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Review

Human movement analysis using stereophotogrammetry Part 1: theoretical background

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Abstract

This paper sets the stage for a series of reviews dealing with the problems associated with the reconstruction and analysis of in vivo skeletal system kinematics using optoelectronic stereophotogrammetric data. Instantaneous bone position and orientation and joint kinematic variable estimations are addressed in the framework of rigid body mechanics. The conceptual background to these exercises is discussed. Focus is placed on the experimental and analytical problem of merging the information relative to movement and that relative to the morphology of the anatomical body parts of interest. The various global and local frames that may be used in this context are defined. Common anatomical and mathematical conventions that can be used to describe joint kinematics are illustrated in a comparative fashion. The authors believe that an effort to systematize the different theoretical and experimental approaches to the problems involved and related nomenclatures, as currently reported in the literature, is needed to facilitate data and knowledge sharing, and to provide renewed momentum for the advancement of human movement analysis.

Keywords: Stereophotogrammetry; Human movement analysis; Joint kinematics

1. Introduction

Human movement analysis aims at gathering quantitative information about the mechanics of the musculo-skeletal system during the execution of a motor task. In particular, information is sought concerning the movement of the whole-body centre of mass; the relative movement between adjacent bones, or joint kinematics; the forces exchanged with the environment; the resultant loads transmitted across sections of body segments or between body segments, or transmitted by individual body tissues such as muscles, tendons, ligaments, and bones; and body segment energy variation and muscular work. The 3D realistic representation of the movement of the musculo-skeletal system as seen from a point of view of choice (virtual reality) is a further relevant objective. The quantities that provide the above listed information are either measured or estimated using mathematical models of the musculo-skeletal system. In this way, quantitative descriptions of the functions of the locomotor system and their changes (assessment of enhancement or impairment) and/or of the way an individual executes a motor activity (assessment of activity limitation) are obtained.

Normally, the following quantities are measured. Instantaneous positions of markers located on the skin surface are obtained using stereophotogrammetry (motion capture) either based on conventional photography or optoelectronic sensors [1]. External forces are measured using dynamometers, such as force plates [2]. Electrical activity of muscles is recorded through electromyography [3]. Metabolic energy is assessed using indirect calorimetry. Anthropometric quantities are acquired either using a scale, a tape measure and callipers, or more sophisticated methods such as 3D scanners.

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Following the seminal work by Braune and Fischer [4], the anthropomorphic model used to estimate the quantities that are not directly observable consists of a kinematic chain of links. Each link represents a portion of the human body referred to as body segment. These segments are made of a bony part (segment) and by soft tissues. Bony segments are considered non-deformable and, therefore, are represented using rigid bodies, according to Classical Mechanics. So far, no author has disputed this choice or assessed the inaccuracy that it may introduce in the analysis, provided, of course, that the bony segment represents a single bone. Joints with 1–5 degrees of freedom connect bony segments. The limit cases of 0 and 6 degrees of freedom may be included for the sake of generalization. The number of bony segments and constraints imposed by the joints contribute to the number of degrees of freedom of the model and its structural faithfulness to reality. Soft tissues around the bony segments may or may not be considered deformable. Most of the literature chooses the latter option, that is, the entire body segment is regarded as a rigid body. In principle, under these circumstances, the analysis described above is straightforward. For the most part, Classical Mechanics can solve any related problem and, with the aid of modern computers, can do this without difficulty. However, in recent years some authors have started to advocate soft tissue deformability to be accounted for in human movement modeling as well. It has been shown that by ignoring this deformability, both absolute and relative bony segment movements, reconstructed using non-invasive photogrammetric data obtained by using skin-markers, are affected by inaccuracies that may hinder the practical usability of the results [5–10]. Another issue concerns the inertial effects that tissue deformation (wobbling masses) may have on movement kinetics during highly accelerated movements [11]. These matters were debated at the end of 2001 in the Biomch-L list forum (http://www.isbweb.org).

The above considerations open scenarios within which biomechanists and others in the field may find ample stimuli for original solutions, and human movement analysis may gain a renewed momentum both in science and in several application fields. In addition, a vast consensus on the importance of this discipline and on the fact that resources should be invested for further relevant developments exists among users. For these reasons, we believe that reviewing the relevant state of the art of knowledge is timely.

This paper is the first of a series of reviews that pursues the above-mentioned objective. The focus is placed on the conceptual and analytical bases that are necessary for the reconstruction and analysis of skeletal system movement by using optoelectronic stereophotogrammetry. Note that to pursue this objective, morphological information is also required both for the 3D realistic reconstruction of the skeletal system and for the numerical description of kinematics. For the latter purpose, mostly vector quantities are used and their numerical representation depends on the orthogonal set of axes involved. For reasons of repeatability of kinematic description, the latter axes must also be repeatable and the only way to accomplish this is to define them relative to morphology. The present paper also intends to contribute to the standardization of relevant nomenclature.

Subsequent reviews will deal with the theory and technology of optoelectronic stereophotogrammetry focusing on errors and methods of assessment. The problem of estimating the instantaneous position and orientation of bones using reconstructed skin-marker trajectories will be summarized, with an initial concentration on those aspects likely to be affected by stereophotogrammetric errors. In this case, body segments will be assumed to be rigid and the techniques that apply well only in experimental conditions when the deformation of the soft tissues can be considered non-existent or minimal and therefore disregarded will be reported. Subsequently, the studies that have addressed the problems associated with soft tissue deformation will be reviewed. This will be done both in terms of the assessment of the relative movement between skin markers and underlying bone, and of the minimization of its propagation to joint kinematic variable estimates. A final topic of discussion will be the additional source of error in human movement analysis associated with the registration of morphology with motion data. This is done by reviewing methods devoted to the identification of the location of anatomical landmarks in general, and of the centre of the femoral head in particular.

No mention will be made about the forces involved in the process. However, since the problems associated with myoskeletal kinetics follow the knowledge of how the system moves (inverse dynamics), the perspective of utilizing kinematics for kinetic problem solving should be kept in mind by the reader throughout this series of reviews.

2. Segmental kinematics

The objective of segmental kinematics is the collection of numerical information that allows the reconstruction of a body, considered rigid or not, or bony segment in space in each sampled time instant during the execution of a motor task. For this purpose, two pieces of information are necessary: one relative to morphology and one to movement.

The morphological description of a segment can be obtained by representing it as an ensemble of particles and providing the position vector of each relative to an orthogonal set of axes (local frame):

$$ {}^{1}\boldsymbol{p} = [\,{}^{1}p_x \quad {}^{1}p_y \quad {}^{1}p_z\,]. \tag{1}$$

It follows logically that the more particles used, the more detailed the description will be (Fig. 1).

If the body under analysis is considered deformable, then the vector ${}^{1}\boldsymbol{p}$ must be given for each particle and each sampled instant of time during the observation interval. However, as is often the case in human movement analysis, if the investigator is not interested in the deformations of the segment involved, but only in its global location in space, then this may be considered non-deformable in an absolute sense

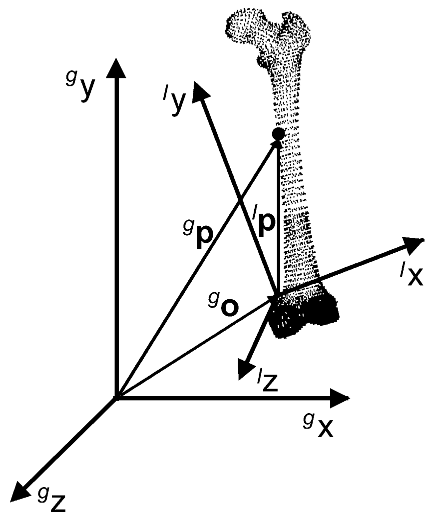

Fig. 1. The position vector of a particle represented in a global (^{g}x, ^{g}y, ^{g}z) and a local (^{l}x, ^{l}y, ^{l}z) frame, indicated as $^{g}\boldsymbol{p}$ and $^{l}\boldsymbol{p}$, respectively.

and represented as a rigid body. This entails enormous simplification since, under this hypothesis, the above mentioned particle position vectors are invariant with respect to time and/or boundary conditions and can, therefore, be measured only on one occasion and under the most favorable experimental conditions. Similar considerations apply to the inertial parameters (e.g., location of the centre of mass, mass moments of inertia) of the segment involved.

The morphology of a segment may be represented with respect to any arbitrary frame, that is, with respect to any observer. Given a local frame and another frame, which we refer to as the global frame, it is possible to derive the position vectors of the particles of the segment under analysis defined in the latter frame ($^{g}\boldsymbol{p}$) provided that those defined in the former ($^{l}\boldsymbol{p}$) are given (Fig. 1). This exercise is called vector or coordinate transformation and is obtained through the following equation (for details, refer to any Classical Mechanics text):

$$^{g}\boldsymbol{p} = {}^{g}\boldsymbol{R}_{l}\,{}^{l}\boldsymbol{p} + {}^{g}\boldsymbol{o}, \tag{2}$$

where

$$^{g}\boldsymbol{R}_{l} = \begin{bmatrix} \cos\theta_{x_g x_l} & \cos\theta_{x_g y_l} & \cos\theta_{x_g z_l} \\ \cos\theta_{y_g x_l} & \cos\theta_{y_g y_l} & \cos\theta_{y_g z_l} \\ \cos\theta_{z_g x_l} & \cos\theta_{z_g y_l} & \cos\theta_{z_g z_l} \end{bmatrix} \tag{3}$$

defines the orientation of the local, relative to the global, frame and is referred to as the orientation matrix, and $^{g}\boldsymbol{o}$ is the position vector of the origin of the local frame relative to the global frame, and defines the position of the former relative to the latter. The column elements of the matrix in (3) are the direction cosines, or the unit vector components, defining the orientation of each local frame axis relative to the global frame. With reference to these nine matrix elements, it is important to emphasize that they are not independent. In fact, taking into account their definition and the fact that the frame axes they define are mutually orthogonal and that triplets of them represent unit vectors, six scalar equations may be written that reduce the number of independent elements to three. In summary, three scalar independent quantities define the relative orientation, and three the relative position. The ensemble of position and orientation of any one frame relative to another, that is, of a rigid body relative to another, is referred to as *pose*.

If the problem is representing the segment under analysis in virtual reality, given the invariant position vector of its particles relative to a local frame, then, by providing the computer with the above-mentioned six quantities, it is possible to view the segment from any other global perspective.

The mathematical tool illustrated above may be used to describe segment movement as well. In fact, if the pose of the local frame is described in each sampled instant of time during movement relative to a global frame by giving the six independent scalar quantities implied in $^{g}\boldsymbol{R}_{l}$ and $^{g}\boldsymbol{o}$, then the segment morphology ($^{l}\boldsymbol{p}$) can be reconstructed in its instantaneous location ($^{g}\boldsymbol{p}$) through Eq. (2). It is interesting to emphasize that this approach, based on the assumption of rigidity, allows the description of the pose of a body using only six numerical values for each sampled instant of time. To these values, the time invariant local coordinates of the particles used to represent the morphology must be added for virtual reality representation of the movement.

3. Global and local frames: terminology

The description of the skeletal-system movement involves the definition of specific sets of axes or frames that are either global or local.

3.1. Global frames

In a movement analysis laboratory, the following inertial, global, frames can be defined (Fig. 2) [12,13].

Photogrammetric frame

This is the set of axes in which marker position coordinates are provided by the stereophotogrammetric system. These are arbitrarily defined relative to the calibration object or procedure used.

Motor task frame

This frame is consistent with the analyzed motor task and sometimes describes its basic features. For instance, when locomotor acts are investigated, one axis of the frame indicates the mean direction of progression, possibly including the orientation of the floor (in case of non-level locomotion). According to the general recommendations from the International Society of Biomechanics [14,15], in human movement analysis orthogonal coordinate systems should have the *X*-axis pointing forward in most locomotor tasks coinciding with the direction of progression, *Y* pointing vertically upwards, and *Z* pointing to the right.

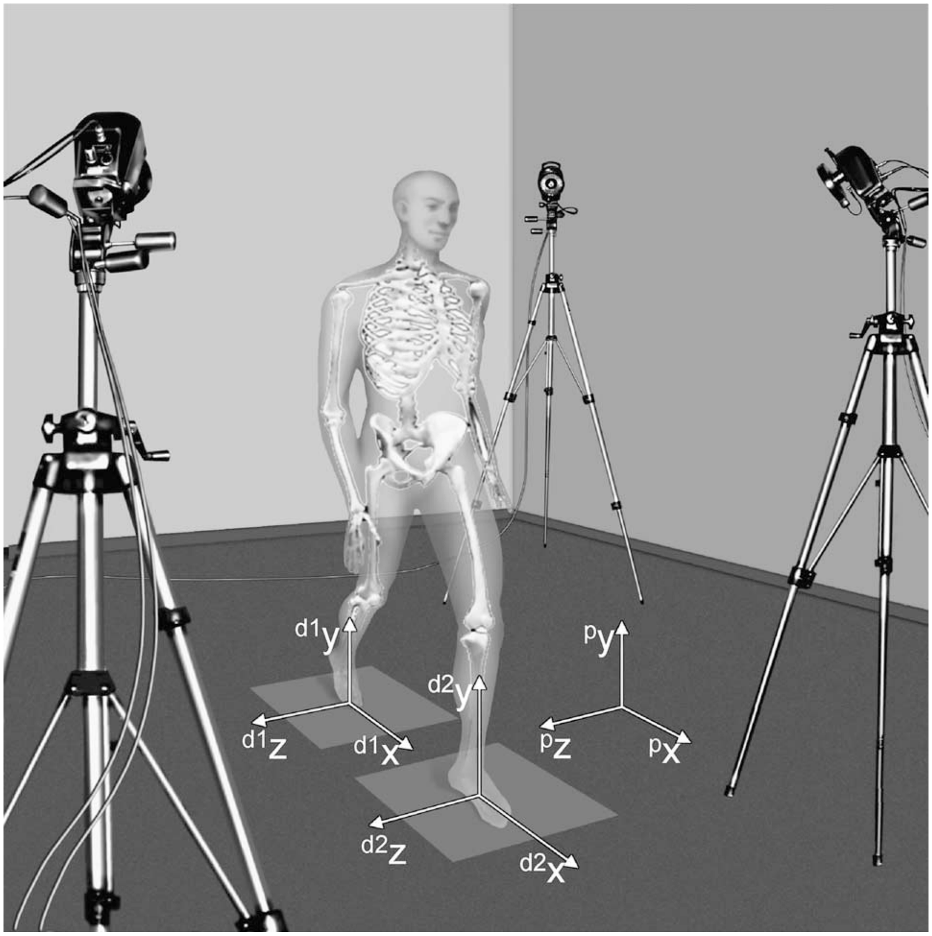

Fig. 2. The human movement analysis laboratory. Basic measurement instruments are depicted together with their systems of axes (p: photogrammetry; d: dynamometry). If level walking is analyzed, the motor task frame may coincide with the frame of one of the two force plates.

Dynamometer frame

This is the frame in which force and moment components are given by the instrument and is defined by the relevant calibration matrix.

Plumb line

This is a single axis and represents the orientation of the gravity line, usually assumed to point downward.

As implicit in the previous section, within the same experiment, different mechanical quantities are measured with respect to different global frames. However, normally, their interpretation, or use as input to the mathematical models that allow for the estimation of non-measurable quantities, requires that all of them be represented in the same frame (primary global frame). The latter role is usually assumed by the motor task frame. Thus, a *global frame calibration* procedure must be carried out. This consists of the determination of the position vector and the orientation matrix of all secondary global frames involved relative to the primary global frame (${}^{\mathrm{pg}}\boldsymbol{R}_{\mathrm{sg}}$, ${}^{\mathrm{pg}}\boldsymbol{o}$). This allows for the transformation of any vector given in the former frames into a vector in the primary frame (see Eq. (2)). From an operative point of view, ad hoc experiments are carried out which allow for the determination of the position vectors of selected fiducial points in both the secondary and primary global frame. By using an adequate number (N) of these points and feeding their position vectors into equations having the same form of Eq. (2), where the secondary global frame takes the place of the local frame, the unknown orientation matrix and position vector are estimated by the following equation:

$$ {}^{\mathrm{pg}}\boldsymbol{p}_{\mathrm{k}} = {}^{\mathrm{pg}}\boldsymbol{R}_{\mathrm{sg}}\,{}^{\mathrm{sg}}\boldsymbol{p}_{\mathrm{k}} + {}^{\mathrm{pg}}\boldsymbol{o}, \quad \mathrm{k} = 1, \ldots, N \tag{4} $$

For the sake of accuracy, this estimation counts on a redundant number of fiducial points and uses a least squares approach [16]. A typical example is the determination of the pose of the force plate frame relative to the photogrammetric frame by using a set of three or more markers located in known positions in the former frame [17].

3.2. Local frames

A generic local frame rigidly associated with a bony segment is referred to as *technical frame* (TF) [12–15,18]. These frames are used to describe the location in space, either stationary or time-varying, of the segment under analysis (Fig. 3).

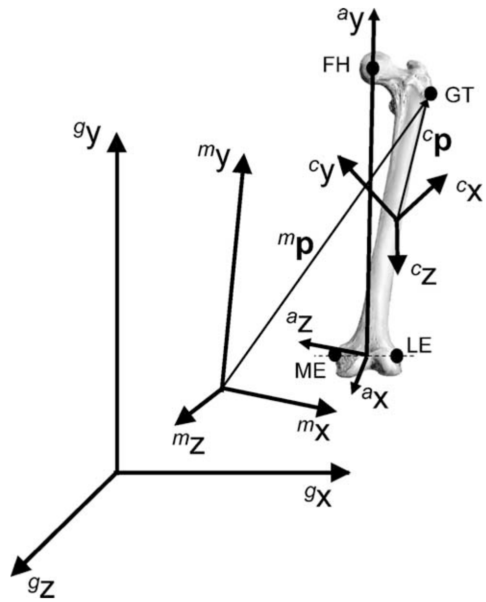

Fig. 3. Morphological (${}^{m}x$, ${}^{m}y$, ${}^{m}z$) and marker cluster (${}^{c}x$, ${}^{c}y$, ${}^{c}z$) technical frames, and anatomical frame (${}^{a}x$, ${}^{a}y$, ${}^{a}z$). The latter frame is defined as having the *y* axis joining the midpoint between the lateral and medial femoral epicondyles (LE, ME) and the centre of the femoral head (FH) with positive direction proximal, the *z* axis lies in the plane defined by the *y* axis and FH and points from left to right, the *x* axis is orthogonal to the *yz* plane with its positive direction forward [12]. The position vectors of a selected anatomical landmark (greater trochanter, GT) in the marker cluster (${}^{c}\boldsymbol{p}$) and morphological (${}^{m}\boldsymbol{p}$) technical frames are also shown.

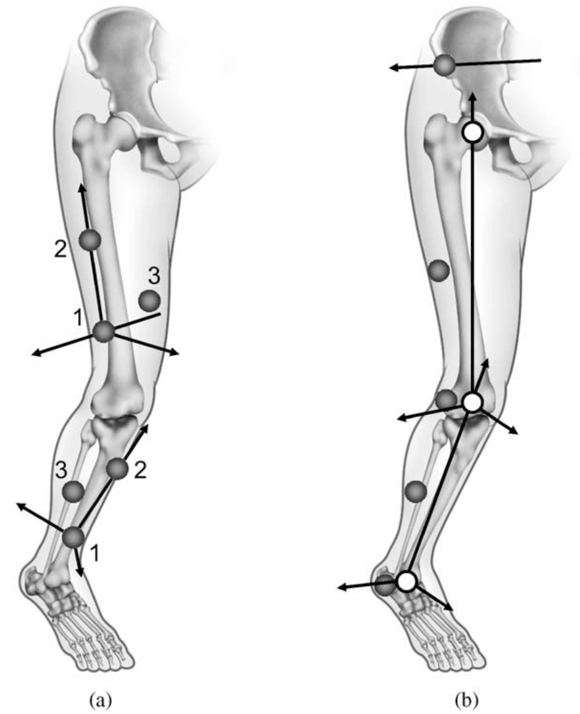

Fig. 4. Examples of marker set and marker cluster technical frame. (a) three technical markers (filled circles) for each bony segment; the cluster technical frame is constructed using the following rule: ${}^{g}\boldsymbol{p}_1$ is the position vector of the frame origin, the y axis is oriented as $({}^{g}\boldsymbol{p}_2 - {}^{g}\boldsymbol{p}_1)$, and the x axis as $({}^{g}\boldsymbol{p}_3 - {}^{g}\boldsymbol{p}_1) \times ({}^{g}\boldsymbol{p}_2 - {}^{g}\boldsymbol{p}_1)$; the z axis is oriented so that a right handed frame is constructed; (b) marker set up that uses virtual markers (open circles): the centre of the acetabulum is determined in the pelvic technical frame using regression equations and pelvic dimensions [23,24] and made to coincide with the centre of the femoral head, a point medial to the lateral femoral epicondyle of a given quantity is supposed to be rigid with the tibia, and, similarly, a point medial to the lateral malleolus is supposed to be rigid with the foot [20,21]. In this way three markers for each body segment analyzed are made available.

Morphology technical frame (MTF)

This is the TF used in the course of the experiments that provide the segment morphology. It is defined by the technique and/or measuring equipment used and may be regarded as arbitrary.

Marker cluster technical frame (CTF)

This is the TF used to describe the movement of a segment and is reconstructed using the instantaneous position of at least three non-aligned superficial markers associated with the bony segment and tracked by a photogrammetric system (Fig. 4a). These markers, which are named *technical markers*, are positioned to comply with technical requirements such as visibility to a sufficient number of cameras and to minimize relative movement between them and underlying bone. Normally, their position has no repeatable reference to the morphology of the segment. For this same reason, the CTF has an arbitrary position and orientation with respect to the bone, which depend on both the location of the markers and the analytical procedure used to generate them [16,19]. In order to economize the number of markers, some authors construct some CTFs using *virtual markers*. These are points on a segment for which the location is determined, through some geometric rule, relative to the position of the technical markers in the relevant CTF. If a virtual marker, thus obtained, is supposed to be shared with an adjacent segment, then it may be used to construct the CTF of the latter segment. This is the case, for instance, when the two segments involved are hypothesized to be joined by a spherical hinge and the virtual marker is the centre of rotation [20,21] (Fig. 4b).

Normally, the instrumentation used to record morphology information is different from that used to reconstruct the segment movement, and the two procedures are separate both in time and location. Therefore, the two TFs referred to above are different (Fig. 3). This circumstance raises a problem. In order to represent the segment in its instantaneous pose, both movement and morphology data must be given with reference to the same TF. Thus, a transformation of the position vectors given in the MTF into position vectors in the CTF, or vice versa, must be carried out (*movement-morphology data registration*). For this purpose an *anatomical calibration* procedure must be carried out (Fig. 5). Similar to the global frame calibration procedure, the position vectors of a number of selected points belonging to the segment under analysis must be made available in both TFs involved (${}^{m}\boldsymbol{p}$ and ${}^{c}\boldsymbol{p}$ in Fig. 3). These points must coincide with anatomical landmarks (AL) so that they be identifiable in a repeatable fashion [22]. Superficial ALs, usually bony prominences,

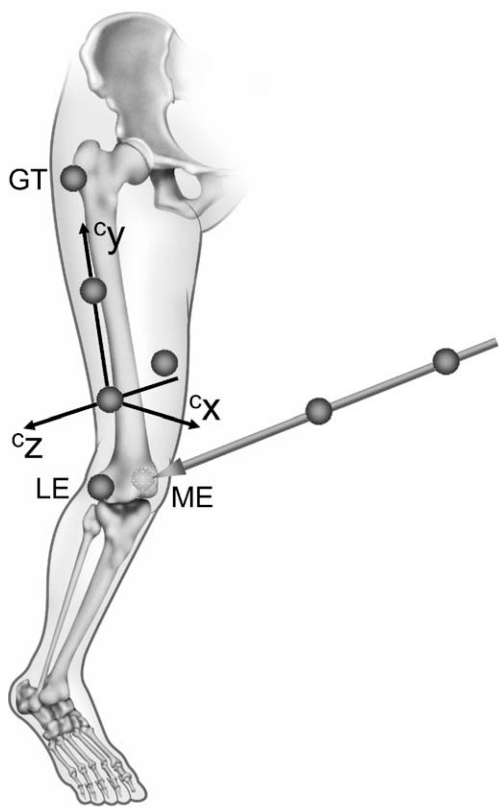

Fig. 5. Anatomical calibration using stereophotogrammetry. The following external, palpable, anatomical landmarks are indicated: prominence of the greater trochanter external surface (GT), medial epicondyle (ME), lateral epicondyle (LE). The location of the external anatomical landmarks relative to the marker cluster technical frame (${}^{c}x$, ${}^{c}y$, ${}^{c}z$) may be reconstructed using markers denoting the anatomical landmarks, or using a wand which carries a cluster of at least two markers. Prior to recording, the end point of the wand, the position of which relative to the latter cluster of markers is accurately known, is made to coincide with the target anatomical landmark.

are used and identified by palpation, and their position in the CTF is determined by locating markers on them (*anatomical markers*) and using stereophotogrammetry. These markers may be removed prior to tracking the movement under analysis, unless they are also made to play the role of technical markers (Fig. 4b). Internal AL positions are normally estimated using the location of superficial ALs and predictive models [20,23–25]. In the case of the centre of the femoral head, the fact that it can be considered to coincide with the centre of rotation of the femur relative to the pelvis allows its location to be determined using movement data (*functional approach* [18,25]). The position of the ALs in the MTF is determined using a *virtual palpation* procedure [26]. A possible alternative to the above-mentioned procedure consists of the determination of the position in the CTF of a highly redundant number of unlabeled points of sufficiently large portions of the bone under analysis [27–29].

Anatomical frame

As opposed to the TFs, the location of which, relative to the underlying bony segment, is arbitrary and, as such, non-repeatable, anatomical frames (AF) are defined specifically to meet the requirements of intra- and inter-subject repeatability. In addition, their planes normally approximate the frontal, transverse and sagittal anatomical planes. This is achieved by setting a geometric rule that constructs the AF using selected ALs determined in the CTF through the anatomical calibration exercise illustrated above (Fig. 5) [14,15,22]. To this end, anatomical markers may also be placed in points that do not denote ALs but lie on anatomical planes as identified by the operator [21,22] (Fig. 4b). Alternatively, when the bone morphology is available, the AF can be defined using the intrinsic wealth of morphological information and first represented in the MTF and, then, in the CTF through the registration procedure illustrated above. This topic will be discussed further in a subsequent review paper.

Following the suggestion made in Cappozzo et al. [12], some authors refer to the general approach to human movement reconstruction presented in the latter two sections as calibrated anatomical system technique (CAST).

4. Joint kinematics

Joint kinematics is the description of the relative movement between two contiguous bony segments, the proximal (p) and the distal (d). Given the orientation matrices ${}^{g}\boldsymbol{R}_{\mathrm{d}}$ and ${}^{g}\boldsymbol{R}_{\mathrm{p}}$, and the position vectors ${}^{g}\boldsymbol{o}_{\mathrm{d}}$ and ${}^{g}\boldsymbol{o}_{\mathrm{p}}$ of the local frames associated with the two segments with respect to a selected global frame, the following expressions can be obtained:

$$\boldsymbol{R}_{\mathrm{j}} = {}^{g}\boldsymbol{R}_{\mathrm{p}}^{\mathrm{T}}\,{}^{g}\boldsymbol{R}_{\mathrm{d}}, \qquad \boldsymbol{t}_{\mathrm{j}} = {}^{g}\boldsymbol{R}_{\mathrm{p}}^{\mathrm{T}}({}^{g}\boldsymbol{o}_{\mathrm{d}} - {}^{g}\boldsymbol{o}_{\mathrm{p}}), \tag{5}$$

where $\boldsymbol{R}_{\mathrm{j}}$, referred to as the joint orientation matrix, and $\boldsymbol{t}_{\mathrm{j}}$ as the joint position vector, carry complete information about orientation and position (pose) of the distal segment relative to the proximal segment and, thus, about joint kinematics. $\boldsymbol{R}_{\mathrm{j}}$, by its own nature, describes the joint orientation, taking as reference the orientation when the two local frames involved are aligned ($\boldsymbol{R}_{\mathrm{j}} = \boldsymbol{I}$; where $\boldsymbol{I}$ is the identity matrix).

In human movement analysis, the quantities that describe joint kinematics must be repeatable. In addition, it is desirable that they lend themselves to be interpreted consistently with the language in use in functional anatomy and related disciplines. It can be said that the objective of biomechanics in this case is to render anatomically valid and reliable measurements.

As far as repeatability is concerned, the following arguments can be made. Given a relative orientation of the two contiguous segments, the value of the scalar quantities that appear in $\boldsymbol{R}_{\mathrm{j}}$ and $\boldsymbol{t}_{\mathrm{j}}$ depend on the pose of the two local frames used to derive them relative to the segments. Thus, for each segment involved, a frame must be used that can be identified in a repeatable fashion. The AFs defined in the previous section comply with this requirement. A possible

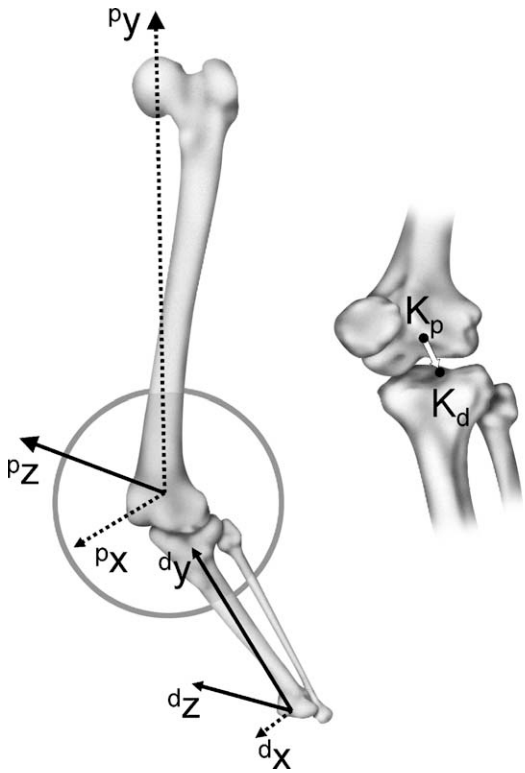

Fig. 6. Proximal ($^{\mathrm{p}}x$, $^{\mathrm{p}}y$, $^{\mathrm{p}}z$) and distal ($^{\mathrm{d}}x$, $^{\mathrm{d}}y$, $^{\mathrm{d}}z$) anatomical frames used to describe joint kinematics. In the hypothesis of using the Cardan convention, the three rotations used to describe the joint rotational degrees of freedom are thought to occur in sequence about the $^{\mathrm{p}}z$ (or $^{\mathrm{d}}z$) axis (flexion-extension), the $^{\mathrm{d}}x$ axis (adduction–abduction), and the $^{\mathrm{d}}y$ axis (internal–external rotation). The points defined in the proximal (K_{p}) and in the distal frames (K_{d}) used to describe the joint translational degrees of freedom are also indicated.

alternative for the identification of appropriate proximal and distal AFs, is making reference to the so-called joint axes. Some joints have a dominant rotational degree of freedom for which a mean axis of rotation may be defined. Examples in this respect are the knee and the ankle joints. Based on this consideration and when applicable, it is possible to construct the relevant AFs by using this axis in addition to selected anatomical landmarks [30,31]. Whether this functional axis should be subject specific, as the anatomical landmarks are, or estimated using some predictive model is still a matter of discussion.

Therefore, the joint position vector and orientation matrix should be calculated using Eq. (5) and the relevant proximal and distal AFs (Fig. 6). For the sake of comparison, data sharing, and knowledge building, for each bony segment, a specific AF should be agreed upon by the professional or scientific community involved and standardized [14,15].

With respect to the interpretability and consistency with the language of functional anatomy, it is desirable that the six independent scalar quantities inherent in $\boldsymbol{R}_{\mathrm{j}}$ and $\boldsymbol{t}_{\mathrm{j}}$ be three angles (three rotational degrees of freedom) and three lengths (three translational degrees of freedom) defined relative to given axes. Mechanics provides several methods that permit the extraction of the latter quantities from the joint orientation matrix and position vector. The problem is that this is true from the analytical point of view, but whether the three angles and the three lengths thus obtained represent an acceptable answer to the above-mentioned issue, is a matter that needs to be expounded upon.

4.1. Translational degrees of freedom

The relative position between two adjacent bones is described by making reference to the vector ($\boldsymbol{t}_{\mathrm{j}}^{*}$) joining a point defined in each of the proximal (K_{p}) and the distal local frames (K_{d}) (Fig. 6). If K_{p} and K_{d} are the origins of the two frames, this vector coincides with $\boldsymbol{t}_{\mathrm{j}}$. For the sake of the already-mentioned repeatability issue, these reference points should coincide with anatomical landmarks.

The next problem consists of the definition of the anatomical axes with respect to which the scalar components of the above-mentioned vector should most effectively be represented [31]. This is an issue that has not been as yet sufficiently debated in the literature. The reason for this may be that the variations in magnitude of this vector during movement are normally too small to be resolved by the presently available experimental and analytical methods.

4.2. Rotational degrees of freedom

Assuming that, to start with, the two AF axes are aligned, the distal AF can reach any orientation relative to the proximal AF by undergoing three successive rotations, each time about one of the six axes involved in its current orientation. The three angles thus obtained are used to describe the joint instantaneous orientation.

Calling $\{x_{\mathrm{p}}y_{\mathrm{p}}z_{\mathrm{p}}\}$ the proximal and $\{x_{\mathrm{d}}y_{\mathrm{d}}z_{\mathrm{d}}\}$ the distal system of axes, if $\{x_{\mathrm{d}}y_{\mathrm{d}}z_{\mathrm{d}}\}$ is rotated by an angle α about the x_{p} or x_{d} axis, then the relevant orientation matrix is:

$$\boldsymbol{R}_{\mathrm{j}\alpha} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{6}$$

Similarly, the orientation matrices obtained from rotations about the y_{p} or y_{d} axis (β) and about the z_{p} or z_{d} axis (γ) are given respectively by:

$$\boldsymbol{R}_{\mathrm{j}\beta} = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, \tag{7}$$

$$\boldsymbol{R}_{\mathrm{j}\gamma} = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{8}$$

These matrices are referred to as basic rotation matrices [32–34]. As mentioned previously, any orientation of the distal frame with respect to the proximal frame can be thought of as the result of three successive and ordered basic rotations. After these basic rotations have occurred, the joint orientation matrix may be obtained using the following rules [32]:

- Initially, both $\{x_p y_p z_p\}$ and $\{x_d y_d z_d\}$ are thought to be coincident, and hence the orientation matrix is a 3×3 identity matrix $\boldsymbol{I}$.
- If a rotation occurs about an axis of the proximal frame, then one has to *pre-multiply* the previous orientation matrix with the appropriate basic rotation matrix.
- If a rotation occurs about an axis of the distal frame, then one has to *post-multiply* the previous orientation matrix with the appropriate basic rotation matrix.

Thus, if, for example, it is hypothesized that the three consecutive rotations occur, first, around the z_p axis (that coincides with the z_d axis), second, around the current orientation of the x_d axis, and, third, around the current orientation of the y_d axis, then the orientation matrix is:

$$\boldsymbol{R}_j = \{[(\boldsymbol{R}_{j\gamma}\boldsymbol{I})\boldsymbol{R}_{j\alpha}]\boldsymbol{R}_{j\beta}\}; \tag{9}$$

which can be written as

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} = \begin{bmatrix} \cos\gamma\cos\beta - \sin\gamma\sin\alpha\sin\beta & -\sin\gamma\cos\alpha & \cos\gamma\sin\beta + \sin\gamma\sin\alpha\cos\beta \\ \sin\gamma\cos\beta + \cos\gamma\sin\alpha\sin\beta & \cos\gamma\cos\alpha & \sin\gamma\sin\beta - \cos\gamma\sin\alpha\cos\beta \\ -\cos\alpha\sin\beta & \sin\alpha & \cos\alpha\cos\beta \end{bmatrix} \tag{10}$$

From this system of equations the angles α, β and γ can be obtained as:

$$\alpha = \sin^{-1} r_{32}, \qquad \beta = \sin^{-1}\left(\frac{-r_{31}}{\cos\alpha}\right),$$
$$\gamma = \sin^{-1}\left(\frac{-r_{12}}{\cos\alpha}\right). \tag{11}$$

Note that a singularity condition occurs when α equals $\pm\pi/2$ rad (gimbal-lock) and, therefore, large errors may occur when α approaches those values. In addition, the sequence with which the three rotations are made to occur cannot be changed consistent with the fact that matrix multiplication is not commutative (Eq. (9)).

If the sequence of rotations involves the three axes of the proximal or distal frames, then the Cardan, or Bryant, convention is used. The specific sequence of basic rotations used in the example, chosen among the several sequences that are possible, is consistent with the so-named Grood and Suntay's convention [36]. This was first proposed for the description of the angular motion of the lower limb joints since, through a proper selection of the AFs, the above-mentioned singularity condition may be avoided, and the desired consistency with the language of functional anatomy achieved [14,15,34–36]. If the AFs are chosen so that the x axes are antero-posterior, the y axes are longitudinal, and the z axes are medio-lateral relative to the bony segments involved (Fig. 6), then the angles α, β and γ may be effectively interpreted as the extent to which the joint is abducted or adducted, internally or externally rotated, and flexed or extended, respectively, relative to the reference aligned orientation.

The three above-mentioned rotations are often described as occurring about three non-orthogonal axes: the z_p axis, a floating axis (an axis orthogonal to both the z_p and the y_d axis), and the y_d axis [36]. It is evident that when the second rotation occurs, the floating axis coincides with the x_d axis. Thus, there is no difference between the two ways of presenting this subject matter.

It is important to remember that the three angles referred to do not describe real rotational movements. Although they may be given a physical meaning, they simply represent a conventional, univocal way of describing instantaneous relative orientations.

Any given orientation of the distal AF with respect to the proximal AF can also be described by assuming that it is reached, from an initially aligned condition, through a single rotation by an angle θ, around an axis with unit vector $\boldsymbol{n}$ [34,37]. Thus the joint orientation may be described using the orientation vector $\boldsymbol{\theta}_j = \theta_j \boldsymbol{n}_j$. This vector can be derived from the orientation matrix $\boldsymbol{R}_j$ and vice versa. The scalar components of this vector may be represented in either AFs, which, apart from a sign inversion, would be identical [37] or in any set of axes of choice, be they orthogonal or not. The specific choice depends, again, on the consistency of the results with the language of functional anatomy.

The components of the orientation vector $\boldsymbol{\theta}_j$ should not be interpreted as actual rotations about the AF axes, but simply as an algebraic method to express a vector in a given coordinate system. Unlike position vectors, and consistent with what has been noted with reference to the Cardan angles, the orientation vectors are not additive. For example, if $\boldsymbol{\theta}_{j1}$ and $\boldsymbol{\theta}_{j2}$ represent the orientation vectors of two different orientations of the $\{x_d y_d z_d\}$ with respect to the $\{x_p y_p z_p\}$ system of axes, the orientation vector that describes the rotation from orientation 1 to orientation 2 is not equal to the difference $\boldsymbol{\theta}_{j2} - \boldsymbol{\theta}_{j1}$. Additivity is valid only under special conditions such as consecutive rotations about parallel axes (planar movements) or infinitesimal rotations. An interesting feature of this convention relates to the fact that it is not prone to gimbal-lock [37].

A third approach may be proposed for the description of a joint's rotational degrees of freedom. It is based on the projection of axes of an AF onto the planes of the other AF, and in the determination of the angles formed by these projections with suitably selected AF axes [38,39]. As such, it is referred to as a geometrical convention. For example, in the instance of the knee joint, the following rotation angles can be defined [38]:

- Flexion-extension angle: the angle formed by the y axis of the tibia and the projection of the y axis of the femur onto the xy plane of the tibia.
- Abduction-adduction angle: the angle formed by the y axis of the tibia and the projection of the y axis of the femur onto the yz plane of the tibia.
- Internal-external rotation angle: the angle formed by the x axis of the tibia and the projection of the x axis of the femur onto the xz plane of the tibia.

This approach is intuitive and close to joint motion representations in functional anatomy. However, these angles are computed following a totally arbitrary definition, which has no consistency whatsoever with the sequence of rotations characteristic of the Cardan angles or the orientation vector components [34].

4.3. Comparison among different angular conventions

In the previous sections, it has been shown that a given joint orientation may be thought of as being reached through a specified sequence of three rotations. In order to emphasize the heavy dependence of the three rotation angles on the specific sequence used, the data in Table 1 are reported. From them, it appears evident also that the largest angle (γ) is least sensitive to the chosen sequence [34].

In order to appreciate the difference between the results yielded by the different conventions illustrated in the previous section, photogrammetric data obtained from an adult subject during a level walking trial have been processed consistently with the following angular conventions:

(a) the Cardan convention suggested by Grood and Suntay [36] ($z_p x_d y_d$ sequence);
(b) joint angles obtained following the geometric approach detailed above [38];
(c) the orthogonal projections of the orientation vector $\boldsymbol{\theta}_j$ onto the proximal (thigh) AF [37]; and
(d) the non-orthogonal projections of the orientation vector $\boldsymbol{\theta}_j$ onto the joint axes ($z_p x_d y_d$) used in (a), taken in their instantaneous orientation.

The femoral and tibial AFs were constructed consistently with the definitions reported in [13].

Table 1
Angle values (°) obtained using different Cardan sequences (indicated by the sequence of the relevant axes) to describe a given relative orientation between two bony segments

	$x_p z_d y_d$	$x_p y_d z_d$	$z_p x_d y_d$	$y_p z_d x_d$	$y_p x_d z_d$	$z_p y_d x_d$
α	11.5	6.2	10.0	7.1	6.1	10.0
β	10.7	9.3	5.0	5.7	9.4	4.9
γ	29.5	29.9	30.0	30.7	30.9	30.9

α: rotation about the x_d-axis; β: rotation about y_d-axis; γ: rotation about z_p-axis (see Fig. 6). The sequence $z_p x_d y_d$ corresponds to that proposed in [36].

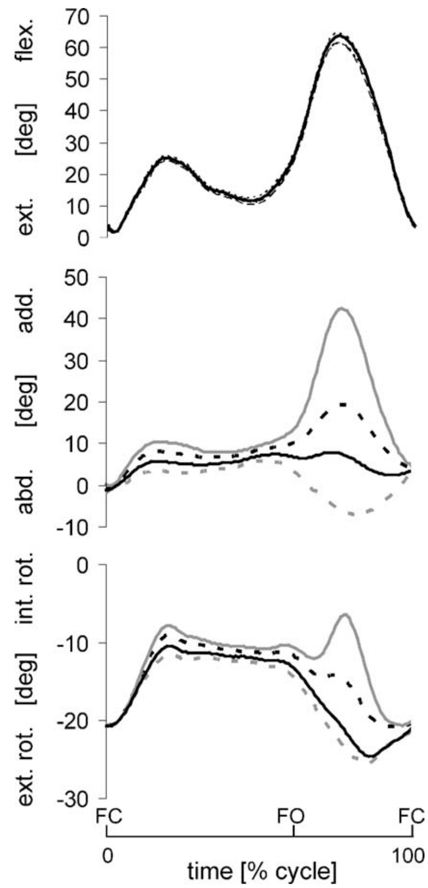

Fig. 7. Knee joint rotational degrees of freedom, during a gait cycle of a healthy subject, described using four different methods: (a) the Cardan convention [36], solid black; (b) a geometric approach [38], solid grey; (c) the orientation vector components as projected onto the axes of the proximal (femoral) anatomical frame [37], dashed black; (d) the orientation vector components as projected onto the axes used for the Cardan rotation sequence [34] (Fig. 6), dashed grey. While the subject assumed an up-right posture, for each of the four methods, knee flexion, adduction, and internal rotation had the following values, respectively: (a) 7°, 6°, −21°; (b) 8°, 5°, −22°; (c) 6°, 7°, −21°; (d) 4°, 8°, −20°. FC: foot contact; FO: foot off.

The results reported in Fig. 7, relative to knee angular kinematics, show that while only minor differences can be observed in the flexion/extension angles, the differences in both abduction/adduction and internal/external rotation angles are substantial. As expected, the angles assessed while the subject assumed an upright posture were also different (Fig. 7). These data do not indicate which convention is best, but they do underline the fact that, for the sake of information and data sharing, an agreement within the human movement analyst community on a selected convention seems imperative.

5. Conclusions

To proceed to the description of segmental kinematics the following information must be acquired:

- The position vector and orientation matrix of a local frame for each musculo-skeletal model segment, relative to a selected global frame, in each sampled instant of time (${}^{g}\boldsymbol{o}_{l}$, and ${}^{g}\boldsymbol{R}_{l}$), and
- the position vectors of selected particles of the link segments in the relevant local frame.

If required, a registration procedure between movement and morphological data must be implemented.

When the objective is the description of joint kinematics during the execution of a motor task, after having defined an AF for each bone involved in the analysis, the following procedure must be implemented:

- Identification of the position vectors of the anatomical landmarks or unit vectors of the functional axes used for defining the AFs in the relevant TFs,
- determination of the position vector and orientation matrix of the AFs relative to a selected global frame (${}^{g}\boldsymbol{o}_{d}$ and ${}^{g}\boldsymbol{o}_{p}$, ${}^{g}\boldsymbol{R}_{d}$ and ${}^{g}\boldsymbol{R}_{p}$), and
- identification of the position vectors of a point (K_p) in the proximal AF and of a point (K_d) in the distal AF.

In addition the following convention choices must be made:

- The convention to be used to describe the instantaneous joint orientation among the three conventions described above (or others), and
- the three axes with respect to which the position vector is represented (normally among the axes of the two AFs involved).

With reference to the joint orientation vector approach, a further convention choice relates to the set of axes with respect to which its scalar components are represented.

All of the above mentioned convention decisions have important effects on the results of the analysis and must, therefore, be stated very clearly when these results are shared.

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