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Review

# Quantification of soft tissue artifact in lower limb human motion analysis: A systematic review

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ABSTRACT

This systematic review critically evaluates the quantification of soft tissue artifact (STA) in lower limb human motion analysis. It has a specific focus on assessing the quality of previous studies and comparing quantitative results. A specific search strategy identified 20 published articles or abstracts that fulfilled the selection criteria. The quality of the articles was evaluated using a customised critical appraisal tool. Data extraction tools were used to identify key aspects reported in the articles. Most studies had small sample sizes of mostly young, slim participants. Eleven of the reviewed articles used physically invasive techniques to assess STA. STA was found to reach magnitudes of greater than 30 mm on the thigh segment, and up to 15 mm on the tibia. The range of soft tissue artifact reached greater than 25 mm in some cases when comparing the results of reviewed studies.



## 1. Introduction

Stereophotogrammetry [1] is the most frequently used method of clinical human motion analysis [2]. Due to inaccuracies related to working with biological systems [3], there are limitations in the way 3D motion data are acquired. Markers attached to the skin move with respect to the underlying bones that they are intended to represent [4]. This error is known as ‘‘soft tissue artifact’’ (STA).

STA arises from movement or deformation of the subcutaneous tissues associated with muscular contractions, skin movement and inertial effects [5]. The extent of STA for any movement depends upon the physical characteristics of individuals [6], marker locations [7] and the nature of the movement task being performed [8]. The exact magnitude of STA in kinematic calculations has been difficult to determine. Leardini et al. [3] summarised the different methods used to assess and compensate for STA. Here, we provide a systematic review and critical evaluation of the published literature on methods to quantify STA. The review will analyse the quality of the available literature and aim to summarise assessment techniques used to quantify the effects of STA on kinematic results. Furthermore, the review identifies what is known about STA in current motion analysis practice.

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## 2. Methods

### 2.1. Search strategy

An electronic search of the following international databases was performed in November 2008; MEDLINE (1950), Embase (1980), Cinahl (1982), Web of Science (1900), Biosis (1969) and Inspec (1898). Keywords in the search strategy included ‘minimise’, ‘motion analysis’, ‘skin movement’, ‘soft tissue displacement’, ‘artifact’ and ‘error’. Key search terms were matched with medical subject headings (MeSH) and exploded to include all subheadings where relevant. Truncations and wildcards were used to enable the search to retrieve all possible variations of a specific root word. Targeted searching was conducted to identify literature that may have been overlooked by electronic database searching. This included online searching of journals likely to contain relevant articles. A manual search of reference lists of relevant studies also identified articles for the review.

### 2.2. Inclusion and exclusion criteria

The titles and abstracts of articles retrieved from the search strategy were assessed by a single reviewer (AP). Articles were included when they satisfied the following criteria: (1) study included human participants, (2) gait or functional tasks were investigated, (3) an implied or documented objective to quantify STA in the article, (4) 2D or 3D motion analysis techniques, (5) pelvic and or lower limb data, and (6) full scientific papers and abstracts. Excluded from the review were studies published only as conference proceedings and articles using artificial or additive error [9].

### 2.3. Data extraction

A customised data extraction form was developed based on previous systematic reviews of associated areas [10–13]. The major data extraction themes were; introduction, equipment and setup, methodology, results, discussion and conclusion. These themes were selected to create a comprehensive illustration of each article for analysis and assessment of the quality of the available scientific literature. Three reviewers (AP, BG and MS) piloted the data extraction form to ensure review process was reliable.

**Table 1**
Quality analysis form used in systematic review[a].

| Question |
| --- |
| 1. Are the research objectives clearly stated? |
| 2. Is the study design clearly described? |
| 3. Were participant characteristics adequately described? |
| 4. Was sampling methodology appropriately described? |
| 5. Was sample size used justified? |
| 6. Were marker locations accurately and clearly described? |
| 7. Was marker attachment method clearly described? |
| 8. Was equipment design and set up clearly described? |
| 9. Were movement tasks clearly defined? |
| 10. Was the gold standard used appropriately justified? |
| 11. Were the analytical techniques clearly described? |
| 12. Were appropriate statistical analysis methods used? |
| 13. Were the main outcomes of the study clearly stated? |
| 14. Were direct results easily interpretable? |
| 15. Was the effect of direct results on output considered? |
| 16. Were key findings supported by the results? |
| 17. Were limitations of the study clearly described? |
| 18. Were key findings supported by other literature? |
| 19. Were conclusions drawn from the study clearly stated? |

[a] Questions were scored as follows: 2 = Yes; 1 = Limited detail; 0 = No.

### 2.4. Quality assessment

In systematic reviews, quality assessments are performed in addition to data extractions to enhance the standard of the review and reduce reviewer bias [14,15]. A number of standardised checklists exist which assist in the systematic assessment of the quality of published studies [16–20]. Downs and Black [21] concluded that it is feasible to assess the methodological quality of non-randomised trials by developing a checklist to produce a profile of the study alerting readers to manuscript strengths and weaknesses [21].

A customised quality assessment tool was developed because no standardised or validated quality assessment tool existed for the evaluation of articles in this field. The tool was based upon principles extracted from a number of sources including generic systematic review principles [14,15,19], The Delphi List [20], the STROBE statement [22] and articles regarding the feasibility of quality checklists for systematic reviews [16,21]. Quality extraction tools used in other systematic reviews of motion analysis with broadly similar themes [10,11,13] were also consulted.

The quality assessment tool used for this systematic review was developed around the major research aims (Table 1). A scored checklist was used to allow for an overall assessment of each article and provide a measure of the standard of work in the field. Each question was rated zero, one or two.

Three reviewers (AP, BG and MS) independently scored each article. Discrepancies found in responses after the review process were discussed by all reviewers. It was planned that major discrepancies unable to be resolved by the reviewers would be taken to a third party (MM) for resolution.

## 3. Results

### 3.1. Search yield

The initial electronic search of the selected databases yielded 662 published articles. Hand searching of article reference lists and journal table of contents identified one scientific article that had not been found by previous searches. Following the application of inclusion and exclusion criteria, 20 articles were selected for review. Details of reviewed articles are summarised in Table 2.

### 3.2. Quality of reviewed articles

The quality of the reviewed articles is summarised in Table 3. Most of the reviewed articles demonstrated high quality in the areas of research objectives, study design, description of marker location and attachment, reporting of main outcomes and key findings and the conclusions drawn. Many articles had limited sample size description, and statistical analysis. In nine of the reviewed articles [8,23–30], findings were not clearly supported by the literature and in six, limitations were not clearly described [5,8,25,31–33]. Meta-analysis was not used in this systematic review because the articles did not provide a sufficient number of similar studies of the same lower limb site. It was therefore not possible to determine an overall treatment effect or equivalent measure. A number of articles [6,32–35] demonstrated high content quality, scoring 80% or greater.

### 3.3. Participants

The reviewed articles tested participants with varying ages and physical characteristics. Six articles provided insufficient data regarding the physical characteristics of tested participants. The number of participants varied throughout the reviewed articles with the greatest number being 18 [30]. Eleven articles [6,8,23–27,29,33,35,36] tested five participants or less. Age was mostly restricted to young (18–30 years) or middle aged (30–60 years) participants. No children were tested in any of the reviewed articles. Body mass index was used to estimate the body composition of participants. The majority of participants had BMI less than 25, indicating that they were a healthy weight for their height.

### 3.4. Movement analysis

A variety of methods were employed for movement analysis. Thirteen articles used 3D stereophotogrammetry [5,6,8,23–27,32,34,36–38] and one article [35] used 2D video motion analysis techniques for primary motion capture. The remaining articles used Fluoroscopy [29,31,33], X-ray radiographs [28,30] and MRI [39] for both primary motion capture and a gold standard comparison. Thirteen of the reviewed articles [5,6,8,23,25,28,30,32,34–38] reported the use of physically invasive gold standard techniques such as intra-cortical bone pins or X-ray radiation.

### 3.5. Analytical techniques

Two broad categories of analytical techniques were used to obtain kinematics from raw data (Table 4). One article [28] uses direct anatomical modelling, this assumes markers representing anatomical landmarks are fixed in the model, with no error between the modelled and measured marker locations. All other articles used kinematic fitting techniques. In kinematic fitting methods segment kinematics are obtained by minimising some cost function, for example, the least squares error between modelled and measured marker positions [5,6,23–25,27,31,33–35]. Modelling techniques utilising technical frames with one [5,6,27,32,33,37,38] or two statics [23,24] were also utilised in conjunction with kinematic fitting. Most articles described this process well.

### 3.6. Quantification of STA

The quantification of STA was achieved by direct (Table 5) and indirect (Table 6) measurement approaches. Direct measures reported the actual movement of markers with respect to the underlying bone and indirect measures reported the effect on joint angles and segment translations.

## 4. Discussion

### 4.1. Quality

Five of the reviewed articles were of high quality [6,32–35]. A number of articles were deemed to be less satisfactory with only one article scoring less than 50% on the quality assessment. There

**Table 2**
Data extraction results from reviewed articles.

| Reference | Article | Participants | Age | BMI | Motion analysis | Gold standard | Limitations | | Conclusions |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Reviewer | Author | Author |
| [28] | Maslen and Ackland | 10 | 27 (18–35) | 24 | X-ray | X-ray | 2D X-ray only static images between movements | 2D analysis only | Significant discrepancies in the locations of skin and skeletal markers were observed |
| [5] | Cappozzo et al. | 7 | 25 (17–33) | 23.7 (21–29) | 3D | External fixation device | Invasive and small sample different attachments fracture healing may alter gait | | Markers located on the skin above ALs[a] undergo error relative to the bone proportional to joint displacement |
| [29] | Sati et al. | 3 | | – | Fluoroscopy | Fluoroscopy | Small sample size systematic errors only tested knee markers | Small sample difficulty with marker resolution | Data from this method is fundamental in improving acquisition methods to minimise STA |
| [23] | Cappello et al. | 1 | Young | – | 3D | External fixation device | Invasive and small sample cycling task only multiple calibrations introduce error | Multiple calibrations introduce error | MALC[b] improves the estimation of ALs using more accurate interpolation in the range of 3° and 3 mm. |
| [8] | Fuller et al. | 2 | 38 (35–40) | 27 (25–29) | 3D | Intra-cortical pins | Invasive and small sample bone and skin separately tested | | Skin mounted marker data are inappropriate for tracking the underlying bones. |
| [6] | Holden et al. | 3 | 33 (28–36) | 25 (22–29) | 3D | Percutaneous skeletal trackers | Invasive and small sample no thigh data | PST device limited to use in safe areas Shank segment only | The greatest errors were along and around the shank long axis, PST[c] may eliminate surface movement errors |
| [35] | Reinschmidt et al. | 5 | 29 | 24 | 3D | Intra-cortical pins | Invasive and small sample Small capture vol (3 camera) ankle markers on shoes | Invasive Small capture volume Assume skin marker movement not restricted by pins | Tibiofemoral and AJC[d] rotations must be interpreted with caution when measured with external markers |
| [37] | Andriacchi and Alexander | 10 | 32 | 20.2 | 3D | Intra-cortical pins | GS[e] data not from same sample PCT[f]—high system demand | Comparison data not from same sample practical limits to PCT | PCT[f] provides a unique approach to the measurement of 3D human motion |
| [27] | Lucchetti et al. | 3 | 34 (27–45) | 23 (20–24) | 3D | | No gold standard Small sample only one joint time-consuming | 'Ad hoc' movements make process long only one joint considered | Through compensation, errors diminish to allow small joint movement information to be obtained |
| [26] | Karlsson and Tranberg | 1 | 35 | 27 | 3D | | Invasive and small sample size series of static postures load used not defined | Only static postures small sample size | Static and dynamic STA give contrary indications to best attachment sites |
| [36] | Alexander and Andriacchi | 1 | 46 | 27.5 | 3D | External fixation device | Invasive and small sample unrepresentative of in vivo | Invasive therefore may not be representative of normal movement | Interval deformation improves reconstruction of 3D limb motion by 33% (pos.) and 25% (orient.) compared with rigid body techniques |
| [38] | Manal et al. | 7 | | 25 (19–29) | 3D | Percutaneous skeletal trackers | Invasive and small sample size participants were slim Best case scenario | Slim participants best case scenario | Estimates of tibial translation with a measurement resolution better than 3 mm are unlikely |
| [32] | Houck et al. | 2 and 13 | 37 (35–38) | 26 (25–27) | 3D | Intra-cortical pins | Invasive and small sample size only 85% of gait cycle assessed | | FTD[f] method presents a practical alternative to recording tibio-femoral motion over the first 85% of stance |
| [33] | Stagni et al. | 2 | 66 (64–67) | 23 (22–24) | 3D | Fluoroscopy | Invasive and small sample size abnormal population (total knee replacement patients) | | The proximal thigh shows the largest STA which is subject- and task-specific |
| [34] | Benoit et al. | 8 | 26 (22–32) | 24.7 (20–29) | 3D | Intra-cortical pins | Invasive and small sample assumes normal distribution Assumes pin rigidity | Reduced skin movement due to bone pins lack of pin rigidity | A standard error of measurement in the region of 3° and 5 mm could be used when reporting kinematic data |

**Table 2** (*Continued*)

| Reference | Article | Participants | Age | BMI | Motion analysis | Gold standard | Limitations | | Conclusions |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Reviewer | Author | Author |
| [24] | Cappello et al. | 2 | 66 (64–67) | 23.0 (22–24) | 3D | Fluoroscopy | Small sample time-consuming | Time-consuming during experimental procedures | Double ALC[g] improves the calculation of knee joint rotations and translations but is task and subject specific |
| [39] | Sangeux et al. | 11 | 33 (23–55) | – | MRI | MRI | Series of static postures confined space restricted activity | Small MRI acquisition volume restricted to static postures | The method developed can be used in assessing marker sets for clinical kinematic analyses |
| [25] | Gao et al. | 2 | Cadaver | 0/0 | 3D | Intra-cortical pins | Tested cadaver tibia muscle contractions not considered | | Least squares best reduces soft tissue artifact post capture |
| [31] | Garling et al. | 10 | 73 (53–82) | 30.0 (26–35) | Fluoroscopy | Fluoroscopy | Small sample size variation due to axis definition | | Clustered markers result in large STA irrespective of the fixation method |
| [30] | Südhoff et al. | 18 | 25 (22–32) | 23 (20–28) | X-ray | X-ray | Invasive and small sample size Series of static postures | Small group sample size invasive | This study highlights that no system can limit displacement in the transverse plane |

[a] ALs, anatomical landmarks.
[b] MALC, multiple anatomical landmark calibration.
[c] PST, percutaneous skeletal trackers.
[d] AJC, ankle joint centre.
[e] GS, gold standard.
[f] FTD, femoral tracking device.
[g] ALC, anatomical landmark calibration.

were a number of domains which were not addressed adequately by any study, for example, most studies did not perform sample size calculations or state the sampling strategy used. It can be difficult to recruit large samples for studies using techniques which are physiologically or radiologically invasive. This makes the use of sample size calculations important, to ensure studies are adequately powered to be generalisable. Domains considered to have variable quality (average score <1.6) included participant characteristics, marker locations, justification of gold standards, description of equipment used and results. Of note, 40% of papers investigating STA did not clearly describe marker locations.

As a result of the quality evaluation of the reviewed articles a table of recommendations for future STA studies was created (Table 7). This checklist identifies specific points within the various domains that any well designed study should cover.

### 4.2. Techniques

A variety of techniques have been used to assess STA in the past. This is supported by the number of different techniques apparent in Table 4. Studies aiming to assess STA in human motion analysis most often used a gold standard comparison technique. Nearly half of the reviewed literature uses gold standard techniques requiring metal pins to be inserted through the skin and soft tissues into the bone [5,6,23,25,34–38]. Most of these studies were published from 1998–2004. The past use of invasive gold standard measurement techniques has allowed for the identification of their limitations. Some of these limitations, such as pin bending and antalgic gait [6], were suggested by Holden et al. to potentially affect the outcome of kinematic measures. Further to these limitations, such invasive methods constrain the movement of the soft tissues, thereby potentially limiting the measured artifact range [3].

A transition from physically invasive techniques to radiological and analytical techniques can be seen, particularly in studies published from 2005 onwards. X-ray radiography captures only still frames [28,30] whereas fluoroscopy [24,29,33,40] allows participants to move freely whilst simultaneously capturing surface markers and the motion of the underlying skeletal system. A more recently used gold standard is MRI as recommended by Sangeux et al. [39]. One benefit of MRI is that it does not subject participants to ionising-radiation which may be experienced during X-ray or fluoroscopy. At present however, MRI is limited to static or quasi-static investigations.

Analytical techniques have similarly shown transitional changes over time (Table 4). Those based on direct anatomical modelling [28] progressed to use technical marker sets with a pre-defined relationship between the anatomical and technical coordinate systems [23,24] and least squares calculation techniques [5,6,23–25,27,31,33–35]. Andriacchi and Alexander later proposed the point cluster technique to compensate for STA [24,30]. In addition to kinematic fitting techniques, Cappello and others demonstrated the use of multiple anatomical landmark calibration for the same purpose [23,24,41,42]. Although these more recent techniques have led to advances in STA research, they have not always been accompanied by changes in clinical practice. Recent work [43–45] suggests that global optimisation techniques might be adopted to reduce the contribution of STA although one paper has suggested that this is not as reliable as double anatomical calibration [41].

There is a clear progression in the methodology of STA research in 3-DGA. 3D motion analysis is used in many gait laboratories throughout the world as a tool to assist with clinical and surgical planning for patients [46]. New techniques to conduct more accurate 3-DGA are being developed; however, they are not being translated into clinical practice. It is essential that techniques developed to improve the accuracy of 3D motion capture are

**Table 3**
Quality analysis results from reviewed articles.

| Article | Question number | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| [28] Maslen and Ackland | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 0 | 1 | 2 |
| [5] Cappozzo et al. | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 0 | 2 |
| [29] Sati et al. | 2 | 2 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 2 | 1 | 0 | 2 | 2 | 1 | 2 | 0 | 1 | 2 |
| [23] Cappello et al. | 2 | 2 | 0 | 0 | 0 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | 1 | 2 |
| [8] Fuller et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 1 | 2 | 1 | 0 | 2 | 2 | 2 | 2 | 0 | 0 | 2 |
| [6] Holden et al. | 2 | 2 | 2 | 1 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 1 |
| [35] Reinschmidt et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| [37] Andriacchi and Alexander | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 2 | 1 | 1 | 2 | 0 | 2 | 1 | 1 | 1 | 1 | 2 | 0 |
| [27] Lucchetti et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 0 | 2 | 1 | 2 | 2 | 2 | 2 | 0 | 1 | 2 |
| [26] Karlsson and Tranberg | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 1 | 2 | 0 | 2 | 0 | 2 | 2 | 0 | 2 | 0 | 1 | 2 |
| [36] Alexander and Andriacchi | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 0 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| [38] Manal et al. | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |
| [32] Houck et al. | 2 | 2 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 0 | 2 | 2 | 1 | 0 | 2 |
| [33] Stagni et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 0 | 2 |
| [34] Benoit et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| [24] Cappello et al. | 2 | 2 | 1 | 0 | 0 | 2 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 0 | 1 | 2 |
| [39] Sangeux et al. | 2 | 2 | 1 | 1 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 2 | 2 | 2 | 1 | 2 | 2 |
| [25] Gao et al. | 2 | 2 | 2 | 0 | 0 | 1 | 2 | 0 | 0 | 0 | 1 | 2 | 2 | 2 | 1 | 2 | 0 | 0 | 1 |
| [31] Garling et al. | 2 | 2 | 2 | 0 | 0 | 2 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 1 | 2 | 0 | 1 | 0 | 2 |
| [30] Südhoff et al. | 2 | 2 | 2 | 0 | 0 | 2 | 2 | 1 | 2 | 2 | 2 | 1 | 2 | 0 | 2 | 2 | 0 | 1 | 2 |

Items were scored from 0 to 2. Questions related to the description or justification of (1) Objectives; (2) Study Design; (3) Participant characteristics; (4 and 5) Sample Size; (6 and 7) Marker locations; (8) Equipment; (9) Movement tasks; (10 and 11) Gold standard and Model; (12) Statistics; (13) Outcomes; (14 and 15) Results; (16 and 17) Key Findings; (18) Limitations; (19) Conclusion.

**Table 4**
Categories of analytical techniques.

| Family | Method | Sub-type | Articles |
|---|---|---|---|
| Kinematic fitting methods | Direct | Anatomical or plug-in-gait/vicon clinical manager | [28] |
| | Schut | Schut 1960 | [8] |
| | Least squares | Spoor and Veldpaus 1980 | [5,6,25] |
| | | Arun 1987/Challis 1995/Soderkvist 1993 | [23–25,27,31,33–35] |
| | Point cluster technique | Andriacchi 1998 | [25,37] |
| | | Alexander and Andriacchi 2001 | [36] |
| | Solidification | Cheze 1995 | [49] |
| | 3D models registration | | [30,31,39] |
| | No optimisation or unknown | | [28,29,32] |
| Modelling | Anatomical | | [26] |
| | Technical + static calibration | 1 Static | [5,6,27,32,33,38] |
| | | 2 Static | [23,24,41,42] |
| | Technical + medical images | Biplanar X-ray | [30,34] |
| | | MRI | [39] |
| | | Fluoroscopy | [29] |
| | Unknown | | [26] |

clinically applicable to allow for improvements in the quality of clinical lower limb motion analysis [47].

### 4.3. What is known about STA

It was not possible to perform a meta-analysis on the results due to a lack of homogeneity of the data [17]. Results were acquired through different methods, from different lower limb segments for different tasks. This review has enabled the identification of previously measured STA quantities at specific anatomical locations during human motion. These results provide confirmation that STA measurements differ depending on study methods, task and segment under analysis. The gold standard measurements and activities undertaken are not consistent for STA measurements over time. For the accurate comparison of results and conclusions regarding the reliability of the results, more consistent procedures would be required.

There are some obvious outliers in direct results obtained from the reviewed articles. The study by Karlsson and Tranberg [26], which gives the lowest direct STA measurements for the greater trochanter and lateral epicondyles, also receives a low quality score. This study investigated the stiffness of different attachment sites along the leg by measuring marker displacement when a force is applied directly to the marker. This method was not considered to be clinically relevant.

Markers over the anatomical landmarks of the thigh exhibit significant STA (>10 mm) (Table 5). The lateral epicondyle is particularly susceptible to STA with direct measurements generally greater than 20 mm [5,8]. Errors at the knee joint line reach over 40 mm [29]. Markers elsewhere on the thigh (clusters) do not seem as prone to STA with movement in the range of 7–12 mm [39,42]. Overall, the evidence obtained from the reviewed articles shows that markers on the tibia are less susceptible to STA than markers on the thigh. Similar measurement techniques find from 3 mm [26] to 15 mm [5] of displacement at the lateral malleolus.

The compiled results of indirect STA measurements (Table 6) indicate that STA is dependant upon the segment under analysis and the locations that have been instrumented to represent the underlying musculoskeletal structures. The indirect measurements of STA are highly variable, for example, STA is high for the thigh, ranging from 22–31 mm of translational [33,39] and 12–15° of rotational error [31,39]. STA for the foot was moderate, ranging

**Table 5**
Direct results obtained from reviewed articles.

| Direct | | | | | | |
|---|---|---|---|---|---|---|
| Landmark | Measure of artifact | | | Activity | Gold standard | Reference |
| | X (mm) | Y (mm) | Z (mm) | | | |
| Greater trochanter | 20 | 10 | 10 | Hip flexion | External fixation devices | [5] |
| | 10 | 15 | 20 | Cycling | Intra-cortical bone pins | [8] |
| | 7.3 | 12 | 8.4 | | External fixation devices | [23] [i] |
| | 6.7 | | 4.4 | Relaxed | | [26] |
| | 7.5 | | 4.0 | Tensed | | [26] |
| Lateral epicondyle | 30 | 5 | 10 | Knee flexion | External fixation devices | [5] |
| | 12 | 20 | 20 | Walking | Intra-cortical bone pins | [8] |
| | 25 | 20 | 20 | Cycling | Intra-cortical bone pins | [8] |
| | 16 | | 14 | Knee flexion | Fluoroscopy | [29] [a] |
| | 4.0 | | 2.4 | Relaxed | | [26] |
| | 4.0 | | 1.3 | Tensed | | [26] |
| Thigh cluster markers | 11 | 11 | 8.5 | Sit-to-Stand | Fluoroscopy | [33] [b] |
| | 5.6 | 4.9 | 10 | Hip extension | Fluoroscopy | [33] [b] |
| Head of the fibula | 10 | 10 | 10 | Knee flexion | External fixation devices | [5] |
| Lateral malleolus | 7.5 | | 7.5 | | X-ray radiography | [28] |
| | 15 | 10 | 10 | Ankle flexion | External fixation devices | [5] |
| | 7.0 | | 3.0 | Relaxed | | [26] |
| | 6.0 | | 3.0 | Tensed | | [26] |
| Shank cluster markers | 3.9 | 4.7 | 6.0 | Sit-to-stand | Fluoroscopy | [33] [b] |
| | 9.8 | 10 | 8.7 | Hip extension | Fluoroscopy | [33] [b] |

[a] Article reports results as RMSE or RMSD (mm).
[b] Article reports results as mean of the standard deviation marker displacement relative to the bone (mm).

**Table 6**
Indirect results obtained from reviewed articles.

| Indirect | | | | |
|---|---|---|---|---|
| Segment | ▲ Translation (mm) | ▲ Rotation (°) | Gold standard | Reference |
| Knee kinematics | 11 | | Percutaneous skeletal trackers | [6] |
| | 3 | 3 | External fixation devices | [23] |
| | | 2.1, 2.6, 3.9 | Intra-cortical bone pins | [35] [a] |
| | 14 | 4.3, 4.3, 8.4 | Intra-cortical bone pins | [35] [b] |
| | 13 | 6 | | [27] [a] |
| | 22 | 4.5 | Intra-cortical bone pins | [34] |
| | 0–40 | 15 | MRI | [39] |
| | 2.0, 2.8, 2.1 | 10–35 | MRI | [39] [c] |
| | | 1.5, 1.4, 1.6 | Fluoroscopy | [24] |
| Tibia/shank | 10 | 8 | Percutaneous skeletal trackers | [6] |
| | 7.1, 3.7, 2.1 | | Percutaneous skeletal trackers | [38] |
| | 14.1, 11.8, 8.3 | 0.3–2 | Percutaneous skeletal trackers | [38] |
| | 21 | 0.4–1.5 | Fluoroscopy | [33] |
| | 0.7–4 | 10 | Intra-cortical bone pins | [25] |
| | 0.01–0.8 | 4 | Intra-cortical bone pins | [25] |
| | 11 | | Fluoroscopy | [31] [c,d] |
| | 8 | | Fluoroscopy | [31] [b,e] |
| | 2.7 | | X-ray radiography | [30] |
| Femur/thigh | 6.5, 5.5, 10 | 8, 10, 9 | External fixation devices | [36] |
| | 3.5, 3, 3 | 2, 4.5, 4 | External fixation devices | [36] |
| | 31 | | Fluoroscopy | [33] |
| | 22 | 15 | MRI | [39] |
| | 17 | 12 | Fluoroscopy | [31] [b,d] |
| | 7.5 | 12 | Fluoroscopy | [31] [b,e] |
| | 4.5 | | X-ray radiography | [30] |
| Foot and ankle | 2.7–14.9 | | X-ray radiography | [28] |
| | | 3.1, 2.5, 3.5 | Intra-cortical bone pins | [35] [a] |
| | | 5.9, 5.2, 5.8 | Intra-cortical bone pins | [35] [b] |

[a] RMS difference.
[b] Maximum difference.
[c] Finite helical axis.
[d] Plate mounted markers.
[e] Strap mounted markers.

from 3 to 15 mm of translation error [28] and up to 2–6° of rotational error [35]. It was found that STA at the foot and ankle is highly dependant upon the load applied [28]. STA was small for the tibial segment, where translational error ranged from 0.01 mm [25] to 14.1 mm [38] and rotational error ranged from 0.3° [25] to 10° [31]. None of the reviewed articles investigated STA at the pelvis. One article was found which investigated the in-vivo motion of the lumbar spine [48]. This article makes reference to STA at the pelvis; however, it was not suitable for inclusion in this review.

There are some outliers in the results of indirect measurement of STA. The study by Gao et al. [25] indicates particularly optimistic

**Table 7**
Recommendations for future STA studies.

| Domain | Recommendation |
|---|---|
| Methods | |
| Participants | Inclusion criteria. Recruitment strategy. |
| Equipment and setup | Description of laboratory setting, data capture setting, marker set description (in sufficient detail to be reproduced), biomechanical model (in sufficient detail to be reproduced). |
| Study design | Tested movement task. |
| Sample size | How has sample size been determined? |
| Statistical methods | Description of statistical methods. Do these provide outcomes with the same units as the measured variables to ensure generalisability of results? |
| Results | |
| Participants | Adequate description of participant characteristics. |
| Data | Report of descriptive measures as well as more complex movement data. Always examine entire range of movement to ensure completeness of results. |
| Implications | Consider impact on clinical practice. |
| Discussion | |
| Limitations | Critical discussion of limitations of results. |
| Outcomes | Comparison of results with those already published in the literature. |

results for the tibia. This study used cadaver specimens. In doing so, much of the contribution of muscular contractions would be removed from the measurement of STA. On the other hand, Sangeux et al. [39] reported pessimistic findings for the knee. This could be attributed to the technique used for obtaining results. Indirect measurements from the Finite Helical Axis (FHA) description of the analysed movement were used which is known to be sensitive to measurement inaccuracies.

The activity performed was considered to affect the amount of STA in kinematic measurements in a number of studies [5,8,33]. Fuller et al. [8] investigated cycling and walking activities, the results show little difference in the effect of STA at both the greater trochanter and the lateral epicondyles. Stagni et al. [33] investigated hip extension and sit-to-stand (STS) activities and the STA effect on the thigh and shank marker clusters. Interestingly, the effect was reversed between the thigh and shank, where STS produced greater error at the thigh, and hip extension produced greater error at the shank. Cappozzo et al. [5] also investigated STA at various anatomical landmarks during different joint movements. They found maximal errors at the greater trochanter during hip extension, lateral epicondyles and head of the fibula during knee flexion and lateral malleolus during ankle flexion. These findings show that maximal errors will be encountered when a segment undergoes movement, or when a marker location is on a joint line [29].

There were no differences between direct and indirect measurements of STA. Both found the thigh to have the greatest error due to STA followed by the foot and ankle. Both measurements also showed tibial segment kinematics to be less affected by STA than the thigh and foot.

### 4.4. Limitations

There were several limitations of this systematic review. The search strategy was specifically designed to include only English language publications; therefore some articles may have been overlooked. Considerable emphasis was put on subjective opinions of reviewers. The quality scoring system was particularly generous in some domains with a score of "1" requiring only partial explanations, for example, basic descriptive statistics were awarded a score of "1" in the statistical analysis domain. This could affect the quality outcome of the reviewed article, implying a better result than may be realistic.

## 5. Conclusions

Despite the quality of the literature being generally high, there were no conclusive solutions to the issue of STA in human motion analysis. Reviewed studies have shown the effect of STA is dependant upon marker location, activity performed, the instrumented segment and individual participant characteristics. STA was found to be in the vicinity of 40 mm for some areas of the thigh. The results indicated that the tibia is less susceptible to STA, shown by the decrease in direct and indirect error measurements reaching maxima of no greater than 12 mm. Whilst it is possible to draw such broad conclusions from these studies, it is important to bear in mind that methodological limitations of experimental work limit the confidence that can be placed upon many of the more detailed measures. Future work to more accurately measure STA [43–45] validated by medical imaging modalities may still be required in order to progress our understanding of STA and devise effective methods compensating for it in 3D human motion analysis.

## Conflict of interest

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