Custom clamp in biochamber | 70 | heated temperature | dynamic | dynamic | soleus tendon | ultimate tensile stress, elastic modulus, toughness |
of the tendon together with the bones. The bone was secured in custom-designed fixation frame with screws. The precision of the drill was ensured by an outer polyethylene mold. [115, 116] In a special case, the bone is inserted into a separately moulded block while the free tendon is pulled by the clamp. The solution allows to investigate the relationship between bone and tendons. (Fig. 2). [117]

Some researchers used custom-designed clamps, where the bone block was secured with either interface polymethylmethacrylate-PMMA or polyurethane [107] (Fig. 3). A solution can also be applied where the natural tendon is fixed by a bone block at one end and by a
pneumatic clamp to prevent slippage [110] (Fig. 4). Here, it is particularly important to prevent slippage between the clamp and the tendon, therefore the surface is scratched by sand spraying in several cases.

**Cooled clamps**

A basic condition for an appropriate measurement method is to prevent the tendon from slipping out of the clamp, therefore various methods are applied for establishing an adequate connection. One of the reasons for slippage is that the tendon is damp. Therefore it is expedient to continuously freeze the surroundings of the clamp, which naturally scratches the surface. It is expedient to use dry ice or liquid nitrogen for freezing. A disadvantage is that it is not easy to place the freezing substance in the surroundings of the clamp [35–39, 41–46, 48, 49, 51–53, 55, 57, 62, 64, 65, 69, 70, 72, 73, 75, 76, 80, 82, 84, 87, 89, 90, 92–94, 96, 99, 103, 108, 109, 111]. Particular care should be taken that the entire tendon is not completely cooled / frozen because thus the mechanical properties of the tendon are changed. A basic solution for all clamps is that the natural tendon (without the bone) is squeezed between two metal grips, and the two metal grips are fastened to each other by screws. Connection between the grips and the tendon is further increased by grooved metal or plastic inserts fixed on the internal surface of the grips [35–39, 41–46, 48, 49, 51–53, 55, 57, 62, 64, 65, 69, 70, 72, 73, 75, 76, 80, 82, 84, 87, 89, 90, 92–94, 96, 99, 103, 108, 109, 111]. In certain cases, the tendon and the clamp are congealed together, so they work together properly; furthermore, no slippage occurs between tendon and clamp and the tendon does not get torn near the clamp, either [42, 65]. This method can be used in case of tendons of different sizes and types.

However, one of the simplest solutions is that the clamps or clamp inserts can be cooled separately before measuring, regardless of the tensile machine. In this case, they should be placed in a deep-freezer for at least 24 h. The tendon is placed into the cooled clamp; the grips squeezing the tendon can be fixed in one or two rows (Fig. 8) [69, 108].

One of the major advantages of cooled clamp use is that they are designed to prevent slippage between the clamp and the tendon, therefore the surface is scratched by sand spraying in several cases.

**Heated clamps**

Measurements conducted in an environment of room temperature, using room-temperature or sooled clamps, greatly differ from the temperature of the natural surroundings of tendons (37 °C). Environment temperature presumably affects mechanical properties: more accurate results are yielded if tests are conducted at body temperature. In order to ensure this, it is expedient to use heated clamps [50, 81, 86, 104, 113, 114]. A disadvantage is that, contrary to cooled clamps, the connection between the clamps and the tendon is not improved, but it is also important that it is not deteriorated, either. In general, it is expedient to use a heated liquid for warming [50, 81, 86, 104]; heat insulation should be provided around both the clamps and the component to be examined (Fig. 11) [114]. The measurement can also be performed in a bath filled with heated liquid, which is continuously monitored. It is a basic requirement that the heated liquid should not deteriorate the properties of the tendon (Fig. 12) [81]. The circulation of the liquid simulates the behavior of the blood. (Fig. 13) [104].

**Discussion**

The clamp should be designed to prevent the slippage of the tendon from the clamp, but the clamping force should not change the tensile state of the tendon to be examined. The aim of this systematic literature review is to investigate and categorize existing clamps used in the determination of the biomechanical properties of tendons such as maximum load, maximum strength, modulus of elasticity, ultimate strain, and stiffness. A variety of clamps for use during the endurance test of tendons were categorized according to the temperature used during the measurement. The clamps are divided into three groups: room temperature, cooled and heated clamps. The second goal of our review is to overview of clamps on the following aspects: name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters and summarize in Table 1, as a comprehensive catalogue. The clamps are divided into three groups: room temperature, cooled and heated clamps. The collected information from the articles included name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters. The data are summarized in Table 1.

The metal U-shaped frame (Fig. 1) allows for bone–tendon strength to be studied [115, 116]. This clamp also ensures stability of the tendon, not letting it slip out. Because the tendon is clamped tightly, tissue texture can be damaged. In several cases, capture is performed using natural bones (Figs. 1 and 2) or artificial blocks (bone cement, silicone, artificial resin) (Fig. 3) [107, 110]. Natural tendon ends can be captured by custom – generally pneumatic – clamps (Figs. 4 and 6), or embedded in artificial material (Fig. 5) [56, 106]. All of these ensure that
the tendon does not slip out, but both need to be monitored for the polymer to graft adhesion [56, 77–79, 106]. In those cases, the force awakening between the clamping heads ensures the success of the measurement [56, 77, 106, 107, 110] [78, 79]. Natural and artificial blocks or hydraulic presses keep the tendon in place. [107, 110].

The wedge-grip clamp and the aluminum grips with polymer liners and the strain gauge clamp are similar (Figs. 5 and 6); however, adhesion between the polymer and the tendon can be monitored [56, 106], 40,59,60. Advantages of room temperature clamps include easy usage and no requirement for any measurement preparation. The disadvantage is that room temperature clamps can damage tendon texture, can cause the tendon to tear at the point of fixation, and the tendon can slip out.

In multiple research projects, cooled clamps are used for measuring the biomechanical properties of a tendon [42, 65, 69, 73, 108]. A great advantage of frozen clamps is that surfaces are naturally made coarse by freezing, which assists in establishing an appropriate connection between the clamp and the tendon. The solution is relatively simple: the tendon can be fastened by two metal grips fixed by screws. The first type of cooling is freezing the clamp before testing (Fig. 8). This requires a freezer that can freeze at -70°C to -80°C. The frozen clamp also has to be attached to the machine. The tendon takes on the clamp’s temperature over time.
The clamps shown in Figs. 9 and 10 use a dry ice container for cooling. The dry ice container allows for the tendon and the clamp to be cooled at the same time. Dry ice needs to be added during measurements, as it evaporates over time [42, 65, 73]. Both of these types of cooled clamps stop the tendon from slipping out. Cooled clamps allow for the tendon to freeze at the point of fixation, causing the tendon to tear at the weakest point [69, 108].

Heated clamps are required to be used for measurements at human body temperature (37°C) [42, 65, 69, 73, 81, 104, 108, 114]. Leading-edge measurement designs (Fig. 13) can also imitate a human body environment (temperature, blood circulation). [104]. Heated clamps have the same disadvantages as room temperature clamps; the tendon can easily slip out, can be damaged by the clamp, or tear at the point of fixation [81, 104, 114].

**Limitation**

This study focused on the investigation and categorization of existing clamps used in the determination of biomechanical properties. Due to the use of different tests and tendons, they were compared based on individual criteria. It is recommended that for subsequent tests, measurements be made only with refrigerated clamps. From the measurements made in this way, a meta-analysis of the results is obtained. This study provides an overview of clamps and does not represent the modernity of any method.

**Conclusions**

The objective of this systematic literature review is to investigate and categorize existing clamps used in the determination of the biomechanical properties of tendons such as maximum load, maximum strength, modulus of elasticity, ultimate strain, and stiffness. A variety of clamps for use during the endurance test of tendons were categorized according to the temperature used during the measurement. The clamps are divided into three groups: room temperature, cooled and heated clamps. The collected information from the articles included name of clamp, author and date, type of clamps, type of endurance test (static or dynamic), type preloading (dynamic or static), type of tendon and measured and calculated parameters given in Table 1. summarized.

On the basis of systematic literature review, the mechanical properties determined for using with cooled clamps proved to be more reliable than room temperature and heated clamps. The main advantage is that there is no limit to the type and length of the tendon. The dry-ice clamp instead of liquid nitrogen is recommended for the clamping of tendons, because dry ice is cheaper to acquire than liquid nitrogen. Liquid nitrogen evaporates
**Fig. 9** Cooled clamps with different ice chambers a) custom-designed clamp [42] b) factory clamp [65]

**Fig. 10** Screwed custom clamps with aluminium chamber for dry ice [73]
faster than dry ice. It is also easier to work with dry ice, permission is not needed for use, and it does not need to be stored in a container. In similar quantities, liquid nitrogen is colder than dry ice, which can harden the whole tendon, not just at the point of fixation.

Disadvantages of room temperature and heated tendons are that they can damage the tendon’s texture and have a greater chance of slipping. During the measurement, a great force is created at capture, therefore an inaccurate result can be obtained. In the case of heated clamps, it should be taken into account that living tissue, when removed from the cadaver, begins to decay. This decay can be accelerated by the warm environment, which can lead to a distortion of the results. Since there is no unlimited amount of human tissue available, the most accurate measurement setup should be used [118–121].

Abbreviations
ACL: Anterior cruciate ligament.
Supplementary Information

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Additional file 1: Emphasis.

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Authors' contributions

DF, BK analyzed and interpreted the patient data regarding the hematological disease and the transplant. DF, RK performed the histological examination of the kidney and was a major contributor in writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available from authors of not open access journals but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from Denes Farago upon reasonable request and with permission of authors of not open access journals. All data generated or analysed during this study are included in this published review.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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