BUTTERWORTH HEINEMANN

Clinical Biomechanics Vol. 10, No. 4, pp. 171–178, 1995

0268-0033/95 $10.00 + 0.00

Papers

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

A Cappozzo[1], F Catani[2], U Della Croce[1], A Leardini[2]

[1]Istituto di Fisiologia Umana, Università degli Studi 'La Sapienza', Roma; [2]Laboratorio 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 arthroplasty or tendon lengthening and transfer[1]. 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 effects[2]. 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 artefacts[3–7].

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 frame[8–10].

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 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 Brecce 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 LJMG. 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 $\det(\mathbf{R}) = +1$ (orthogonal matrix $\mathbf{R}^T\mathbf{R} = \mathbf{I}$) 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: i^{th} 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 are[23]:
${}^{l}\mathbf{R}_{Ft}$: orientation matrix of the technical frame of the foot with respect to the laboratory frame.
${}^{l}\theta_{Pa}$: orientation vector of the anatomical frame of the pelvis with respect to the laboratory frame.

The position of the vector of the i^{th} 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:
${}^{l}\mathbf{m}_{P2}$: position vector of 2^{nd} 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 position and orientaton of the anatomical frame of a generic body segment (B) is depicted.

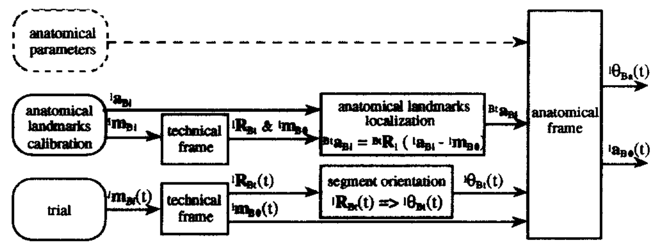

Figure 6. Block diagram for the determination of an anatomical frame orientation and position.

For body segment B and the i^{th} anatomical landmark, the anatomical landmark calibration procedure provides the time invariant technical markers (${}^{l}\mathbf{m}_{Bi}$) and anatomical landmarks coordinates (${}^{l}\mathbf{a}_{Bi}$) in the laboratory frame. Calculations yield the anatomical landmark local coordinates in the technical frame (${}^{Bt}\mathbf{a}_{Bi}$), that is the calibration parameters.

The movement trial yields, for each body segment, the technical marker trajectories (${}^{l}\mathbf{m}_{Bi}(t)$). Based on these trajectories, the orientation matrix (${}^{l}\mathbf{R}_{Ba}(t)$) and the position vector (${}^{l}\mathbf{m}_{B0}$) of the technical frame can be estimated in each sampled instant of time[3–7,24]. The orientation vector (${}^{l}\theta_{Ba}$) is obtained from the relevant orientation matrix (${}^{l}\mathbf{R}_{Ba}(t)$) using, for instance, the equations reported in Spoor and Veldpaus[3].

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 (${}^{l}\theta_{Ba}(t)$) and position (${}^{l}\mathbf{a}_{B0}(t)$) 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 paper[27].