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Evaluation of functional methods for human movement modelling

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Purpose: accurate assessment of human joint parameters is a critical issue for the quantitative movement analysis, due to a direct influence on motion patterns. In this study three different known functional methods are experimentally compared to identify knee joint kinematics for further gait and motion analysis purposes. Methods: taking into account the human knee physiology complexity, within its roto-translation, the study is conducted on a lower limb mechanical analogue with a polycentric hinge-based kinematic model. The device mimics a joint with a mobile axis of rotation whose position is definable. Sets of reflective markers are placed on the dummy and flexion-extension movements are imposed to the shank segment. Marker positions are acquired using an optoelectronic motion capture system (Vicon 512). Results: acquired markers' positions are used as input data to the three functional methods considered. These ones approximate the polycentric knee joint with a fixed single axis model. Different ranges of motion and number of markers are considered for each functional method. Results are presented through the evaluation of accuracy and precision concerning both misalignment and distance errors between the estimated axis of rotation and the instantaneous polycentric one, used as reference. Conclusion: the study shows the feasibility of the identification of joint parameters with functional approaches applied on a polycentric mechanism, differently from those usually conceived by the reviewed algorithms. Moreover, it quantifies and compares the approximation errors using different algorithms, by varying number and position of markers, as well ranges of motion.

Key words: *functional analysis, motion analysis, human modelling, joint kinematics*

1. Introduction

Applied biomechanics has become instrumental for human movement analysis, in order to quantify the human body motion and to assess joint kinematics, as well dynamics. Human joint kinematics is hence useful in research areas like gait analysis, prosthetic and rehabilitation, ergonomics, sport sciences, body biodynamics and ageing condition evaluation, due to the proper role in each one. Indeed, the assessment of joint parameters, like axes (AoRs) or centers (CoRs) of rotation highly conditions human motion patterns analysis, due to the direct effects on the lower limbs kinematics and dynamics computation.

All these aspects justify the necessity to accurately assess joint parameters. To this end, two main requirements have to be considered: the motion data acquisition and the human body modelling. The first one is made possible throughout different systems: among all, the already spread optoelectronic systems used for motion capture are based on stereophotogrammetric technique and rely on the concurrent use of video-cameras and markers, properly attached on body segments in order to be tracked. However, the use of optical tracking systems has been hindered in practice due to several reasons mainly concerning the subject constrained freedom of movement. Alternative motion capture systems have been then proposed, such as the wearable inertial sensors, so as to identify human motion, as well as joint kinematics [24]. Once motion data have been acquired, the second requirement deals with the association of this information on body segments, taking into account an easy assumption of human body made up of rigid segments, connected by mechanical joints, properly identified with

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adequate degrees of freedom. Joint models are important to the presented purpose, since they allow to assess parameters and to acquire data not directly measurable on subject.

The assessment of joint kinematics, particularly during motion analysis and gait analysis sessions, is often based on the geometrical, as well as on motor assumption concerning the point (or the joint) about which two segments are in relative motion. The determination of this point, within its parameters like CoR and AoR is often difficult to measure in vivo, representing a crucial issue during movement analysis, especially in non-standard applications or when considering people affected by pathologies or presenting physical deformities directly compromising motion tasks as well as kinematics outcomes [1]–[3], [10], [13], [23].

Joint parameters can be basically assessed according to different approaches, namely the *predictive* and the *functional* method. The former, which is currently adopted by the clinical laboratories for measurements and human movement analysis, is based on regression equations [12], [19] taking into account both a specific 3D position of markers corresponding to some externally palpable bone landmarks and anthropometric measurements. Thus, this approach requires to adopt specific protocols for markers positioning on anatomical landmarks [4], [7], for then using motion data as input for the equations. This approach is simple and immediate, despite it may lack accuracy. Indeed, the necessity of proper marker positioning is one of the drawbacks, due to the not often easy anatomical landmark identification. Also, this approach is not so suitable for people who present bone-deformities or for nonstandard cases, e.g., in the presence of a disease, providing several sources of errors [3], [15], [22].

Functional methods have been recently introduced to overcome some limitations characterizing the predictive approach. Firstly, they do not refer to empirical relations and are just based on the relative motion between a couple of body segments, with respect to the identified joint. This approach does not imperatively require a specific markers positioning on anatomical landmarks, while a group of at least three markers equipped on each rigid body is the only requirement for the computation of relative segments position and orientation. These approaches are hence potentially suitable in cases of motor deficit, becoming adaptable for several people categories.

Among the functional approaches, several strategies have been presented in literature, providing another sub-classification in fitting approaches (FA) and transformation techniques (TT), just diversified for the analytical formalism. The first FA category encompasses variants of the sphere fitting methods, where the center and the radius are optimized to best fit the markers position trajectories [17]: each marker can rotate about the same joint axes or center with a separate arc [9], [11] without a rigid body assumption. On the contrary, TT considers each body as a rigid one, allowing to assess joint parameters with rigid body transformations, like rotation matrices and translation vectors [20], [25]. This enables defining local coordinates system and appropriates transformations into a common reference frame, assuming the joint CoR as a fixed point.

When comparing in vivo different functional methods, the main drawback is that the evaluation of their precision, influenced by soft tissue artefacts (STA) [15] can be managed only through comparison with standard methodologies that present their own sources of inaccuracy. Some authors [5], [6], [8], [14], [16], [18], proposed a preliminary validation of functional methods using either virtual joint models with computer simulations or mechanical analogues.

Generally, functional methods provide more accurate results according to what is reported in literature [5], [9], [11], [14], [16]–[18], [20], [25], compared to the predictive ones. They are nevertheless based on several combinations of kinematical and geometrical constraints, as well as on optimization techniques, providing good results just in certain conditions [5], [6], e.g., with a proper range of motion (RoM).

Compared to human joints usually assumed as single hinge joints or monocentric spherical ones, the knee presents a more complex pattern of motion that varies according to the relative position between the adjacent segments. Thus it cannot be perfectly modeled as a single hinge with a fixed axis only, but it is needed to consider its roto-translation to reduce, e.g., the cross-talk problem during walking. To the best of the authors' knowledge, up to now no comparison of different methods applied to a system with mobile AoRs had been performed. The present work deals with the comparison of three functional methods to identify the mean axis of rotation in a polycentric hinge for the knee joint: the first algorithm is a fitting approach and comes from Halvorsen (H method) [11]. The other two methods are transformation techniques, respectively Spoor–Veldpaus (SV method) [20] and SARA [6].

In order to investigate and properly compare these different methodologies, a dummy leg articulated with a polycentric knee joint model had been used. The device mimics a joint with a mobile axis of rotation whose position is definable. The three functional methods, which approximate the polycentric knee joint with a single axis model, have been implemented with data obtained by laboratory trials.

Results are presented through the evaluation of misalignment and distance errors between the estimated axis of rotation and the instantaneous polycentric one, used as reference due to its known kinematics.

2. Materials and methods

The so-called functional or formal methods have been analyzed to assess the knee joint parameters using a polycentric hinge mechanism emulating the joint itself. Thus they provide a reconstruction of the knee joint kinematics, using groups of markers placed on both the thigh and the shank segments in relative motion with respect to the joint itself, according to a personalized choice for the positioning protocol.

2.1. Mechanical analogue

Once established that human knee joint cannot be modeled as a single hinge, with just a fixed AoR, a different joint modeling is considered here, in order to be able to identify a mobile axis (or center) of rotation, in addition to the fixed one. To this end, a polycentric hinge model was considered. In particular, a mechanical analogue has been realized by means of a dummy leg and of a pair of orthopedics polycentric hinges, externally fixed, as shown in Fig. 1a and 1b.

In particular, each polycentric hinge is composed of three roads, connected with hinges plate. Each hinge is then rigidly coupled to a cogwheel, in order to obtain a gear in correspondence to the center of the second road. This mechanism constrains the entire movement of the three roads, allowing the third element to rotate at 2θ angle with respect to the horizontal direction, when the second has rotated at θ angle. In particular, the first road within its gear is fixed on the thigh segment of the dummy leg, while the third one is fixed on the shank. The mechanical analogue allows flexion/extension movement in the sagittal plane, from 0° (dummy extended) up to 120°, not considering other movements right now (e.g., internal/external rotations and abduction/adduction motion), taking into account that its kinematics is often considered only by the flexion-extension axis only. According to this model reported in Fig. 2, the relative axis of rotation of the shank with respect to the thigh (geometric AoR) can move on a circle centered in the thigh gear component, unless for not meaningful variation due to geometric and assembling tolerances of the dummy, covering an α angle of flexion/extension, according to the RoM.

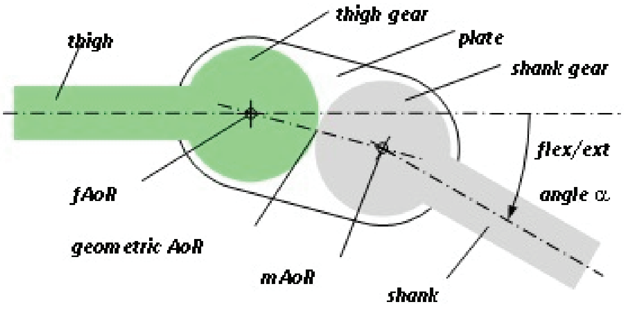

Fig. 2. Polycentric hinge section

2.2. Functional algorithms considered

As explained above, a functional approach can be useful for estimating joint parameters, trying to overcome some limitations currently presented with the standard predictive techniques, prone to errors arising from anatomical landmarks identification and anthropometric regression equations [4], [12], [19]. Among

Fig. 1a. Polycentric hinge

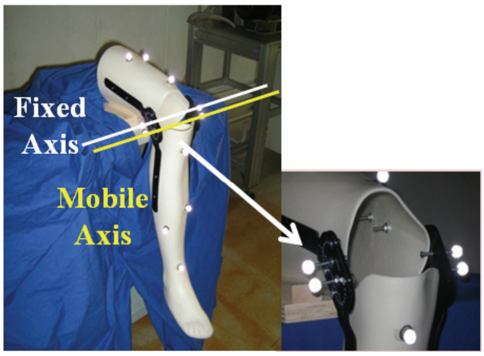

Fig. 1b. Dummy leg and polycentric hinges

several alternatives to the standard methods, three main functional methods [11], [20] and [6] are discussed here, implemented and tested on the dummy mechanical analogue, although the presence of a different mechanism with respect to the joint with which they were originally developed and processed. A fitting approach FA and two different transformation techniques TT (one and double sided), are reviewed.

The former, the H-method [11], is based on the motion data acquired from a set of markers, from which it is possible to assess the AoR by minimizing two objective functions. The main features of this algorithm are reported here:

- a versatility of application to different joint types (single hinge or ball-and-socket one);
- the absence of a rigid body condition, even if each marker can rotate around the same AoR (or CoR);
- the use of two objective functions that are minimized to assess the directional cosines of the AoR and its localization respectively, simply indicating a point on it.

In particular, the AoR can be assessed as a vector which best fits the rotational axis perpendicular to the plane containing several marker displacement vectors, evaluated between two frames accurately far, so as to cover a proper RoM.

The second method, which can be indicated as the SV-method, from the authors' names [20] is a one sided transformation technique, which assumes one segment, therefore the CoR in static condition. This algorithm also takes into account the markers motion data, allowing joint parameters to be estimated, according to a double process. In particular, this algorithm considers:

- a rigid body condition, assuming a constant distance of each marker on the respective segment;
- a rigid motion description with transformations of rototranslation in the space, by means of rotation matrices and translation vectors, which are unknown;
- the use of a singular value decomposition technique (SVD) in order to solve the problem of eigenvalues and eigenvectors, to approximate a pseudoinverse matrix;
- a screw-helical-motion assumption, in order to describe the rototranslation motion as the helical one, considering it between two instants of time (or frames), for the assessment of both the direction and the location of the AoR in space.

Finally, the SARA method [6], according to the acronym of "Symmetrical Axis of Rotation Assessment", is instead a two sided transformation technique, because it does not require a stationary CoR, allowing both segments to be considered in relative motion. The main features in this case are the following:

- the absence of stationary assumption of one segment (both can move);
- the lack of assumption related to the type of joint and the presence of a relative motion between the segments considered;
- the definition of a local reference system for each segment;
- the assessment of both orientation matrices and translation vectors, in order to compute the transformations between the local reference system into a common global one;
- the use of a linear least square approach to solve the optimization problem.

With this algorithm, two arbitrary points on the joint axis in the local coordinate systems are assessed to minimize an objective function, with the hypothesis that each one must be constant relative to each segments, and that through appropriate transformations into a global reference system there can be a unique estimation for such a parameter.

Once the algorithms had been implemented in Matlab environment, according to the relative analytical approaches researched in literature [11], [20] and [6], an experimental session was carried out in order to validate the functional methods with the proposed polycentric knee joint model.

2.3. Experimental session

A relative swing motion of the shank with respect to the thigh segment of the dummy leg was chosen in order to assess the main flexion/extension joint kinematics, as well the parameters of interest. All the algorithms proposed required motion data as input and, to this end, a stereophotogrammetric motion capture technique was considered. Indeed, nowadays, among several systems used to achieve the motion capture, the optoelectronic ones are usually chosen. They required both the use of a videocamera based system, operating in the visible range or in the near infrared, and a set of markers placed on the body segment, according to the standard or to different protocols.

For this study, a Vicon 512 motion capture system (Oxford Metrics, Oxford, UK) was used within its 6 infrared cameras. Concerning instead the concurrent use of markers, reflective ones of 14 mm in diameter were considered. A variable number of markers between 10 up to 12 was selected, according to this customized positioning protocol: 3 markers were placed on the thigh segment, just to verify the static condition; 4 markers were used for the polycentric kinematics identification. In particular, two couples of markers were properly screwed on both lateral hinges termini, according to what is represented in Fig. 1b, in order to identify both the fixed axis of rotation (fAoR) and the mobile one (mAoR). Finally a variable number of 3 up to 5 markers were arbitrary placed on the shank dummy segment, trying to cover the entire body volume, positioning them, e.g., on the lateral, medial, frontal and medial-frontal plane of the shank.

Several flexion/extension sessions were executed, considering the RoM of about (0°–90°) at 0.3 Hz. Spatio-temporal trajectories of markers were acquired with respect to the global laboratory reference frame, according to the Vicon system and then a post-processing data analysis was performed for the assumed goals.

In particular, the use of a rigid phantom made possible to avoid the use of proper filtering techniques for the soft tissue artifact removal and tracked marker trajectories were just smoothed. Two different movement scenarios were considered in order to validate and compare the aforementioned algorithms with a polycentric knee joint model. In particular, proper intervals were selected in order to cover two RoMs of about 55° (ROM I) and 20° (ROM II) for each flexion, or extension. Concerning the selection of frames for the first two methods (H and SV), authors have not considered two subsequent time instants, due to the possibility to compute better results between frames far apart [11], hence with displacements of the markers large enough.

Thus, the coupling of different frames was chosen: starting from the total number *n* of frames for each swing session, observation sets from (1 to *n*/2 + 1), (2 to *n*/2+2) up to (*n*/2 to *n*) were selected in order to generate two virtual merged initial and final frames of about the first *n*/2 and the second one respectively. The joint parameters, like the direction and the location of the AoRs have been hence assessed by means of H and SV algorithms, according to this proper frames coupling and by varying the number of markers on the shank from at least 3 up to 5.

The third SARA algorithm, instead, just takes into account the minimum number of 3 markers on both segments, in order to define the local reference frames. Thus, considering just the segments posing variation during the entire movement and not single marker trajectory displacements, a standard frame coupling was considered.

3. Results

Validation of the functional methods applied to the lower limb dummy is discussed here considering the presented results. This allows to better clarify how the algorithms have been used and compared. In particular, once both the fAoR and the mAoR have been identified as the lines passing through each couple of markers on the relative hinges termini, the direction of the estimated AoR was computed with each algorithm.

For what concerning instead its location at the polycentric knee joint model level, a point of intersection between the assessed AoR and a plane containing the fixed joint center (fCoR) and perpendicular to the axis itself, was assessed. Related instead to the polycentric joint centers of rotation, while the mobile (mCoR) and the geometric one (gCoR) were always assessed as the intersection point between the considered sagittal plane at the knee level and the relative

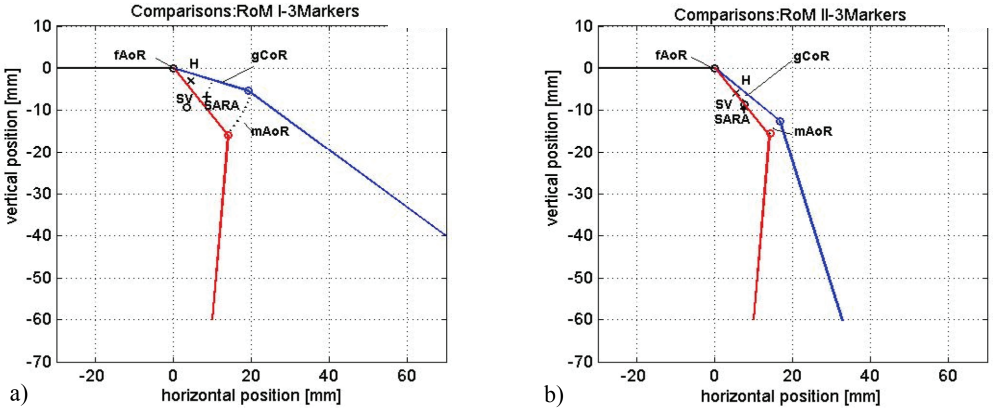

Fig. 3. Limits dummy segments position on the sagittal plane with the assessed mean CoR with respect to the gCoR for method H (**x**), SV (**o**) and SARA (+), according to the RoM I of 55° (a) and RoM II of 20° (b)

mAoR and the geometric axis of rotation, the fixed one (fCoR) was identified as the midpoint between the first couple of markers, placed on the hinge termini, relative to the thigh segment road.

The limit positions of the dummy segments, within the described geometric, mobile and fixed entities are shown in Fig. 3a–3b: red lines and blue ones indicate the starting and the final configurations of swing motion, respectively. According to these figures, the sagittal *xz*-plane configuration was represented related both to the two RoMs and to the use of 3 markers placed on the shank for the H, SV and SARA algorithms.

The feasibility of the presented functional methods, applied to the dummy knee joint model, is discussed here through the evaluation of misalignment (MEs) and distance (DEs) errors for the AoR direction and the CoR location, respectively. In particular, for each swing session *i* and the frames *j* considered, errors are computed as follows

$$ME_i[°] = \cos^{-1}\left(\frac{\overrightarrow{fAoR}\cdot\overrightarrow{AoR_i}}{\|\overrightarrow{fAoR}\|\cdot\|\overrightarrow{AoR_i}\|}\right), \tag{1}$$

$$DE_i[\text{mm}] = \text{mean}\,(|\overrightarrow{CoR_i} - \overrightarrow{gCoR_{i,j}}|)\,. \tag{2}$$

Concerning the distance errors, these were evaluated considering the mean value of the distribution of the processed knee joint centers. In particular, it is possible to derive a trend related to the curve of distance, for each swing session. Figure 4 shows this trend, considering, e.g., one of the swing sessions for ROM I of the H algorithm, varying also the number of markers (M) on the shank. According to the location of the assessed AoR, at the knee level, along the sagittal direction, it is possible to deduce from this trend where the point is approximately located with respect to the trajectory of the geometric center of rotation (gCoR).

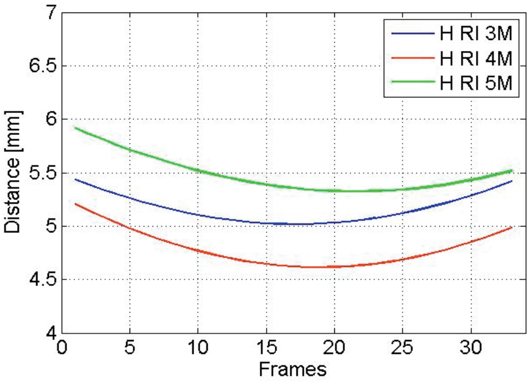

Fig. 4. Example of distance curve trend between the assessed CoR and the polycentric gCoR obtained with H-algorithm

The accuracy and precision of each algorithm analyzed are evaluated by means of the mean ± standard deviation values, obtained from the MEs and DEs, according to formulas (1) and (2). Thus, the mean misalignment and distance errors have been obtained from flexion/extension sessions analyzed with each algorithm,

Table 1. Averaged misalignment errors for the direction of the assessed AoR

ME [°] (Accuracy ± Precision)							
RoM		RoM I = 55°			RoM II = 20°		
Methods		H	SV	SARA	H	SV	SARA
N. markers	3	0.67 ± 0.04	1.70 ± 0.22	1.15 ± 0.20	1.18 ± 0.24	1.85 ± 0.34	1.73 ± 0.17
	4	0.72 ± 0.03	1.43 ± 0.10	*	1.17 ± 0.35	1.78 ± 0.41	*
	5	0.69 ± 0.05	1.39 ± 0.11	*	1.15 ± 0.32	1.59 ± 0.33	*

* for SARA algorithm just a subset of 3 markers was considered.

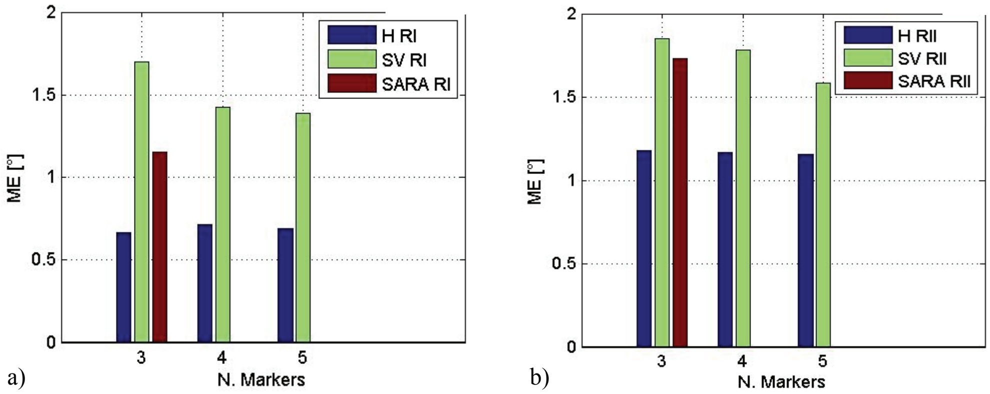

Fig. 5. Histogram distribution for the averaged *ME* [°]. (a) RoM I and (b) RoM II

Table 2. Averaged distance errors for the location of the assessed AoR

DE [mm] (Accuracy ± Precision)							
RoM		RoM I = 55°			RoM II = 20°		
Methods		H	SV	SARA	H	SV	SARA
N. markers	3	5.39 ± 0.21	5.22 ± 0.94	1.81 ± 0.16	3.77 ± 0.22	3.78 ± 1.86	4.57 ± 1.29
	4	5.32 ± 0.40	5.68 ± 1.27	*	4.10 ± 0.25	4.07 ± 1.70	*
	5	5.63 ± 0.22	5.97 ± 1.37	*	5.61 ± 0.20	4.25 ± 1.71	*

* for SARA algorithm just a subset of 3 markers was considered.

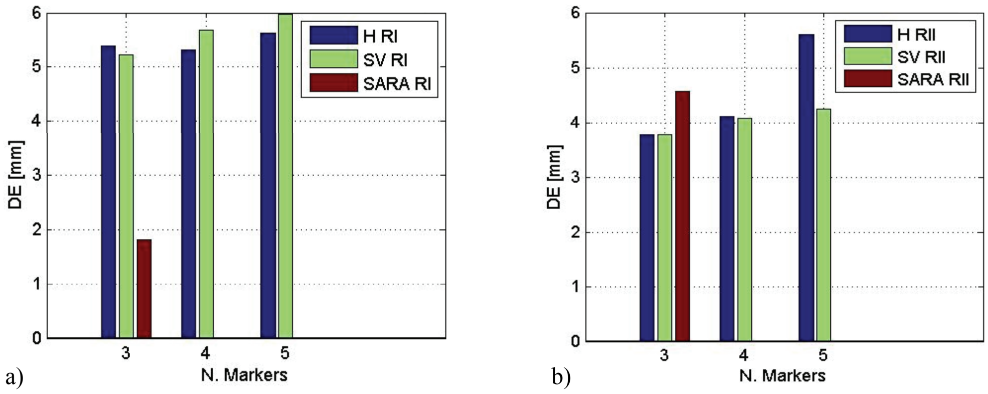

Fig. 6. Histogram distribution for the averaged *DE* [mm]. (a) RoM I and (b) RoM II

for both RoMs and are reported in Tables 1 and 2, respectively. Related histograms distributions of the averaged MEs and DEs are reported in Fig. 5a, 5b and 6a, 6b, respectively, for each motion analyzed.

4. Discussion

The estimation of joint parameters is important particularly during a quantitative motion analysis, for the assessment of, e.g., the knee joint kinematics, due to the possibility of assessing and monitoring some abnormalities. The determination of a single center of rotation is often not capable of describing such a complex pattern of motion.

In this study, three different functional methods had been experimentally implemented and compared to identify knee joint parameters. Taking into account the complexity of human knee physiology, the study was conducted on a lower limb mechanical analogue with a polycentric hinge, thus considering both a fixed axis of rotation (fAoR) and a mobile one (mAoR).

Halvorsen, Spoor-Veldpaus and SARA algorithms, already tested by other authors [18], [16] and [6] with fixed hinge systems, had been implemented. It is obvious that, in the specific case of a polycentric knee hinge, the estimated AoR is a unique fixed average axis estimation of the geometrical AoR between shank and thigh segments.

Few previous comparative studies on single hinges model or with computer simulation have been performed [5], [16], but an investigation on the relative performances seems difficult to ascertain due to varying test conditions and kinematics.

The obtained results show nevertheless a potential feasibility of application for the declared purposes. Values obtained in this study are of the same order of magnitude as the ones reported in [18], [16] and [6], confirming that the use of these algorithms is theoretically sound also if tested on a type of joint which differs from the reviewed ones; however errors of misalignment (ME) and position (DE) between the estimated AoR and the geometric one cannot be directly compared with literature results, due to the different hinge types commonly considered [2], [4], [12]. It has been provided that the estimated AoR depends on the flexion-extension RoM, as reported in a survey on functional methods used for joint axes estimation based on single hinge joint and computer simulations [5].

As a matter of fact, large range of the flexion-extension angle entails wider displacement of the geometric AoR and hence a greater DE, as reported in [5], with the exception of the SARA method, as summarized in Table 2; this behavior is intrinsic in functional methods that estimate an average AoR. Vice versa, ME decreases with a larger RoM consistently with literature studies [6], [16]. In addition, the accuracy deviations could be probably due to the realization of the mechanical analogue and to the polycentric hinges fixation on the dummy leg itself.

Concerning the number of markers taken into account on the shank, they have a certain influence on the DEs that increase with more markers, while they do not influence the MEs, despite some slight improvements for the SV case.

So far, the influence of marker misplacements associated with local shifting or deformation of the limb skin, which usually are the main causes of artefacts in human gait analysis [15], [21], have not been yet applied on the mechanical analogue. Thus, the additional error contribution emulating STA should also be considered in order to analyze the outcomes, taking into account this effect which is the largest source of error [15].

5. Conclusion

The results of the present study reveal that considering a rigid body, all the functional methods examined perform well, giving reliable assessments of the AoR alignment and location also for a polycentric joint mechanism, differently from previous studies.

The study provides a feasibility estimation of joint parameters with functional approaches and seems promising for further developments. Follow-up works to this study are under design: they involve a modified polycentric dummy leg with an artificial skin to generate uncontrolled marker movements similar to those found in clinical trials. As well, experimental trials of innovative algorithms joint model-specific could be considered in order to estimate the instantaneous kinematics of the AoR.

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