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1 **KINEMATIC MODELS OF LOWER LIMB JOINTS FOR**
2 **MUSCULO-SKELETAL MODELLING AND OPTIMIZATION IN GAIT ANALYSIS**

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27 **ABSTRACT**

28 Kinematic models of lower limb joints have several potential applications in musculoskeletal
29 modelling of the locomotion apparatus, including the reproduction of the natural joint motion.
30 These models have recently revealed their value also for in vivo motion analysis experiments,
31 where the soft-tissue artefact is a critical known problem. This arises at the interface between the
32 skin markers and the underlying bone, and can be reduced by defining multibody kinematic models
33 of the lower limb and by running optimization processes aimed at obtaining estimates of position
34 and orientation of relevant bones. With respect to standard methods based on the separate
35 optimization of each single body segment, this technique makes it also possible to respect joint
36 kinematic constraints. Whereas the hip joint is traditionally assumed as a 3 degrees of freedom ball
37 and socket articulation, many previous studies have proposed a number of different kinematic
38 models for the knee and ankle joints. Some of these are rigid, while others have compliant
39 elements. Some models have clear anatomical correspondences and include real joint constraints;
40 other models are more kinematically oriented, these being mainly aimed at reproducing joint
41 kinematics. This paper provides a critical review of the kinematic models reported in literature for
42 the major lower limb joints and used for the reduction of soft-tissue artefact. Advantages and
43 disadvantages of these models are discussed, considering their anatomical significance, accuracy of
44 predictions, computational costs, feasibility of personalization, and other features. Their use in the
45 optimization process is also addressed, both in normal and pathological subjects.

46

47 1. INTRODUCTION

48 Instrumental gait analysis deals with the estimation of kinematics and kinetics at the major joints of
49 the lower limbs, traditionally by means of stereophotogrammetric and dynamometric measurement
50 systems (Cappozzo *et al.*, 2005). As for the former, a number of reflective markers, i.e. the marker-
51 set, are stuck on the skin in correspondence of targeted anatomical landmarks, axes or planes,
52 according to specific protocols and conventions (Wu and Cavanagh, 1995; Wu *et al.*, 2002). From
53 the trajectories of these markers, obtained during the execution of the motor tasks under analysis,
54 three-dimensional body segment position and orientation (altogether hereinafter also referred to as
55 ‘pose’) are calculated together with their relative motion, respectively joint displacements and
56 rotations. For these calculations, many different options exist (Ferrari *et al.*, 2008; Leardini *et al.*,
57 2009; Leardini *et al.*, 2011), as for the selection of the marker-set, corresponding technical and
58 anatomical co-ordinate reference frames and joint conventions. In these series of estimations, the
59 interposition of soft tissues between the markers and the internal skeletal structures, the real target
60 of gait analysis, are particularly critical (Leardini *et al.*, 2005; Peters *et al.*, 2010; Akbarshahi *et al.*,
61 2010). This introduces the so called soft-tissue-artefact (STA), which can be as large as a few
62 centimetres (Stagni *et al.*, 2009). STA does affect final gait measurements much more than the
63 instrumental error derived from the stereophotogrammetric systems (Chiari *et al.*, 2005), and more
64 than the likely erroneous identification of the anatomical landmarks by the operator (Della Croce *et*
65 *al.*, 2005). This is independent from their anatomical typology (bony prominences, joint axes, or
66 internal joint centres) and of their identification via direct placement, instrumental calibration
67 (Kadaba *et al.*, 1990; Cappozzo *et al.*, 1995) or functional tests (Schwartz and Rozumalski, 2005).
68 Soft tissue motion results in deformation of the relevant cluster of markers, as well as in its rigid
69 displacement with respect to the underlying bones. These deformations and displacements are
70 associated to muscle contraction and relaxation, to gravitational and inertial effects, and also to skin
71 sliding, particularly across the joints because of their large rotations. The major problem for the

72 possible identification and reduction of this artefact is that it has mostly the same frequency content
73 of target movement (Leardini *et al.*, 2005).
74 Many are the studies in literature reporting attempts at reducing STA in gait analysis via segmental
75 or global optimization techniques using joint models. The latter is here referred to as multibody
76 kinematics optimization (MKO). From another perspective, many studies have defined
77 biomechanical models able to reproduce joint kinematics that have been applied to MKO
78 approaches. The present is the first review paper where both these series of studies are presented
79 and discussed thoroughly, respectively in Section 2 and 3, for current and future similar exercises
80 on MKO. In Section 3 the review is focused on kinematic joint models, used and validated
81 specifically for the compensation of STA. No single best solution is established as definite in the
82 literature, rather the aim of this review is to clearly define the many various options, being critical
83 on their possible advantages and disadvantages, for anyone then to be able to choose the most
84 suitable one according to the specific contexts and conditions of the optimal estimation. Relevant
85 selection criteria are also discussed based on findings from published studies.

86

87 **2. GAIT ANALYSIS WITH JOINT CONSTRAINTS FOR MKO BASED TECHNIQUES**

88 **2.1 The segmental approach**

89 Many approaches have been proposed to limit STA and its propagation to the final gait analysis
90 measurements. The simplest recommended careful locations of the markers (Cappozzo *et al.*, 1996;
91 Manal *et al.*, 2000; Stagni *et al.*, 2005; Cockcroft *et al.*, 2016), although the major effect, i.e. the
92 rigid displacement of the entire cluster, cannot be removed. At the beginning of more thorough
93 investigations, a pure segmental approach looked at this problem considering single segments
94 separately (single-body optimization), addressing marker cluster deformation and displacement
95 independently from other body segments. Least-squares algorithms (Veldpaus *et al.*, 1988), single-
96 value-decomposition (SVD) (Soderkvist and Wedin, 1993) and the so-called solidification (Cheze
97 *et al.*, 1995) procedures were proposed to reduce STA on analytical bases. A little later, the pliant-

98 surface (Ball and Pierrynowski, 1998) and the point-cluster (Andriacchi *et al.*, 1998; Alexander and
99 Andriacchi, 2001) techniques were also introduced, which implied large clusters of many uniformly
100 distributed markers: eigenvalues and eigenvectors of the corresponding inertia tensors were
101 calculated after having assigned an arbitrary mass to each of these markers. Results in bone pose
102 estimation, obtained with these techniques, were considered satisfactory for position error
103 reduction, but not for the orientation error, which is the main point of interest in gait analysis. A
104 local motion estimation technique was also proposed (Cerveri *et al.*, 2005), using virtual humans
105 and extended Kalman filters to work out kinematics directly from 2D measurements, without
106 requiring the 3D marker reconstruction. To account for the effect of cluster deformation due to
107 STA, a slightly different approach was taken from recognized statistical shape analyses (Taylor *et*
108 *al.*, 2005), the so-called Optimal Common Shape Technique, which extended the SVD procedure
109 over multiple time points. Validation tests on sheep revealed a better performance compared to the
110 point-cluster technique. This paper also concluded that the method is suitable for reducing errors
111 due to the independent motion of markers from the rest of the cluster, but that this cannot reduce
112 errors associated with the synchronous rigid displacement of the cluster as a whole.

113 Another series of studies focused on separate segment pose estimations, but joint motion from the
114 subject under analysis was still taken into account for STA compensation. This was sought either by
115 replicating the anatomical landmark calibration procedure at two extreme positions, i.e. double
116 calibration (Cappello *et al.*, 1997; Cappello *et al.*, 2005), or by a so-called dynamic-calibration of
117 the artefact (Lucchetti *et al.*, 1998). In the latter, STA is meant to be first isolated in a special
118 exercise performed on purpose by the subject, and then compensated based on correspondences of
119 joint angles in this exercise and in the motor task to be analyzed. As a possible improvement, a later
120 study proposed to offset the anatomical landmark position by using a skin marker analytical
121 displacement for correction (Ryu *et al.*, 2009). These three original methods demonstrated to be
122 effective to limit STA propagation in the evaluation of knee joint rotations and displacements
123 (Stagni *et al.*, 2009). The merit of these initial techniques is the partial compensation for the

124 artefact: knowing that it is subject specific, it is first isolated and then subtracted from the overall
125 motion collected in the raw measurements. On the other hand, for these techniques to be applied, a
126 supplementary exercise is required by the subject, and time-consuming additional analyses must be
127 performed after data collection. These techniques are also based on the assumptions that STA is
128 well revealed by the proposed exercise, and that these are repeatable intra- and inter-sessions.
129 Recent in vivo measurements with bone pins on the tibia and femur (Benoit *et al.*, 2015) established
130 explicitly that in soft tissue deformation and displacement, non-rigid (i.e. scaling and deformation)
131 movements of the marker clusters contribute to the overall amount of STA error much less than
132 rigid (i.e. translation and rotation) movements, supported also by a study on running (Dumas *et al.*,
133 2015). These papers concluded that skin marker optimisation, based on isolated segments, which
134 can only minimise non-rigid motion components, is superfluous, and that procedures designed to
135 account for cluster rigid translation and rotation are required to correctly represent body segments
136 motion. It has also been shown that STA is very subject-specific and any custom definition of a
137 model of the artefact is impractical. The use of optimal estimation of bone poses in isolated body
138 segments (single-body optimization) is questioned by these evidences, which also suggest the
139 introduction of thorough overall lower limb models and joint constraints. This will be largely
140 discussed below.

141 **2.2 Multi-body kinematics optimisation - An historical perspective**

142 The real foremost alternative to this series of more local attempts is the MKO approach, which
143 entails searching solutions for the best possible segment pose estimation by considering an entire
144 lower limb multi-body model, namely a kinematics chain made of rigid segments connected by
145 articulating joints. These can be simple lower pairs (such as the hinge or spherical pairs) or more
146 anatomical representation of the joints. The overall concept is to register, for each sample, and in
147 the three-dimensional space, a lower limb kinematic model, which includes skin markers to the
148 cloud of corresponding markers collected during the motion exercise. In other words, the overall
149 configuration of the limb model must be searched to minimize the distances between the model-

150 determined and the measured marker trajectories. The overall kinematics chain must be configured
151 with suitable joint models, and relevant parameters must be defined for each subject to be analyzed.
152 The number and nature of these parameters, such as location of centres, axes, ligament attachments,
153 contact surfaces, etc., depend on the model types, as discussed in depth later.

154 The MKO approach, based somehow on redundancy of information, seemed to have great
155 potentials, as the overall kinematics estimation can take advantage of the joint constraints,
156 information which was ignored by the segmental approaches described above. On the other hand,
157 from the beginning it was clear that the quality of the final results would have been strictly
158 correlated with the general quality and the specific custom configuration of the joint models.
159 Moreover, it poses also a typical iterative optimization problem, with all relevant known issues,
160 such as selection of the variable to be minimized/maximized, efficiency of the search strategy,
161 definition of the search boundaries, identification of local and global minima, etc. The first proposal
162 of this type dates back to 1999 (Lu and O'Connor, 1999), although it addressed the three-
163 dimensional problem of lower limb motion analysis only in analytical terms. A skin marker-based
164 musculoskeletal model was defined imposing spherical joint constraints; the skin marker
165 trajectories were taken from a standard gait analysis, and alleged STA added to these marker
166 trajectories. A global optimisation method was used to determine positions and orientations of a
167 multi-link model based on the minimisation of the weighted sum of squared distances between
168 measured and model-determined marker positions. The results showed a good capacity of this
169 global error compensation scheme to replicate original known motion, which were much better
170 estimated than any direct or segmental based scheme available at the time.

171 A possible development of this first proposal was published later (Charlton *et al.*, 2004), and the
172 relevant technique, i.e. optimised lower limb gait analysis (OLGA), was implemented in the
173 conventional Newington-Helen Hayes gait analysis protocol (Kadaba *et al.*, 1990). With respect to
174 the Lu and O'Connor's method, three-dimensional segment poses were searched following two
175 different optimisation loops: in addition to the initial "Kinematic Fit" as in the previous paper,

176 geometrical parameters that define knee, ankle and foot long axes were also searched within the
177 following “Model Fit” iterative optimization procedure. This would possibly allow a better
178 identification of joint parameters (axes, centres etc.) and therefore joint angles. The improvement
179 compared to the original technique by Lu and O’Connor (Lu and O'Connor, 1999) was claimed in
180 terms of intra- and inter-observer repeatability of the gait analysis variables, and standard deviation
181 of bone length estimations. A further development of this technique was proposed by another team
182 (Reinbolt *et al.*, 2005). Similar to the two-level optimization by Charlton et al. (Charlton *et al.*,
183 2004), “Outer” and “Inner” optimization phases were adjusted in this new order: joint parameters,
184 i.e. positions and orientations of joint axes, and degrees of freedom (DoFs), i.e. lower limb joint
185 rotations and displacements. Differently from the previous study by Charlton et al. (Charlton *et al.*,
186 2004), there was the introduction of a two-axis model for the ankle complex that accounted for the
187 talo-crural and subtalar joint rotations. Although both procedures proposed by Charlton et al.
188 (Charlton *et al.*, 2004) and Reinbolt et al. (Reinbolt *et al.*, 2005) were demonstrated for a specific
189 sets of joint models, they are actually applicable to generic joint geometries.

190 A few years later new investigations were carried out both from the joint constraint and the
191 algorithm efficiency point of view. Andersen et al. (Andersen *et al.*, 2010) studied the effects of
192 including spherical and revolute joint constraints in the analysis of knee kinematics from skin
193 markers during gait. Klous et al. (Klous and Klous, 2010) proposed a new analytical method for a
194 kinematics chain model, featuring spherical pairs at all joints and comparing it with either a
195 previous analytical least-squares algorithm (Veldpaus *et al.*, 1988) or the MKO (Lu and O'Connor,
196 1999), according to the segmental and global optimization approaches, respectively. Because large
197 parts of the equations proposed can be solved analytically rather than only numerically, the speed of
198 convergence for the new method was the highest, although the final inaccuracy was slightly larger
199 than in the original optimisation method, as expressed by the root-mean-square error (RMSE)
200 between the model-determined and actual marker positions. Joint constraint techniques for the
201 reduction of the STA effects have been formulated for the knee also in terms of plausible values for

202 length variations of the main ligaments (Bergamini *et al.*, 2011; Gasparutto *et al.*, 2012), but this
203 will be discussed later.

204 Another original exercise was performed in order to improve the final visual restitution of lower
205 limb joint rotations and displacements, after standard motion analysis data registration techniques
206 based merely on bone morphology (Sholukha *et al.*, 2006). The study was motivated by the
207 unrealistic current graphical representations of three-dimensional motion of the lower limbs,
208 particularly critical in computer-based simulations for medical educational purposes. An iterative
209 registration method was proposed, which implied a kinematics chain with best physiological
210 kinematic representations of the main six joints of the lower limbs, each having known specific 3D
211 kinematics described with a single DoF (O'Connor *et al.*, 1998). The technique included a primary
212 registration at the knee and ankle joints levels, where coupling curves were taken to drive joint
213 motion according to the corresponding flexion/extension DoF from gait analysis. A secondary
214 registration integrated the coupled joint constraints to real motion analysis from a volunteer.
215 Finally, a realistic graphical representation of both the overall skeletal motion and physiological
216 kinematics at the knees and ankles were achieved. The latter enabled by modelled joint rotations
217 and displacements which were integrated in the MKO algorithm.

218 In the past few years, the effect of different models and constraints at the lower limb joints level
219 have been assessed thoroughly (Andersen *et al.*, 2010; Duprey *et al.*, 2010; Gasparutto *et al.*, 2015),
220 as well as the sensitivity to relevant parameters (Valente *et al.*, 2014; Valente *et al.*, 2015; Clement
221 *et al.*, 2015; Ojeda *et al.*, 2016; Clement *et al.*, 2017). The most comprehensive study (Duprey *et al.*
222 *et al.*, 2010) tested the performances of a number of different sets of models of the lower limb joints,
223 and assessed their influence on the overall kinematics, although a gold-standard was not available.
224 Despite few concerns in terms of possible worse pose estimation results (Stagni *et al.*, 2009;
225 Andersen *et al.*, 2010; Li *et al.*, 2012), the introduction of joint models, either by kinematic or
226 anatomical constraints, showed the potential for considerable STA compensation. In addition, these
227 models could be used to estimate the forces exchanged at the anatomical structures (D'Angeli *et al.*,

228 2013; D'Angeli *et al.*, 2016; Moissenet *et al.*, 2014). However, they must be implemented
229 appropriately, with careful parameter search, and validated cautiously, as it is discussed more in
230 details in the following sections.

231 **2.3 Anatomical significance, accuracy, and personalisation feasibility**

232 All these techniques have a value for the description of physiological joint motion, but their
233 reliability and usability still needs to be tested and validated carefully. This additional work is
234 particularly necessary for their use in the description of pathological gait, when the joint function is
235 not natural. In this respect, it is expected that most of the pathological conditions, both abnormal
236 kinematics and lesions at the anatomical structures, are difficult to be replicated in joint models,
237 particularly in case of simple non-anatomical joint constraints. Most papers focus only on knee
238 joint, although these techniques are devoted to understand the physiology and pathology of gait
239 over the entire lower limb. Particularly for joints with complex motion, such as the knee and the
240 ankle, it is expected that the more the joint model is anatomically realistic, the more accurate the
241 final bone pose estimation will be. However, this higher accuracy would require more careful
242 identification of the joint model parameters and therefore higher computational time. A proper
243 validation of these techniques is also a major problem, as described in the next paragraph section.
244 Another limitation of the MKO approach is that the quality of the final estimations is affected by
245 the quality of the collected experimental marker motion data. In particular, the risk of inclusion of
246 joint parameters in the overall optimisation is that a lowest cost function value may imply their
247 erroneous estimation (Reinbolt *et al.*, 2005); in other words, optimized joint parameters provide
248 only the best possible fit to the original raw data, which can be considerably imperfect.

249 In literature these MKO methods are rarely proposed together with relevant, thorough and
250 convincing validation activities (Reinbolt *et al.*, 2005). Some have supported the technique by
251 analytical simulations (Lu and O'Connor, 1999; Reinbolt *et al.*, 2005), but the random error added
252 to each marker trajectory separately does facilitate the task to any such algorithm, and the results
253 are misleading because these perturbations are unrealistic (Benoit *et al.*, 2015). The most accurate

254 condition for these tests would be prescribing skin marker displacements with respect to underlying
255 bone, both in terms of deformation and of rigid motion of the cluster, the latter being very difficult
256 to be removed or compensated. The top condition for thorough validations would have the
257 simultaneous knowledge of marker and corresponding skeletal motion during activities as gold-
258 standard. This is however very difficult to be achieved because of the invasiveness of some imaging
259 techniques or of bone pins. Validation studies using fluoroscopy, stereo radiography or bone pins
260 were however proposed. Since these studies were more related to the validation of specific joint
261 constraints, they will be analysed in the next section. Sensitivity of final joint kinematics estimation
262 to multi-body model parameters (El Habachi *et al.*, 2015; Martelli *et al.*, 2015) shall also be
263 investigated further.

264

265 **3. LOWER LIMB JOINT MODELS FOR MKO BASED TECHNIQUES**

266 Joint models are the core of MKO: different models imply different joint constraints imposed to the
267 relative motion of adjacent body segments, and thus a different overall full-leg motion. A number
268 of joint models have been proposed for each of the main articulations of the lower limb (i.e., hip,
269 knee and ankle) leading to different lower limb models according to their combination. These joint
270 models can be validated individually; however, critical issues such as the choice of the constraint
271 type and the identification of the model parameters can still arise when these models are included in
272 MKO, which can result in critical outcomes of the method. Major efforts have been spent in past
273 and recent works to investigate these issues.

274 The first lower limb models adopted simple lower pairs (sometimes referred to as ideal joints in the
275 literature) to constrain the relative motion of adjacent segments, the most common choices being
276 spherical (S) and revolute (R or hinge) joints. Specifically for the ankle, a further common choice is
277 the 2R constraint, namely two intersecting (Duprey *et al.*, 2010) or non-intersecting (Reinbolt *et al.*,
278 2005) hinges. It is worth noting that, as far as the two hinges represent the tibio-talar and the talo-
279 calcaneal rotation axes, experimental evidence shows that these hinges are not actually intersecting

280 (Dettwylera *et al.*, 2004). The three-segment model by Lu and O'Connor (Lu and O'Connor, 1999)
281 featured two spherical pairs (S-S) to represent the hip and the knee joints. After this seminal work,
282 several different kinematic chains were proposed to model the lower limb, like the S-S-S (Charlton
283 *et al.*, 2004) and the S-R-2R (Reinbolt *et al.*, 2005) to represent the hip, knee and ankle joints
284 respectively (the same order will be used in the following nomenclature), where 2R represents two
285 non-intersecting hinges. A first major result related to the use of the abovementioned pairs, was to
286 avoid the apparent dislocation of the joints. However, these models represent an oversimplification
287 of the anatomy for the knee and ankle joints that, therefore, could not reproduce the physiological
288 motion. For instance, R constrains the joint to rotate about a fixed axis, despite the instantaneous
289 helical axes (IHA) actually varying in these two joints over the flexion arc (Blankevoort *et al.*,
290 1990; Leardini *et al.*, 1999b). Likewise, S constrains the joint to rotate about a fixed point, and this
291 implies that all IHA pass through this point, as well as that joint translation (i.e., the instantaneous
292 joint motion along the IHA) is prevented. This represents a spherical motion in kinematics, and this
293 fixed point is the pivot point (PP). These characteristics do not reflect accurately what is observed
294 experimentally, since IHA motion patterns at the knee and the ankle are not perfectly convergent at
295 a single point and some translations along IHA can be measured (Blankevoort *et al.*, 1990; Leardini
296 *et al.*, 1999b). Some studies (Stagni *et al.*, 2009; Andersen *et al.*, 2010) also reports that S (and
297 similarly also R) cannot reproduce joint displacements, defined as the relative displacement
298 between two reference points (often chosen as coincident with the anatomical frame origins) of two
299 different bony segments. However, this latter S limitation should be clarified and mitigated. The
300 problem in this case lies in the identification of S (namely, of the sphere centre C_S), not in the type
301 of constraint. This because S prevents any relative motion at PP, but not between any other pair of
302 points of the two bodies: joint displacements can be represented if C_S is not placed at the reference
303 points used to measure these displacements. Studies showed indeed that joint displacements are
304 well represented if C_S is placed near the point where the IHA converge the most, i.e. the
305 approximate PP (Sancisi *et al.*, 2011; Sancisi *et al.*, 2014). The joint motion appears highly

306 sensitive to the C_S position, in particular along the proximal-distal and anterior-posterior axes
307 (Sancisi *et al.*, 2015). Errors in the C_S location affect joint motion, thus its careful identification is
308 paramount. However, since C_S is not closely related to any anatomical landmark, its identification is
309 not straightforward. Together with constraint type, parameter identification is a major issue for all
310 these models.

311 The use of simple constraints imposed by lower pairs in the MKO was validated in Stagni *et al.*
312 (Stagni *et al.*, 2009). This is also the first comparison between a MKO technique and fluoroscopy-
313 based motion at the knee measured *in vivo*. High errors were found at the knee level, which were
314 not confirmed in other studies. Andersen *et al.* (Andersen *et al.*, 2010) also validated different lower
315 pair constraints at the knee in a MKO approach *in vivo*. The study compared joint angles obtained
316 at the knee during walking trials using two types of constraints (S and R) or no constraints (N).
317 Similar RMSEs were obtained on the joint angles by S and R (Table 1). In both cases, higher errors
318 were found when compared to N, so that authors suggested that no benefits are obtained for STA
319 reduction if overly simplistic joint models are used, and model parameter identification is not
320 accurate. Opposite results were found in more recent studies (Gasparutto *et al.*, 2015; Richard *et al.*,
321 2016) where S performed better than N, and RMSEs were lower than in Andersen *et al.* (2010)
322 (Table 1), leading the authors to conclude that joint constraints can actually be of value to
323 compensate STA. However, also in these studies the authors concluded that more advanced models
324 implementing anatomical constraints, together with accurate parameter identification, can improve
325 results. The different outcomes from these studies may be due to their different experimental
326 conditions and procedures (i.e. population of subjects, motor task, marker set, gait analysis
327 protocol, etc...), as reported in Table 1.

328 TABLE 1 HERE

329 Coupling curves (CC) defining the motion parameters of a single DoF joint as a function of its
330 flexion-extension, were used to drive joint kinematics (Sholukha *et al.*, 2006; Li *et al.*, 2012;
331 Gasparutto *et al.*, 2015). These curves are usually obtained *in vitro* (Sholukha *et al.*, 2006; Walker

332 *et al.*, 1988) and registered to gait data, constraining the joint to follow an imposed physiological
333 movement. An important drawback of this approach is the lack of subject specificity, which reduces
334 its accuracy when applied to different subjects and it is unfeasible in pathological subjects. Li *et al.*
335 (Li *et al.*, 2012) evaluated the accuracy of a scaled generic lower limb model with knee constraints
336 based on CC (Walker *et al.*, 1988) on ten subjects performing level running and stair-ascent with a
337 posterior cruciate ligament (PCL) injury. It is worth noting that the CC defined in Walker *et al.*
338 (1988) has null medial-lateral displacement. This study reported high RMSEs (Table 1) both for the
339 injured and the healthy knee. Moreover, the error found in every component of the joint motion was
340 equal or greater than the difference between the motion of the injured and healthy knee, concluding
341 that the scaled generic model based on CC was not sensitive to pathological motion. An evaluation
342 of the CC accuracy in vivo at knee level was performed also by Gasparutto *et al.* (Gasparutto *et al.*,
343 2015) confirming Li *et al.* (Li *et al.*, 2012) results in terms of mean RMSEs for ab-adduction, in-
344 external rotation and medio-lateral displacement, while better results were obtained for flexion-
345 extension, antero-posterior and proximal-distal displacements (Table 1).

346 Equivalent spatial parallel mechanisms (ESM) are one-DoF rigid models of the joint that feature a
347 one-to-one representation of the joint anatomical constraints. These have been employed largely for
348 both knee (Wilson and O'Connor, 1997; Parenti-Castelli and Di Gregorio, 2000; Di Gregorio and
349 Parenti-Castelli, 2003; Feikes *et al.*, 2003; Ottoboni *et al.*, 2010) and ankle (Franci *et al.*, 2009; Di
350 Gregorio *et al.*, 2007) joints. These constraints are the articular surfaces and the isometric fibres of
351 the main ligaments, namely the anterior cruciate ligament (ACL), the PCL and the medial collateral
352 ligament (MCL) for the knee, the calcaneal-fibular (CaFiL) and the tibio-calcaneal (TiCaL)
353 ligaments for the ankle. ESM were also proposed to model the whole knee joint, including the
354 patella (Sancisi and Parenti-Castelli, 2011b; Sancisi and Parenti-Castelli, 2011a). All these
355 mechanisms have a strong anatomical basis and proved to be able to well replicate joint passive
356 motion (Franci *et al.*, 2009; Ottoboni *et al.*, 2010). All these models are basically a generalization in
357 the 3D space of previous planar mechanisms, based on the four-bar linkage, where motion is guided

358 by two isometric ligament fibres at the knee (Menschik, 1974; O'Connor *et al.*, 1989; Gill and
359 O'Connor, 1996) and at the ankle level (Leardini *et al.*, 1999a; Leardini *et al.*, 1999b). At the same
360 time, ESM are the basis of mechanisms (called ESMs hereinafter) that feature a one-DoF spherical
361 motion (i.e., a spherical motion constrained along a single path by joint anatomical constraints) and
362 aimed at simplifying the model geometry (Sancisi *et al.*, 2011; Sancisi *et al.*, 2014; Di Gregorio *et*
363 *al.*, 2007).

364 Duprey *et al.* (2010) firstly proposed the use of ESM and ESMs in MKO for the knee and ankle
365 joints (Feikes *et al.*, 2003; Di Gregorio *et al.*, 2007). The hypothesis was that anatomical constraints
366 could allow a better compensation of STA. Moreover, ESM and ESMs allow: (i) model
367 personalization on the specific patient, for example by means of medical imaging, and (ii) model
368 generalization to include ligament stiffness (Sancisi and Parenti-Castelli, 2011c) for kinetostatic and
369 dynamic analysis. In this thorough study (Duprey *et al.*, 2010), seven different kinematic chains
370 were considered for the lower limb: S-S-S, S-S-2R, S-S-ESMs, S-R-S, S-ESM-S, S-R-2R, S-ESM-
371 ESMs, where in this case 2R are two intersecting hinges at the ankle joint. By comparing the
372 outputs of the seven lower limb models, the following was observed: (i) flexion-extension curves of
373 all joints are not or scarcely influenced by the different sets of constraints, (ii) the motion of
374 proximal joints is almost not influenced by the distal ones (only the knee in-external rotation was
375 affected by different ankle constraints), (iii) in-external rotation curves showed higher dispersion
376 compared to other motion parameters in all joints, (iv) only ESM and ESMs can reproduce the
377 known rollback at the knee and rolling at the ankle. This study tested the aforementioned models on
378 five volunteers during gait, but lacked of in vivo data for the model validation. However, relevant
379 results indicated the anatomical constraints imposed by ESM and ESMs as a valuable alternative to
380 the other tested constraints (i.e. 2R and S), since they allow a physiological motion that can be
381 tailored on a specific subject.

382 Further insights in the application of ESM for STA compensation was recently given in Gasparutto
383 *et al.* (Gasparutto *et al.*, 2015). ESM with deformable ligaments are introduced in a two-segment

384 kinematic chain featuring the knee only; the deformation is handled by a purely kinematic approach
385 and is not based on ligament stiffness. This means that ligaments are treated as additional markers
386 and are allowed to minimally vary their length in order to comply with lower limb movements; the
387 objective function to be minimized is changed accordingly, in order to add this further constraint to
388 the one imposed by skin markers. ESM are implemented allowing either no (ΔL_0) (Ottoboni *et al.*,
389 2010), prescribed (ΔL_θ) (Bergamini *et al.*, 2011) or minimized (ΔL_{\min}) (Gasparutto *et al.*, 2012)
390 ligament length variations; N, S and CC constraints are also analysed for comparison. Lowest
391 RMSEs were obtained using ESM with deformable ligaments and S, which showed similar
392 performance. Since ESM geometry was not customized, improvements are expected in possible
393 future personalization. Deformable ligaments showed some improvements with respect to ΔL_0 , in
394 particular for the in-external rotation (Table 1). A systematic error on this motion component could
395 be due to the non-customized model geometry (Richard *et al.*, 2016), which affects rigid models in
396 particular. Indeed, in-external rotation at full extension shows a high inter-subject variability that
397 cannot be handled by ΔL_0 without personalization, whereas deformable models allow small
398 adjustments in their given geometry during the MKO process, to comply with this variability.

399 In general, the identification of model geometrical parameters is becoming increasingly crucial
400 since more advanced models require careful parameter identification. Habachi *et al.* (El Habachi *et*
401 *al.*, 2015) investigated the influence of these parameters on the kinematics of each joint as
402 computed by MKO. The lower limb was modelled by a S-ESM-ESMs kinematic chain with fixed-
403 length ligaments also featuring the patello-femoral joint at the knee (Sancisi and Parenti-Castelli,
404 2011b). Results showed that some parameters highly influence joints motion, both for simple lower
405 pairs (S and R) and for advanced models (ESM and ESMs). However, the higher number of
406 parameters make the latter more likely to be sensitive to parameter variations, as recently observed
407 elsewhere (Sancisi *et al.*, 2015). Therefore, personalization is considered essential for MKO (El
408 Habachi *et al.*, 2015).

409 Recently, subject-specific constraints have been introduced within MKO (Valente *et al.*, 2015;
410 Clement *et al.*, 2015). In particular, subject-specific geometries were used with ESM in the latter
411 study. Four different kinematic chains were compared (i.e., N-N-N, S-S-S, S- ΔL_{\min} -S, S- ${}^c\Delta L_{\min}$ -S,
412 where ${}^c\Delta L_{\min}$ stands for customized minimal ligaments length variation model) and tested against
413 quasi-static bi-planar radiographic images during squat. The effect of subject-specific constraints at
414 the knee was assessed testing these models on ten healthy and ten osteoarthritic subjects. Results
415 showed that personalization improves STA compensation in particular for knee in-external rotation,
416 ab-adduction, antero-posterior and proximal-distal displacements both in healthy and osteoarthritic
417 subjects (Table 1). As shown in previous studies, RMSEs obtained from both ΔL_{\min} and ${}^c\Delta L_{\min}$ are
418 comparable to those from S (Table 1). As discussed above, knee displacements appear null with S
419 constraint since in this case C_S is placed at the joint centre, like in most of MKO related literature.
420 Therefore, this approximation does not appear to affect the errors on antero-posterior, proximo-
421 distal, medio-lateral displacement reconstructions, since these motion components are usually
422 small. However, placing C_S at the joint centre does not produce a physiological motion.

423 Recently, assuming that the final accuracy of MKO analyses could be enhanced by the use of non-
424 rigid constraints, a stiffness matrix was proposed and tested in order to constrain tibio-femoral
425 relative motion (Richard *et al.*, 2016). Despite this constraint is not strictly kinematic, it is reported
426 here since it is handled in MKO similarly to other kinematic constraints that are not relying on the
427 forces applied at the lower limb. The stiffness matrix constraint (K) was compared to N, S and ESM
428 models using the joint motion acquired by bi-planar fluoroscopy as gold-standard. The constraint
429 imposed by the stiffness matrix was obtained by minimizing joint deformation energy. Two
430 subjects were enrolled in this study, and were asked to perform a stair-climbing task. Results
431 confirmed the importance of joint kinematic constraints for STA compensation; moreover, K
432 proved to be a promising alternative compared to rigid models.

433 Finally, the present review focused only on kinematic lower limb joint models, specifically applied
434 in MKO and validated for compensation of STA. Of course many other lower limb joint models can

435 be found in literature, in particular finite element and deformable multibody analyses (Adouni *et*
436 *al.*, 2012; Guess *et al.*, 2013; Lenhart *et al.*, 2015; Shelburne *et al.*, 2004, Sancisi *et al.*, 2011c,
437 Forlani *et al.*, 2015). However, these find noteworthy applications in musculo-skeletal modelling,
438 aimed at increasing anatomical adherence in the description of joint structures, but fall outside the
439 scopes of the present review.

440

441 **4. CONCLUDING REMARKS**

442 Lower limb joint kinematics and kinetics are sought in gait analysis both in clinical and
443 performance analyses, but also in inverse–forward dynamic analyses, and musculoskeletal
444 modelling. To obtain reliable joint kinematics from skin markers, STA represents a major problem,
445 and must be reduced or compensated. Many MKO methods have been proposed, where predefined
446 kinematic models are employed to limit STA by minimizing the differences between model
447 predicted and skin-based marker positions. These lower limb kinematic models include a large
448 variety of different single joint representations, from simple lower pairs to advanced spatial
449 mechanisms. Model parameters, however, should be determined for the specific lower limbs under
450 analysis; in other words, subject-specific models of the joints and overall kinematics chain should
451 be defined each time to improve accuracy. Therefore, the final reliability of these optimization
452 methods depends not only on the chosen lower limb and joint models, but also on any experimental
453 and analytical procedure necessary to estimate the model parameters. Reliability of the estimated
454 lower limb kinematics is also affected by the arrangement of the marker clusters, including relevant
455 trajectory collections, and by the quality of the experimental and analytical procedures implied in
456 the motor tasks necessary to estimate the relevant model parameters. Controversy exists also on the
457 algorithms for solving these medium- and large-scale human movement optimization problems
458 (Koh *et al.*, 2009), but this would require a dedicated paper. The exact single role of these
459 contributions in the overall reliability of the techniques is not well known yet. For this reason, it is
460 also difficult to assess the definite value of these techniques. Nevertheless, with respect to simple

461 lower pairs, anatomical constraints (such as rigid or deformable parallel mechanisms and stiffness
462 matrices) seem to offer results with more physiological motion at the joints, and also have potential
463 for the inclusion of subject-specific joint constraints.

464 To date, in the perspective of STA compensation, the results of anatomical constraints and S are
465 comparable. In fact, the joints of the lower limb show a nearly spherical motion; therefore, an
466 accurately identified S could represent a good alternative to anatomical constraints for applications
467 that do not require a detailed and anatomically coherent description of the musculoskeletal
468 apparatus, such as for example clinical gait analyses in joint arthritis patients. It is expected,
469 however, that anatomical constraints will lead to better results, once a simple experimental
470 procedure will be developed to identify the model parameters. Moreover, only models that feature a
471 direct representation of anatomical structures (i.e. ligaments and articular surfaces), such as rigid
472 and deformable mechanisms, make it possible to obtain estimation of the forces in these single
473 structures, thus extending the analysis from a purely kinematic to a complete musculoskeletal
474 dynamic model. Personalization and, more generally, the identification of the joint parameters on
475 the single subject under analysis is therefore a critical aspect, in particular for more advanced joint
476 models. A number of techniques exist to identify these model parameters, which are closely related
477 to the relevant joint model. However, new procedures have to be defined to identify advanced
478 models in an even more accurate and straightforward way. Among them, predictive procedures able
479 to estimate the subject motion from simple and non-invasive measurements (such as imaging data)
480 (Conconi *et al.*, 2015) may represent a promising tool for the identification of patient-specific
481 anatomical constraint models (Conconi *et al.*, 2016).

482 In spite of the number of joint and lower limb models proposed, STA is still not totally
483 compensated, and MKO accuracy could be largely improved to reconstruct the spatial movements
484 of the main segments of the lower limb during gait. Future investigations should focus on models
485 that represent joint physiological behaviour with improved accuracy. Moreover, whereas large
486 efforts were spent on the knee joint, only little attention has been devoted to the ankle joint so far.

487 Because the accuracy of ankle models also influence the estimation of knee motion (Duprey *et al.*,
488 2010) and, as a consequence, also of the whole lower limb motion, in the future more attention
489 should be devoted to this joint.

490

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494

495 **CONFLICT OF INTEREST**

496 All authors declare not to have any personal or commercial relationships related to this work that
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498

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TABLE CAPTION

731 **Table 1** Mean values and standard deviation of RMSEs of the motion components of the tibio-
732 femoral relative motion as found in the MKO related literature: flexion-extension (FE), ab-
733 adduction (AA), in-external rotation (IER) and antero-posterior (APT), proximal-distal (PDT),
734 medial-lateral (MLT) displacements are reported. For each article the table shows the joint models
735 used (Joints), the identification method of the joint models geometry (Model tuning), the number of
736 subjects involved (Number of Subjects), the marker set adopted (Marker set), the motor tasks
737 performed (Motor Tasks) and the technique used for validation (Validation technique). The symbol
738 “\” stands for empty cell (information, model or parameter not reported in the study).

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Table 1

Article	Joints			Model tuning	Number of Subjects	Marker set	Motor Tasks	Validation technique	RMSE tibio-femoral relative motion [mean (\pm sd)]					
	HIP	KNEE	ANKLE						FE (deg)	AA (deg)	IER (deg)	MLD (mm)	APD (mm)	PDD (mm)
Stagni et al. (2009)	S	S	S	Anatomical landmarks	2 subjects with TKR	Two Marker sets: (i) according to CAST protocol; (ii) 4 markers clusters for both thigh and shank	extension against gravity step-up/step-down sit-to-stand/stand-to-sit	Single-plane fluoroscopy	5.5 (\pm 3.6) 6.8 (\pm 0.5) 8.7 (\pm 0.2)	2.3 (\pm 0.1) 15.7 (\pm 0.4) 12.5 (\pm 0.2)	9.4 (\pm 3.1) 7.9 (\pm 1.6) 10.8 (\pm 1.9)	4.3 (\pm 4.9) 3.0 (\pm 3.4) 5.0 (\pm 5.5)	19.2 (\pm 1.3) 18.5 (\pm 0.7) 19.6 (\pm 2.8)	6.5 (\pm 3.0) 7.5 (\pm 2.9) 8.3 (\pm 1.8)
Andersen et al. (2010)	\	N R S	\	Functional optimisation	6	Benoit et al. (2006),(2007)	Level walking	Bone pins	2.8 (\pm 2.6) 3.8 (\pm 2.4) 3.4 (\pm 2.5)	3.4 (\pm 3.2) 3.4 (\pm 3.2) 3.8 (\pm 3.0)	2.6 (\pm 1.3) 2.5 (\pm 1.2) 2.6 (\pm 1.3)			
Li et al. (2012)	S	CC (Walker et al. (1988))	2R	Scaled generic model	20 (10 healthy, 10 PCL injured)	Vicon Plug-in Gait	Level running	Dynamic stereo radiography	9.1 (\pm 3.2) 3.3 (\pm 1.1)	2.0 (\pm 1.2) 2.5 (\pm 1.7)	6.4 (\pm 4.5) 5.1 (\pm 3.3)	1.9 (\pm 1.2) 1.5 (\pm 0.8)	7.1 (\pm 3.2) 6.1 (\pm 2.5)	8.8 (\pm 3.7) 11.0 (\pm 4.6)
					10 healthy subjects		Level running Stair-ascent		8.8 (\pm 3.3) 3.9 (\pm 1.2)	2.4 (\pm 1.5) 2.8 (\pm 1.6)	6.0 (\pm 3.4) 4.4 (\pm 3.2)	1.9 (\pm 1.3) 1.6 (\pm 1.0)	7.6 (\pm 3.5) 5.9 (\pm 2.5)	9.4 (\pm 3.7) 12.2 (\pm 4.7)
					10 PCL injured subjects		Level running Stair-ascent		9.5 (\pm 3.2) 2.7 (\pm 0.7)	1.5 (\pm 0.7) 2.3 (\pm 1.8)	6.9 (\pm 5.7) 5.8 (\pm 3.5)	1.9 (\pm 1.1) 1.3 (\pm 0.4)	6.6 (\pm 2.9) 6.2 (\pm 2.7)	8.2 (\pm 3.9) 9.7 (\pm 4.4)
Gasparutto et al. (2015)	\	N S ΔL_0 ΔL_{min} ΔL_0	\ Anatomical landmarks Optimized geometry from in vitro data	3	Reinschmidt et al. (1997)	Level running	Bone pins	1.7 (\pm 0.2) 1.7 (\pm 0.1) 1.6 (\pm 0.2) 1.8 (\pm 0.4) 1.7 (\pm 0.2) 1.7 (\pm 0.2)	2.0 (\pm 0.4) 1.6 (\pm 0.5) 2.9 (\pm 0.2) 1.9 (\pm 0.4) 1.6 (\pm 0.5) 2.0 (\pm 0.5)	2.9 (\pm 0.3) 2.4 (\pm 0.1) 6.0 (\pm 0.4) 11.7 (\pm 0.5) 2.6 (\pm 0.1) 3.4 (\pm 0.8)	3.3 (\pm 0.5) 1.4 (\pm 0.2) 1.4 (\pm 0.2) 1.6 (\pm 0.2) 2.6 (\pm 0.5) 1.8 (\pm 0.3)	4.5 (\pm 0.8) 2.5 (\pm 0.6) 3.6 (\pm 1.0) 2.9 (\pm 0.8) 3.8 (\pm 0.5) 2.8 (\pm 0.8)	5.0 (\pm 0.6) 1.8 (\pm 0.3) 2.2 (\pm 0.2) 1.6 (\pm 0.2) 1.7 (\pm 0.2) 1.7 (\pm 0.3)	
Clément et al. (2015)	N S S S	N S ΔL_{min} ΔL_{min}	N S S S	Subject specific bone models	10 healthy subjects	Mounted on three rigid devices attached on the iliac crest, the femoral condyles and the tibial tuberosity	Squat	Bi-planar radiography	0.3 (\pm 0.1) 0.3 (\pm 0.2) 0.3 (\pm 0.2) 0.3 (\pm 0.1)	6.7 (\pm 2.8) 2.7 (\pm 1.3) 2.2 (\pm 1.2) 2.2 (\pm 1.1)	5.4 (\pm 3.7) 6.0 (\pm 4.2) 5.2 (\pm 3.8) 7.3 (\pm 4.9)	2.8 (\pm 2.7) 1.8 (\pm 0.9) 4.3 (\pm 2.4) 2.5 (\pm 1.8)	7.4 (\pm 3.6) 2.2 (\pm 0.9) 3.2 (\pm 2.1) 3.3 (\pm 2.0)	12.0 (\pm 3.8) 2.4 (\pm 1.2) 2.4 (\pm 1.1) 4.0 (\pm 1.2)
					10 osteoarthritic subjects				0.3 (\pm 0.1) 0.3 (\pm 0.1) 0.3 (\pm 0.1) 0.3 (\pm 0.1)	3.5 (\pm 2.8) 5.1 (\pm 1.8) 3.3 (\pm 2.1) 6.4 (\pm 2.3)	5.7 (\pm 4.2) 5.9 (\pm 3.8) 6.0 (\pm 3.9) 5.7 (\pm 4.4)	4.1 (\pm 1.9) 2.8 (\pm 2.0) 4.1 (\pm 2.4) 5.6 (\pm 5.1)	7.0 (\pm 3.9) 2.6 (\pm 1.3) 2.5 (\pm 1.1) 3.9 (\pm 2.0)	7.0 (\pm 4.8) 2.9 (\pm 1.2) 2.7 (\pm 0.9) 4.3 (\pm 1.1)
Richard et al. (2016)	\	N S ΔL_0 K	\ Anatomical landmarks Geometry from in vitro data Based on in vitro data	2	Thigh: 4 markers in the middle + 2 markers at the epycondyles; Shank: tibial tuberosity, fibular head + 2 markers at the malleoli.	Stair-ascent	Bi-planar fluoroscopy	5.4 (\pm 0.9) 4.9 (\pm 1.0) 5.8 (\pm 1.3) 5.3 (\pm 1.1)	2.2 (\pm 0.2) 1.9 (\pm 0.1) 5.3 (\pm 2.0) 1.9 (\pm 0.7)	4.8 (\pm 3.3) 3.9 (\pm 2.0) 15.3 (\pm 7.1) 4.6 (\pm 2.5)	1.6 (\pm 0.1) 1.4 (\pm 0.1) 1.2 (\pm 0.1) 2.6 (\pm 0.2)	6.6 (\pm 2.3) 5.4 (\pm 2.2) 3.5 (\pm 1.8) 3.0 (\pm 0.6)	6.3 (\pm 0.4) 1.5 (\pm 1.1) 2.3 (\pm 2.2) 3.4 (\pm 0.3)	