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# What are the joint models used in multibody kinematic optimisation for the estimation of human joint kinematics? a review

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## Abstract

Human movement analysis is frequently accomplished through multibody kinematic optimisation which enforces joint constraints between adjacent segments. Despite the popularity of the approach, an array of different joint models have been applied in the literature which is known to affect the model-derived kinematics. The purpose of this study was to perform a literature review to determine the different joint models used when applying multibody kinematic optimisation to the full body, upper and lower limbs.

Embase, Medline, Scopus, PubMed, and Web of Science were systematically searched and a total of 66 relevant articles were identified and included in the review.

The main finding was that the upper and lower limb joints were typically modelled as spherical, revolute or universal joints with the purpose of removing non-physiological joint dislocation effects due to soft tissue artefact that would otherwise be predicted with single-body optimisation. A diversity of joint models used in multibody kinematic optimisation was found in the literature. The most frequently used models were the simple, idealised models which, however, have also been criticised for not accurately replicating the detailed joint mechanics. On the other hand, more advanced joint models have emerged, such as parallel mechanisms or coupling equations between the joint degrees of freedom. Nevertheless, no consensus exists on how the joints should be defined to accurately estimate the overall joint kinematics with multibody kinematic optimisation.

The review also revealed that the method has also been referred to under other names such as 'global optimisation' and 'inverse kinematics', which can be misleading since these names also have other, and more accepted, meanings. The authors, therefore, recommend that, in the future, the process is termed multibody kinematic optimisation.

*Keywords: least-squares optimisation, state-of-the-art, kinematic models*

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## 1. Introduction

Multibody kinematic optimisation is increasingly used to determine human joint kinematics from motion analysis systems (*e.g.*, stereophotogrammetry or inertial sensors) by accounting for joint characteristics. The method is alternatively called 'global optimisation', 'inverse kinematics' or 'motion reconstruction' in different research fields. While commonly used methods (*e.g.*, marker-cluster least-squares matching also referred to as single-body optimisation) consider each segment independently, multibody kinematic optimisation determines the pose of all the segments attached by various joints in the same process. The general

principle is typically to minimise, in least-squares sense, the difference between measured and model-determined trajectories of skin markers subject to rigid body and kinematic constraints.

Multibody kinematic optimisation is a key step in musculoskeletal modelling and is commonly used for kinematic and dynamic analysis with the aim of compensating for the soft tissue artefact and avoid apparent joint dislocations found when using single-body optimisation.

The model-derived kinematics largely depends on the definition of the joint models. In this study, a literature review was performed in order to determine the different joint models used in

multibody kinematic optimisation when applied to the full body, upper or lower limbs.

## 2. Materials and Methods

### 2.1. Search strategy

An electronic search was performed (in January 2016) in Embase, Medline, Scopus, PubMed, and Web of Science. Logical expressions for the search included ‘optim\* or kalman’, ‘kinemat\* joint’, ‘subject or human or limb’, and ‘model\* or over\*determ\*’. The search was based on the title, keywords and abstract. Reference list of key studies were also cross-referenced to obtain further articles. The articles retrieved from the search strategy were reviewed according to the following exclusion criteria: no English language, conference proceeding, single body or under-constrained optimisation, no kinematics results reported, predictive simulation, markerless, sensorless or single-camera motion analysis, application in cadaveric specimens, animal, robots and machines. Studies focussing on spine, hand, foot and mandible were also excluded.

### 2.2. Data extraction

The definition of the joint models were extracted from the reviewed articles. The joint models were classified in four categories:

- U (universal),
- H (hinge),
- S (spherical),
- C (joint models that defined closed loops and coupling relations between the joint degrees of freedom).

In this last category and in other miscellaneous cases, the definition of the joint models was detailed.

## 3. Results

### 3.1. Search yield

The search results were Embase: 738, Medline: 729, Scopus: 721, PubMed: 169, Web of Science: 417. After removing duplicates, the number of articles was 1441. According to the exclusion criteria, 55 articles were selected from the search, 8 more articles were obtained by cross-referencing and 4 very recent articles known by the authors were finally added for a total of 66 articles.

### 3.2. Upper limb joint models

Table 1 summarizes the type of joints found in the literature to model the upper limb. The most current open-loop upper limb kinematic chains included universal sterno-clavicular, elbow and wrist joints and a spherical scapulo-humeral joint (Prokopenko et al. 2001; Cerveri et al. 2003; Pontonnier and Dumont 2009; Debril et al. 2011; Fohanno et al. 2013). In this case, no acromio-clavicular joint was

modelled, only a clavicle segment links thorax and humerus.

Table 1: Occurrences of joint models used for wrist, elbow, thoraco-humeral (TH) or scapulo-humeral (SH), acromio-clavicular (AC), sterno-clavicular (SC) and scapuloa-thoracic joints.

	Wrist	Elbow	TH or SH	AC	SC	ST
H	0	5	0	0	0	0
U	<b>9</b>	<b>13</b>	1	0	5	0
S	6	5	<b>17</b>	<b>5</b>	<b>6</b>	0
C	0	0	2	0	0	<b>5</b>

Note: for each joint the value in bold corresponds to the most common model.

Alternatively, sterno-clavicular and acromio-clavicular joints were modelled as spherical (Jackson et al. 2012; Charbonnier et al. 2014; Laitenberger et al. 2015). Elbow and wrist joints were modelled as hinge and spherical, respectively (Cerveri et al. 2003; Ayusawa et al. 2014) or spherical (Roux et al. 2002; Lee et al. 2010; Sholukha et al. 2013).

Additionally, to allow for gleno-humeral translations, two studies considered six degrees of freedom (Roux et al. 2002; van den Bogert et al. 2013) while another considered ‘soft constraints’, that is to say that the spherical joint is modelled with a penalty-based method (Charbonnier et al. 2014).

Conversely, closed loops with thoraco-scapular (point(s)-on-ellipsoid) joint (Bolsterlee et al. 2014; Prinold and Bull 2014; El Habachi et al. 2015), and with humero-radial (spherical), humero-ulnar (linear annular) and radio-ulnar (spherical) joints (Laitenberger et al. 2015) were also proposed.

Other joint models relied on the definition of coupling equations between the degrees of freedom, especially scapular and clavicular rhythms (Sholukha et al. 2013; Seth et al. 2016).

### 3.3. Lower limb joint models

Table 2 summarises the type of joints found in the literature to model the lower limb. The most current lower limb kinematic chains included spherical hip, hinge knee and universal ankle joints (Reinbolt et al. 2005; Reinbolt et al. 2007; Andersen et al. 2009; Andersen et al. 2010; Duprey et al. 2010; van den Bogert et al. 2013; Aguiar et al. 2014; Fohanno et al. 2014; Aguiar et al. 2015; Marra et al. 2015; Martelli et al. 2015; Myers et al. 2015). The universal joint at the ankle was either modelled as concurrent or non-concurrent axes to account for both talocrural and subtalar joints.

Alternatively, spherical hip, knee and ankle joints have been also widely used in multibody kinematic optimisation (Lu and O'Connor 1999; Charlton et al. 2004; Stagni et al. 2009; Duprey et al. 2010; Lee et al. 2010; Groen et al. 2012; Moniz-Pereira et al.

2014; Ojeda et al. 2014; Robinson et al. 2014; Aguiar et al. 2015; Clément et al. 2015). Therefore, only the translations were constrained.

Table 2: Occurrences of joint models used for hip, knee and ankle.

	Ankle	Knee	Hip
H	5	<b>22</b>	1
U	<b>19</b>	1	0
S	14	15	<b>39</b>
C	6	18	0

Note: for each joint the value in bold corresponds to the most common model.

Closed loops (*i.e.*, parallel mechanisms or four-bar mechanisms) were also proposed for the knee (Duprey et al. 2010; Clément et al. 2015; El Habachi et al. 2015; Gasparutto et al. 2015; Valente et al. 2015) and ankle joints (Duprey et al. 2010; El Habachi et al. 2015; Valente et al. 2015).

In the same way as for the upper limb, other knee (Sholukha et al. 2006; De Groote et al. 2008; Scheys et al. 2011; Li et al. 2012; Sholukha et al. 2013; Zheng et al. 2014; Bonnechère et al. 2015; Gasparutto et al. 2015; Martelli et al. 2015; Valente et al. 2015) and ankle joint models (Sholukha et al. 2006; Sholukha et al. 2013; Bonnechère et al. 2015) relied on the definition of coupling equations between the degrees of freedom. Additionally, ‘soft constraints’ that defined deformable ligaments with a penalty-based method were also proposed (Clément et al. 2015; Gasparutto et al. 2015) and a fully deformable knee joint was introduced using a ‘force-dependent kinematics’ method (Marra et al. 2015).

#### 4. Discussion

The objective of the present study was to inventory the current joint models used in multibody kinematic optimisation for the estimation of the skeleton and/or joint kinematics. The main findings were that upper and lower limb joints were often modelled as hinge, universal or spherical joint with the main purpose of avoiding apparent joint dislocations as found when using single-body optimisation.

When joint displacements were of interest, the joints were modelled with three different approaches. First, ‘soft constraints’ were implemented using a penalty-based method (Charbonnier et al. 2014; Clément et al. 2015; Gasparutto et al. 2015). In this approach, a weighted sum of the squared distances between measured and model-determined skin marker trajectories and of the joint dislocations were minimised. The efficiency of the method relies on the choice of the weights. The ‘force-dependent kinematics’ method can be seen as an extension of the ‘soft constraints’ approach with contact and ligament stiffness instead of the numerical weights

(Marra et al. 2015). Second, coupling equations between the degrees of freedom, and in particular between joint translations and rotations, were defined (Sholukha et al. 2006; Sholukha et al. 2013; Seth et al. 2016). The coupling equations were established on cadaver experiments and the consistency with the *in vivo* weight-bearing joint performance remains questioning. For instance, when personalised with bi-planar fluoroscopic data during gait, the coupling equations appeared largely altered at the knee (Zheng et al. 2014). Third, closed loops with simple joints in parallel (*e.g.*, sphere-on-plane contact, point-on-ellipsoid contact, isometric ligament) were proposed (Duprey et al. 2010; Bolsterlee et al. 2014; Prinold and Bull 2014; El Habachi et al. 2015; Valente et al. 2015). The bio-fidelity of such model is to be further validated but this approach has the advantage to be possibility personalised through more conventional medical imaging than fluoroscopy (Clément et al. 2015).

The main limitations of this study are that *i*) the quality of the papers was not assessed and *ii*) that some articles may not be found despite caution in the search. Indeed, the keywords for the search were general since a series of too specific words in pilot searches failed to find the most relevant articles already known by the authors. No keyword was introduced specific to the ‘joint models’ because this study is part of a larger systematic review.

As stated in the introduction, several expressions refer to multibody kinematic optimisation for the estimation of human kinematics when the optimisation problem is over-determined. ‘Global optimisation’ firstly introduced by Lu and O’Connor (1999) also refers to mathematical methods, including stochastic methods and metaheuristics, for finding global optimum. ‘Inverse kinematics’ more generally includes under-determined problems often found in computer animation to generate realistic poses and movements with limited information (*e.g.*, end effector position). To better follow in the future the development and results of such methods, the authors would like to recommend using the formal expression ‘multibody kinematic optimisation’.

#### 5. Conclusion

In conclusion, this literature review revealed that the upper and lower limb joints were often modelled as spherical, hinge or universal even though these fail to estimate joint displacements that are present in some of the non-conforming joints of the human body. When joint displacement estimates were desired, multiple joint models have been proposed but, at this point, there does not appear to be a consensus in the literature of how this is best accomplished.

Finally, several expressions for multibody kinematic optimisation were found, and the authors encourage the community to adapt a consistent vocabulary to avoid confusion with other well-established names

in other fields as since such as 'global optimisation' and 'inverse kinematics'.

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