

Papers

Position and orientation in space of bones during movement: anatomical frame definition and determination

A Cappozzo¹, F Catani², U Della Croce¹, A Leardini²

¹Istituto di Fisiologia Umana, Università degli Studi 'La Sapienza', Roma; ²Laboratorio di Biomeccanica, Istituti Ortopedici Rizzoli, Bologna, Italy

Summary

This paper deals with methodological problems related to the reconstruction of the position and orientation of the human pelvis and the lower limb bones in space during the execution of locomotion and physical exercises using a stereophotogrammetric system. The intention is to produce a means of quantitative description of joint kinematics and dynamics for both research and application. Anatomical landmarks and bone-embedded anatomical reference systems are defined. A contribution is given to definition of variables and relevant terminology. The concept of anatomical landmark calibration is introduced and relevant experimental approaches presented. The problem of data sharing is also addressed. This material is submitted to the scientific community for consideration as a basis for standardization.

Relevance

In order to make movement analysis effective in the solution of clinical problems, a structured conceptual background is needed in addition to standardized definitions and methods. Technical solutions which make data sharing and relevant data banks possible are also of primary importance. This paper makes suggestions in this context.

Key words: Movement analysis, terminology, standardization, anatomical frames

Clin. Biomech. Vol. 10, No. 4, 171–178, 1995

Introduction

Musculoarticular function assessment both in physiological and clinical contexts uses the quantitative description of joint kinematics and the prediction of forces transmitted by the tissues involved. Basically this requires two sets of data: (1) the musculoskeletal geometry and musculotendon parameters; (2) the three-dimensional (3-D) instantaneous position and orientation of the bones and soft tissues, and the external forces and couples acting on the relevant body segments during the execution of the physical exercise under analysis. Interactive graphics-based models of the musculoskeletal system are being developed which permit a better understanding of normal function and the simulation of surgical procedures such as joint arthro-

plasty or tendon lengthening and transfer¹. The accuracy and repeatability of the predictions of these models, whether used in an analysis or synthesis exercise, critically depend on the accuracy and repeatability of the input data and parameters which also set a limit to the complexity and sophistication of both the analytical and graphic models. The experimental determination of the position and orientation of bones in space during function is one of the most critical variables in this context.

The orientation and position in space of a bone, dealt with as if it were a rigid body, entails the definition of an orthogonal frame, named bone-embedded frame, rigid with the bone and numerically described with respect to a given observer using a position vector and an orientation matrix or an orientation vector.

This paper deals with the definitions and experimental protocols related to the estimation of these bone-embedded frames. Experimental data are assumed to be acquired using a stereophotogrammetric technique which entails the possibility of reconstructing the 3-D laboratory position of points, represented by light-

Received: 22 February 1994

Accepted: 6 May 1994

Correspondence and reprint requests to: Prof A Cappozzo, Istituto di Fisiologia Umana, Università degli Studi 'La Sapienza', 00185 Roma, Italy

emitting or reflecting markers, in each sampled instant of time. This study considers only the pelvic and lower limb bones. Methodological considerations can, however, be extended to any musculoskeletal subsystem.

Definitions

Bone-embedded frames

The definition of a bone-embedded frame includes the hypothesis of rigidity of the bone. For practical purposes, bone-embedded frames ought to meet the following requirements:

1. Their determination from experimental data should be repeatable both inter- and intra-individually.
2. In view of the quantitative description of the relevant joint kinematics they should possibly incorporate or permit the determination of suitable axes with respect to which both rotations and translations of the joint may be defined (joint axes).
3. Since the analysis of the limb will be dynamic they should permit an easy implementation of the estimation techniques aimed at the location of the body segment centre of mass and principal axes of inertia. In addition sufficient information must be available to locate the reference system with respect to which the intersegmental loads are calculated.
4. Requirements associated with the description of muscle and ligament line of action and the location and orientation of the articulation surfaces must also be taken into careful consideration.

It is evident that the above-mentioned requirements are met by frames rigidly associated with the anatomy of the bone. Their identification will therefore be based on the location of a number of anatomical landmarks. A bone-embedded frame which meets these requirements is termed an anatomical frame.

Marker points

All stereometric techniques entail indicating target points by convenient markers, the physical realization of which depends on the particular technique used. These markers are assumed here to be associated with cutaneous (external) and not bony (internal) points; that is invasive experimental approaches are not taken into consideration.

The marker points need to be selected according to the following experimental requirements:

1. Sufficient measurements (three-image coordinates) should be available on the markers from the available cameras at any given time.
2. For a given experiment, the light emitted or reflected from markers should be oriented within the field of view of a sufficient number of cameras.
3. The distance between three markers associated with each body segment and the offset of any marker from the line joining the other two should be sufficiently large so that error propagation from

reconstructed marker coordinates to the bone orientation in space will be minimal.

4. The relative movement between markers and underlying bone should be minimal.
5. Mounting the markers on the experimental subject should be a fast and easy operation.
6. It should be possible to place markers despite the presence of appliances such as orthoses, prostheses, or external fracture fixators.

Markers may be either directly located on the skin surface or mounted on fixtures attached to the body segment using, for instance, elastic bands. As opposed to skin markers, this latter method has the following advantages:

1. Marker mounting on patients is easier (especially when active markers are dealt with because one cable per fixture may be used).
2. Sufficiently wide elastic bands help to reduce soft-tissue movements.
3. Marker-light emission may be suitably oriented.

Fixtures may be rigid (plates) or not. In the former case the rigid geometric relationship between markers, which may be associated with a redundant number of them, may be exploited to reduce photogrammetric error effects². However, any possibility of compensating for the artefacts due to the relative movement between skin and bone, the so-called skin movement artefacts, is lost. On the contrary, by using non-rigid fixtures or skin markers and in the hypothesis of somewhat uncorrelated local movement of the markers, algorithms may be implemented which compensate for the above-mentioned artefacts³⁻⁷.

Technical frames

The frame determined using marker point coordinates is referred to as technical frame and is considered a bone-embedded frame. Due to both photogrammetric errors and experimental artefacts, the technical frame is always the result of an estimate.

Provided they are consistent with the practical requirements listed above, three markers may be placed on three anatomical landmarks of a body segment and used to define a technical frame which may coincide with an anatomical frame. However, this may mean using more than one stereo pair and may prevent the reconstruction of the trajectories of anatomical landmarks located in awkward positions. Some authors place markers on two anatomical landmarks, which define one frame axis, and use a third point which, in association with the anatomical landmarks, defines a bone anatomical plane and therefore the other two axes of the frame⁸⁻¹⁰.

Anatomical landmarks often do not satisfactorily comply with the above-mentioned experimental requirements and therefore may not represent ideal locations for marker placement. As will be discussed later, major problems encountered are associated with marker-bone relative displacement and marker visibility to the cameras. Thus markers may have to be

positioned on the body surface giving priority to the experimental requirements and with no controllable reference to the anatomy of the relevant bone.

Although embedded in the bone, technical frames may in fact be in a thoroughly arbitrary and non-repeatable geometric relationship with respect to it¹¹⁻¹³. This calls for the acquisition of more information to estimate the spatial location of anatomical landmarks and thus the position and orientation of bone-embedded frames closely related to the anatomy of the bone, that is of anatomical frames. This information consists of the coordinates of an adequate number of anatomical landmarks in the relevant technical frame (anatomical landmark parameters) which can be determined through *ad hoc* acquisitions. This procedure is termed anatomical landmark calibration and will be described below¹⁴.

Anatomical landmarks

Anatomical landmarks in the pelvis, thigh, shank, and foot that may be of relevance in the present context are reported in Table 1 and Figures 1-3, in one lower limb. Terminology used to describe these landmarks was derived from well-established anatomical literature¹⁵ and care was taken to describe the smallest possible area of the bone for each landmark.

Most of these anatomical landmarks are relatively easy to identify within small areas and can be located by palpation using the indications provided in Hoppenfeld¹⁶ and Benedetti et al.¹⁷. Consequently they can be calibrated using the techniques mentioned

below. On the contrary landmarks AC, FH, and IE are derived from these and/or other measurements.

As seen in the next section, the anatomical landmarks reported in Table 1 for each body segment are redundant with respect to those strictly necessary to identify the anatomical frames. However, this redundancy may allow for best estimates of these anatomical frames, for identifying joint axes, and for a realistic graphical representation of the bones. In addition some of the listed anatomical landmarks are good candidates as reduction points for the calculation of the intersegmental couples, seen as estimates of muscular and ligament moments, as well as for the estimation of joint linear displacements.

Anatomical frames

It is desirable that the anatomical frames be explicitly defined and standardized. This helps the exchange of information concerning a number of parameters, which include position and orientation of joint axes, the body segment inertia parameters, the intersegmental load reduction points, and musculoskeletal geometrical parameters.

Both position and orientation of anatomical frames should be defined, whenever possible, using observable anatomical landmarks. These landmarks should be chosen so that they are relatively easy to identify by palpation and their determination repeatable, as with the landmarks listed in Table 1. The use of predicted points, as suggested in Vaughan et al.¹⁸, such as the so called joint centres or the segment centres of mass, may significantly

Table 1. Anatomical landmarks. The anatomical landmarks indicated with (a) are used to define the anatomical frames. Those indicated with (b) are landmarks which may be used to determine the location of other a-type landmarks or to improve its estimation. Others (c) may be used for more realistic graphical representations of the bones and/or geometrical models of muscles and ligaments

<i>Hip bone</i>		
(a)	ASIS	anterior superior iliac spine
(a)	PSIS	posterior superior iliac spine
(b)	AC	centre of the acetabulum
<i>Femur</i>		
(a)	FH	centre of the femoral head
(c)	GT	prominence of the greater trochanter external surface
(a)	ME	medial epicondyle
(a)	LE	lateral epicondyle
(b) (c)	LP	anterolateral apex of the patellar surface ridge
(b) (c)	MP	anteromedial apex of the patellar surface ridge
(b) (c)	LC	most distal point of the lateral condyle
(b) (c)	MC	most distal point of the medial condyle
<i>Tibia and fibula</i>		
(c)	IE	intercondylar eminence
(a)	TT	prominence of the tibial tuberosity
(a)	HF	apex of head of the fibula
(a)	MM	distal apex of the medial malleolus
(a)	LM	distal apex of the lateral malleolus
(b) (c)	MMP	most medial point of the ridge of the medial tibial plateau
(b) (c)	MLP	most lateral point of the ridge of the lateral tibial plateau
<i>Foot</i>		
(a)	CA	upper ridge of the calcaneus posterior surface
(a)	FM	dorsal aspect of first metatarsal head
(a)	SM	dorsal aspect of second metatarsal head
(a)	VM	dorsal aspect of fifth metatarsal head

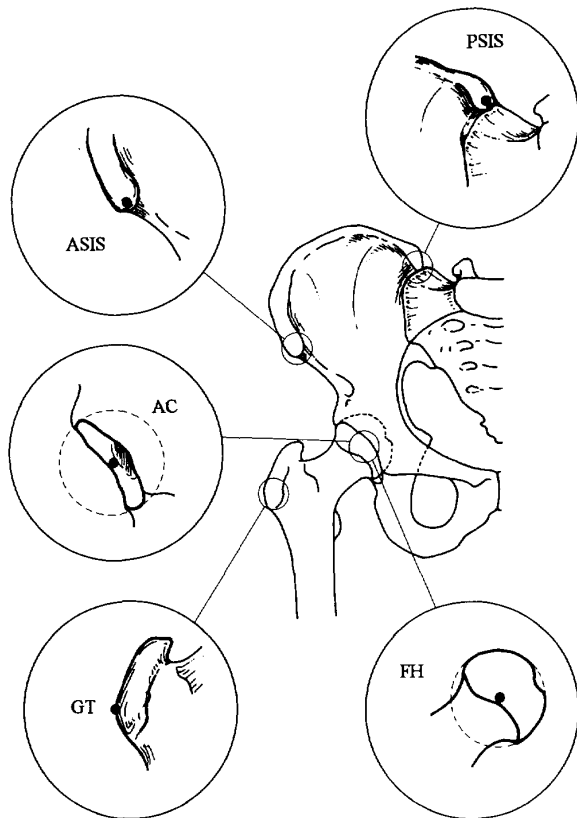


Figure 1. Anatomical landmarks in the pelvis and proximal femur.

lower the intersubject reliability of the results. A point approximating to the knee centre or the midpoint between the femoral condyles is sometimes used to define the tibia embedded frame^{11,18}. We suggest that a segment anatomical frame should be based on points belonging to that segment only. This means that no kinematic constraints are imposed between adjacent bones and all 6 degrees of freedom are respected. Anatomical frame axes should approximate symmetry axes and define the standard anatomical planes of individual segments also when significant deformation has occurred.

The pelvic girdle comprises three separate bones, the two hip bones and the sacrum. In this study the relative movement between these bones is considered negligible. Morphological sagittal asymmetries can, however, be taken into account.

The posterior and middle segments, and the metatarsal bones of the foot, are considered to be rigidly connected.

Based on the criteria mentioned above and the anatomical landmarks listed in Table 1 the following right-handed anatomical frames are proposed for pelvis and both right and left lower limb bones (Figure 4). In this description, anatomical planes are defined with respect to the standing subject in the 'anatomical position'.

Pelvis (right and left hip bones and sacrum)

O_p — The origin is at the midpoint between the

anterior superior iliac spines (RASIS and LASIS).

z_p — The z axis is oriented as the line passing through the ASISs with its positive direction from left to right.

x_p — The x axis lies in the quasi transverse plane defined by the ASISs and the midpoint between the PSISs and with its positive direction forwards.

y_p — The y axis is orthogonal to the xz plane and its positive direction is proximal.

Right and left thigh

O_t — The origin is the midpoint between the lateral and medial epicondyles (LE and ME).

y_t — The y axis joins the origin with the centre of the femoral head (FH) and its positive direction is proximal.

z_t — The z axis lies in the quasi frontal plane defined by the y axis and by the epicondyles with its positive direction from left to right.

x_t — The x axis is orthogonal to the yz plane with its positive direction forwards.

Right and left shank

O_s — The origin is located at the midpoint of the line joining the lower ends of the malleoli (MM and LM).

y_s — The malleoli and the head of the fibula landmarks (HF) define a plane which is quasi-frontal. A quasi-sagittal plane, orthogonal to the quasi-frontal plane, is defined by the midpoint between the malleoli and the

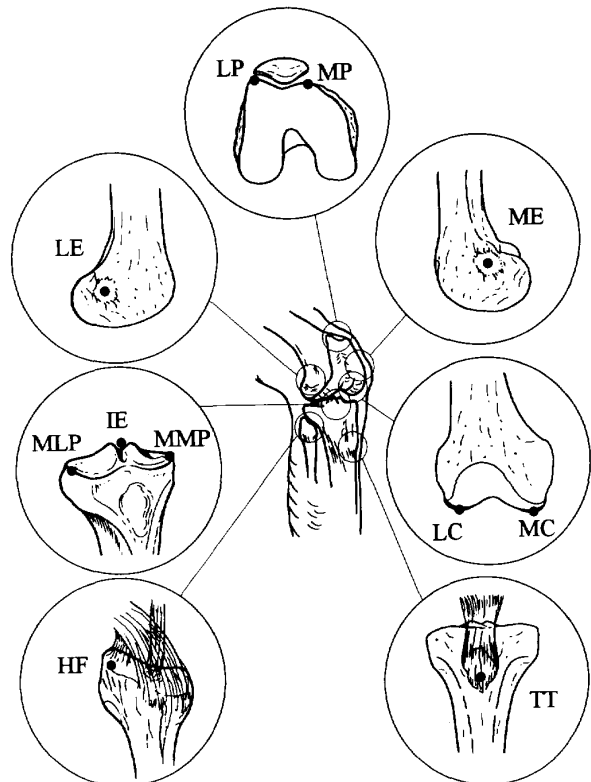


Figure 2. Anatomical landmarks in the distal femur and proximal tibia and fibula.

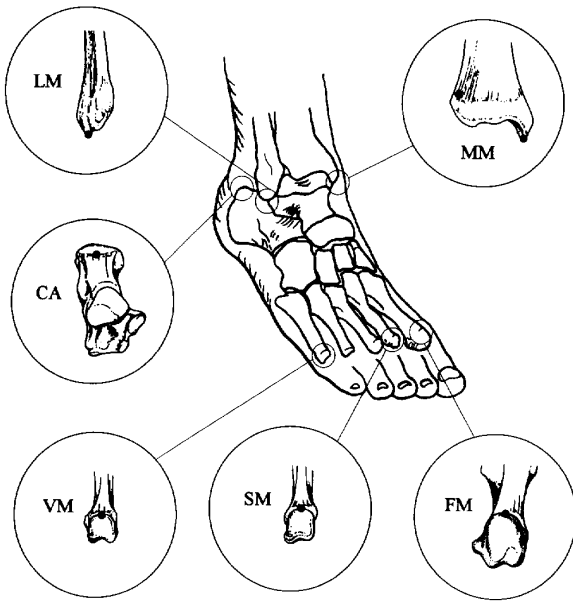


Figure 3. Anatomical landmarks in the distal tibia and fibula and in the foot.

tibial tuberosity (TT). The y axis is defined by the intersection between the above-mentioned planes with its positive direction proximal.

z_s — The z axis lies in the quasi-frontal plane with its positive direction from left to right.

x_s — The x axis is orthogonal to the yz plane with its positive direction forwards.

Right and left foot (talus + calcaneus + cuboid + navicular + lateral, medial, intermediate cuneiform + metatarsals)

O_f — The origin is located at the calcaneus landmark (CA).

y_f — The calcaneus and the first and fifth metatarsal heads (FM and VM) define a plane which is quasi-transverse. A quasi-sagittal plane, orthogonal to this latter plane, is defined by the calcaneus landmark and the second metatarsal head (SM). The y axis is defined by the intersection of these two planes and its positive direction is proximal.

z_f — The z axis lies in the quasi-transverse plane and its positive direction is from left to right.

x_f — The x axis is orthogonal to the yz plane and its positive direction is dorsal.

Experimental protocol

The location of the anatomical landmarks in the technical frames must be established.

It must be noted that, for those bony landmarks which are palpable, the thickness of the soft tissue interposed between cutaneous surface and bone is often neglected and thus an adequately identified skin mark is taken as the anatomical landmark and, in the following, it will be referred to as such.

If the anatomical landmark lies on the cutaneous

surface, then its coordinates in the technical frame may be determined by placing a marker on it. The subject is asked to assume a posture which allows both the anatomical and the technical markers to be seen by two or more cameras. Then at least one frame is recorded. Obvious vector calculations follow. The procedure may have to be repeated for each anatomical landmark and the subject may be required to assume different postures in order to make both the anatomical and the technical markers visible to the cameras. Markers used for the identification of the anatomical landmarks are, of course, removed before the physical movement is performed¹².

Anatomical landmark location may also be determined using a pointer on which a minimum of two markers have been mounted at an adequate distance (Figure 5). The experimenter points the tip of the pointer onto the anatomical landmark so that the markers on the pointer and the relevant body segment technical markers are visible to the cameras. Then at least one frame is recorded. This procedure is repeated for each anatomical landmark. Through obvious geometric calculations and using the reconstructed position of the pointer markers, the location of the anatomical landmarks may be determined. This method is usually more practical than the one presented previously, especially when the anatomical landmark is in an awkward position.

When the anatomical landmark to be calibrated is internal to the body, that is at a distance from the surface greater than the skin and subcutaneous tissue thickness, the method of the pointer may still be used provided that the anatomical landmark is on the line defined by the two pointer markers and the position relative to them is known.

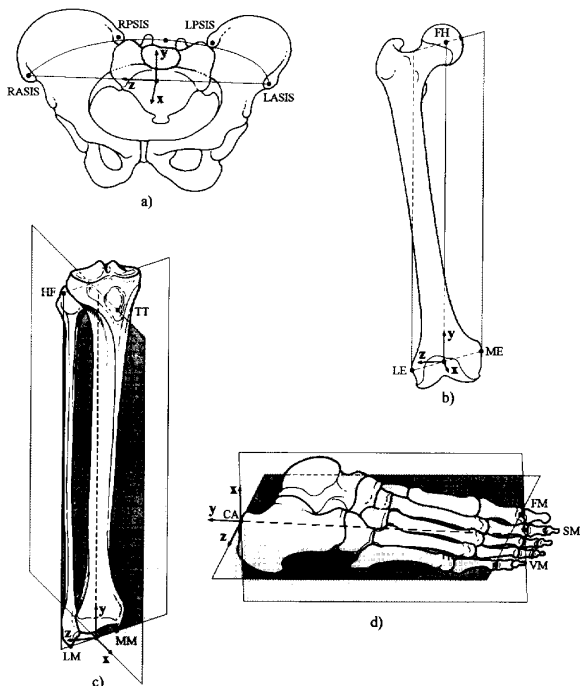


Figure 4. Bone embedded anatomical frames (for symbols see Table 1).

If two landmarks are a short distance apart as seen by one or more cameras and their positions are used to determine the orientation of a frame axis, then in order to avoid macroscopic inaccuracies on this orientation the following technique may be used: the two landmarks involved are calibrated simultaneously using a pointer which, besides indicating their locations, makes the orientation of the relevant axis visible to the operator¹⁹. Typically this technique may be applied to the femoral condyles and to the malleoli.

Anatomical landmark calibration may also be carried out using roentgenographic and anatomical measurements¹¹.

If no other practical way is available, other techniques entailing more or less important assumptions may be used. When an anatomical landmark may be approximated by a joint centre, as is the case with the centre of the acetabulum (AC), the calibration may be carried out using a functional approach based on the assumption that the joint centre coincides with the pivot point of the movement between the adjacent segments^{12,13,20,21}. However, under pathological circumstances this method may be difficult to use and may be unreliable. The location of an anatomical landmark in the relevant frame may also be determined by assuming that during a given posture it coincides with another landmark in a different frame which can be calibrated more easily. For instance the centre of the femoral head (FH) in the femoral technical frame may be determined by assuming that it coincides with the centre of the acetabulum while the subject assumes a predefined posture (for instance, standing posture). Similarly the intercondylar eminence (IE) in the tibia may be calibrated as coinciding with the midpoint between the femoral MC and LC while the subject assumes a predefined posture. It is clear that even when using these approaches no restriction is imposed on the 6 degrees of freedom of the bone involved, it may only be a matter of accuracy associated with the anatomical frame estimation.

In the following an experimental protocol based on this approach will be referred to by the acronym CAST, which stands for 'calibrated anatomical systems technique'.

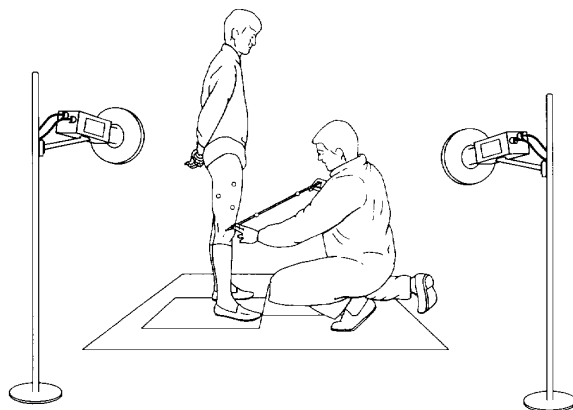


Figure 5. Femur anatomical landmark calibration using a pointer. Circles indicate possible markers.

Data format

Different laboratories use different marker locations and procedures to reconstruct the position and orientation of bones during physical movement. However, the results obtained using these diverse approaches may be presented through a unified symbolic procedure which can incorporate all possible experimental protocols and allow for the same data processing and thus variable definition and representation.

Based on the considerations made previously the instantaneous position and orientation of a bone in space should be represented by a technical frame defined with respect to the laboratory frame and numerically described in each instant of time by the following data set^{3,22} (see the Appendix for symbols)

a position vector of the origin
 ${}^l\mathbf{m}_{B_0} = | {}^l m_{x_{B_0}}, {}^l m_{y_{B_0}}, {}^l m_{z_{B_0}} |$

and an orientation vector
 ${}^l\theta_{B_t} = | {}^l\theta_{x_{B_t}}, {}^l\theta_{y_{B_t}}, {}^l\theta_{z_{B_t}} |$

This latter vector can be calculated from the frame direction cosines (orientation matrix) and represents a compact form for representing the relevant information.

To this data the time invariant local coordinates of n relevant anatomical landmarks are added:

calibration parameters
 ${}^{B_t}\mathbf{a}_{B_i} = | {}^{B_t} a_{x_{B_i}}, {}^{B_t} a_{y_{B_i}}, {}^{B_t} a_{z_{B_i}} | \quad i = 1 \text{ to } n$

The above data set thoroughly defines the location of the bone in space and allows for the definition of an anatomical frame and/or joint axis. More details about this matter are provided in the Appendix.

If anatomical landmarks are designated by markers, then relevant calibration parameters are readily available. Otherwise these may be estimated using direct anatomical measurements or through a calibration procedure (CAST).

Conclusion

This paper is intended to contribute to the methodology to be used for the description of movement both in research laboratories and in clinical centres and to the standardization of estimated quantities.

Of course each laboratory must remain free to use its accustomed experimental protocol of choice, presumably chosen as the most practical for both the population of subjects the laboratory usually deals with and the specific equipment used. However, for both scientific and practical reasons the results of the tests must be provided in a standard form. This unavoidably entails a preprocessing of the measured data. It is important to realize that this preprocessing does not imply a commitment to one description of joint kinematics and dynamics. This could be changed at any time. In addition, data collected in the past may be presented in this standard form and therefore

contribute to knowledge and to an updated data bank.

We propose a data format for these preprocessed data which is compatible with most experimental protocols and which, if standardized, would allow for the use of the same data processing methodology, that is the same software. This means that end results would be the same irrespective of the specific experimental technique used (marker placement, for instance) and therefore directly comparable. It should also be noted that this data presentation format embodies the specific experimental protocol used and that this may be unknown to the remote user.

It is evident that end results may be characterized by different levels of accuracy depending on the experimental set up and protocol. It is thus desirable that the results of simple tests, which allow for an estimation of both accuracy and precision of measurements, are appended to the actual experiment results.

In summary, this paper contains the following proposals:

- a number of selected anatomical landmarks of the lower limb bones and of the pelvis have been identified;
- anatomical systems of axes for the pelvis and lower limb segments have been defined and are proposed for standardization;
- an experimental protocol (CAST) has been described which is not subject to standardization and is simply meant to enrich relevant knowledge and help the user to define his/her own protocol;
- proposal of a preprocessed gait data format which refers to the position and orientation in space of the body segments involved during the movement which are proposed for standardization; this data file is intended for use in exchange between laboratories and to be fed into concerted data processing softwares.

Associated with the above objectives and proposals an effort to contribute to a standard glossary is considered as having high priority.

Acknowledgements

This work was carried out within the CEC programme AIM—project A-2002 CAMARC-II (Computer Aided Movement Analysis in a Rehabilitation Context II). The constructive discussions which the authors had with the project partners both individually and during plenary reunions about the problems addressed in this paper are gratefully acknowledged.

Copies of the CAMARC II Internal Reports and Deliverables quoted in this paper may be requested from the Project Coordinator Prof Tommaso Leo, Università degli Studi di Ancona, Dipartimento di Elettronica ed Automatica, Via Breccia Bianche, I-60131 Ancona, Italy.

References

- 1 Delp SL, Loan JP, Hoy MG et al. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng* 1990; 37: 757–67
- 2 Angeloni C, Cappello A, Catani F, Leardini A. Evaluation of soft tissue artefacts in the *in-vivo* determination of human knee instantaneous helical axis. In: *Proceedings of II International Symposium on 3-D Analysis of Human Movement* Poitiers, France, 30 June–3 July 1993; 57–60.
- 3 Spoor CW, Veldpaus FE. Rigid body motion calculated from spatial coordinates of markers. *J Biomech* 1980; 13: 391–3
- 4 Veldpaus FE, Woltring HJ, Dortmans LJM. A least-squares algorithm for the equiform transformation from spatial marker coordinates. *J Biomech* 1988; 21: 45–54
- 5 Cheze L. *Contribution à l'Etude Cinématique et Dynamique in Vivo de Structures Osseuses Humaines par l'Exploitation des Données Internes*. [Thèse de l'Université C Bernard Lyon 1], 1993
- 6 Söderkvist I, Wedin P-A. Determining the movements of the skeleton using well-configured markers. *J Biomech* 1993; 12: 1473–77
- 7 Wang X, Rezgui MA, Verriest JP. Using the polar decomposition theorem to determine the rotation matrix from noisy landmark measurements in the study of human joint kinematics. In: *Proceedings of II International Symposium on 3-D Analysis of Human Movement*, Poitiers, France, 30 June–3 July 1993; 53–6
- 8 Andriacchi TP, Andersson JBJ, Fermier RW et al. A study of lower limb mechanics during stair climbing. *J Bone Joint Surg* 1980; 62-A: 749–57
- 9 Kadaba MP, Ramakrishnan HK, Wootten ME. Measurement of lower extremity kinematics during level walking. *J Orthop Res* 1990; 8: 383–92
- 10 Davis RB, Ounpuu S, Tyburski DJ, Deluca PA. A comparison of two-dimensional and three-dimensional techniques for the determination of joint rotation angles. In: *Proceedings of the International Symposium on 3-D Analysis of Human Movement*. Montréal, Canada, 28–31 July, 1991; 67–70
- 11 Johnston RC, Brand RA, Crowninshield RD. Reconstruction of the hip. *J Bone Joint Surg* 1979; 61-A: 639–52
- 12 Cappozzo A. Gait analysis methodology. *Hum Movem Sci* 1984; 3: 27–54
- 13 Riley PO, Mann RW, Hodge WA. Modelling of the biomechanics of posture and balance. *J Biomech* 1990; 23: 503–6
- 14 Cappozzo A. Three-dimensional analysis of human walking: experimental methods and associated artefacts. *Hum Movem Sci* 1991; 10: 589–602
- 15 Davies DV, Coupland RE. *Gray's Anatomy*. Thirty-fourth edn. London and Harlow: Longmans, Green and Co Ltd, 1969
- 16 Hoppenfeld S. *Physical Examination of the Spine and Extremities*. East Norwalk, CT, USA: Appleton Century Crofts, 1976
- 17 Benedetti MG, Cappozzo A, Catani F, Leardini A. *Anatomical Landmark Definition and Identification*. CAMARC II Internal Report; 15 March 1994
- 18 Vaughan CL, Davis BL, O'Connor JC. *Dynamics of Human Gait*. Champaign, Illinois: Human Kinetics Publishers, 1992
- 19 Gauffin H, Areblad M, Tropp H. Three-dimensional analysis of the talocrural and subtalar joints in single-limb stance. *Clin Biomech* 1993; 8: 307–14
- 20 Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech* 1990; 23: 617–21
- 21 Cappozzo A, Gazzani F. Joint kinematics. In: Berme N, Cappozzo A, eds. *Biomechanics of Human Movement—Applications in Rehabilitation, Sports and*

Ergonomics. Bertec Corporation, Worthington, Ohio, USA: 1990; 263-74

22 Woltring H. Definition and calculus of attitude angles, instantaneous helical axes and instantaneous centres of rotation from noisy position and attitude data. In: *Proceedings of the International Symposium on 3-D Analysis of Human Movement*, Montréal, Canada, 28-31 July 1991; 59-62

23 Denavit J, Hartenberg RS. A kinematic notation for the lower pair mechanics based on matrices. *ASME J Applied Mechanics* 1955; 22: 215-21

24 Magnani G, Angeloni C, Leardini A, Cappello A. Optimal estimation of rigid body position and attitude from noisy markers coordinates. In: *Proceedings of the XIVth Congress of the International Society of Biomechanics*, Paris, France, 4-8 July 1993; 820-1

25 Paul JP, Morris JRW. CAMARC II — Data exchange. What? Why? How? In: *Proceedings of the Workshop 'CAMARC II: Problems and Perspectives'*. Rome, Italy, 29 February-1 March 1992. Deliverable N2

26 Morris JRW. *Data Storage and Transmission File Syntax and Lexicons*. CAMARC II Internal Report (in press)

27 Cappozzo A, Della Croce U. *The PGD Lexicon*. CAMARC II Internal Report; 15 May 1994

Appendix

Symbols

B: indicates the body segment: B = [P|T|S|F] where P = pelvis, T = thigh, S = shank, F = foot.

Matrices and vectors are indicated by

- R: orientation matrix (3 × 3) with det(R) = +1 (orthogonal matrix $R^T R = I$) between two equal-handed orthogonal sets of axes;
- θ: orientation vector between two equal-handed orthogonal sets of axes;
- m: position vector of a marker or of any point having a known geometric relationship with a cluster of markers;
- a: position vector of an anatomical landmark.

Superscripts and subscripts indicate

set of axes

- l: laboratory frame;
- Bt: technical frame of the segment B;
- Ba: anatomical frame of the segment B.

Points (only subscript)

- Bi: ith point (either marker, any point having a known geometric relationship with a cluster of markers or anatomical landmark) associated with body segment B; a frame origin point is represented with i = 0.

Examples:

The orientation matrix and vector of the frame indicated by the right subscript and given with reference to the set of axes indicated by the left superscript are²³:

- ^lR_{Ft}: orientation matrix of the technical frame of the foot with respect to the laboratory frame.
- ^lθ_{Pa}: orientation vector of the anatomical frame of the pelvis with respect to the laboratory frame.

The position of the vector of the ith point defined on a segment, as indicated by the right subscript, given with respect to the set of axes indicated by the left superscript is:

- ^lm_{p2}: position vector of 2nd marker located on the pelvis expressed in the laboratory frame.

Anatomical frame position and orientation

In the flow chart shown in Figure 6 the determination of the

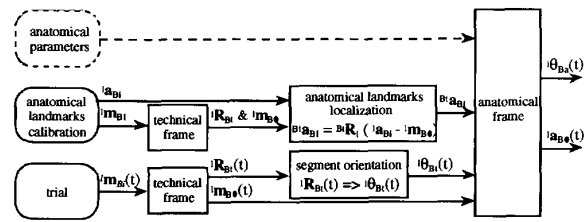


Figure 6. Block diagram for the determination of an anatomical frame orientation and position.

position and orientation of the anatomical frame of a generic body segment (B) is depicted.

For body segment B and the ith anatomical landmark, the anatomical landmark calibration procedure provides the time invariant technical markers (^lm_{Bi}) and anatomical landmarks coordinates (^la_{Bi}) in the laboratory frame. Calculations yield the anatomical landmark local coordinates in the technical frame (^{Bt}a_{Bi}), that is the calibration parameters.

The movement trial yields, for each body segment, the technical marker trajectories (^lm_{Bi}(t)). Based on these trajectories, the orientation matrix (^lR_{Ba}(t)) and the position vector (^lm_{B0}) of the technical frame can be estimated in each sampled instant of time^{3-7,24}. The orientation vector (^lθ_{Ba}) is obtained from the relevant orientation matrix (^lR_{Ba}(t)) using, for instance, the equations reported in Spoor and Veldpaus⁵.

After the determination of the technical frame with respect to which the anatomical landmark positions are defined, it is possible to determine the anatomical frame orientation (^{Ba}θ_{Ba}(t)) and position (^{Ba}a_{B0}(t)) vectors with respect to the laboratory axes consistently with the relevant definition given in a previous section.

In Figure 6 a dashed block is indicated which takes into account the possibility of optimizing the estimation of the anatomical frame axes by using, in addition to the calibration parameters, anatomical parameters derived in an independent way. As an example in this context, it is anticipated here that the present authors are trying to use a 3-D model of the femoral condyle and fit it to the locations of the relevant six anatomical landmarks listed in Table 1 as calibrated *in vivo*. The medial and lateral epicondyles of the resulting anisotropically scaled model are then referred to for the construction of the femoral anatomical frame.

File format specifications

Specifications which define a syntax for data storage and transfer files (DST) have been set for use among the partners participating in the CEC-funded CAMARC II research project^{25,26}. These files are based on an ASCII code. Consistent with this syntax, a lexicon called preprocessed gait data (PGD) has been defined to allow the storage and exchange of gait data consistent with the proposals made in this paper. The report containing all relevant information may be obtained from the corresponding author of this paper²⁷.