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Position and orientation in space of bones during movement: experimental artefacts

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Summary—This paper deals with the experimental problems related to the reconstruction of the position and orientation of the lower limb bones in space during the execution of locomotion and physical exercises. The inaccuracies associated with the relative movement between markers and underlying bone are analysed. Quantitative information regarding this movement was collected by making experiments on subjects who had suffered fractures and were wearing either femoral or tibial external fixators. These latter devices provided frames that were reliably rigid with the bone involved, and hence the possibility of assessing the relative movement between markers mounted on the skin and this bone. Anatomical frames associated with thigh and shank were reconstructed using technical frames based on different clusters of skin markers and their rotation with respect to the relevant bone evaluated. Marker movement was also assessed in subjects with intact musculoskeletal structures using digital videofluoroscopy.

Relevance—The use of movement analysis using stereophotogrammetry in a clinical context is limited by the experimental errors associated with the skin marker movement artefacts. These make the estimation of small, but clinically relevant, angular and linear joint movements critical. This work is intended to contribute to the solution of this problem.

Key words: Movement analysis, stereophotogrammetry, skin movement artefacts

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Nomenclature

Points

— Anatomical landmark:	a point, or effectively small area, reliably identifiable within a biological structure (bone)
— Marker point:	a location on the skin where a skin marker is positioned
— Anatomical skin marker:	a marker positioned on the skin in a location approximating an anatomical landmark
— Technical marker:	a marker positioned in a location which has no anatomical relevance
— Cluster of markers:	a set of markers associated with a bone

Coordinate set of axes (frames) associated with a bone:

— Bone embedded frame:	a set of coordinate axes effectively rigid with the bone
— Technical frame:	a set of coordinate axes estimated from the positions of technical markers (technical cluster)
— Anatomical frame:	a set of coordinate axes estimated from the positions of bone anatomical landmarks

Introduction

Movement analysis in the three dimensions of space requires the determination of the instantaneous position and orientation of systems of axes which can be considered to be rigid with the bones under analysis[1]. To this end stereophotogrammetric systems are used. An adequate number, equal to or greater than three, of light emitting or reflecting markers (*cluster of markers*) are located, either directly or through some kind of fixture, on the skin surface of the body segment of interest. Direct attachment to bones implies an invasive approach and is not normally used. The laboratory coordinates of the markers are reconstructed using relevant images recorded during the subject movement. Subsequently the instantaneous position and orientation of the marker cluster is estimated and associated to the underlying bone.

The use of the concepts of position and orientation means that the cluster of markers is substituted by a rigid body irrespective of the fact that inter-marker distances obtained from experimental data will not be constant. This position and orientation is then assumed as position and orientation of the bone although the individual markers, and/or the cluster of markers, are not rigidly associated with it.

Inaccuracies involved in the above-described procedure are due to:

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a *instrumental errors*, which represent the errors with which marker coordinates are reconstructed in a global frame;

b *skin movement artefacts*, due to the relative movement between the marker and the underlying bone, mostly associated with the interposition of both passive and active soft tissues.

The term experimental artefact refers to an error which originates at the interface between measurement instrument and the substrate which is the object of the measurement. This definition makes it different from the errors which originate within the instrument, the instrumental errors, and makes it clear that it depends on the particular method and the conditions under which the measurement is conducted.

The most critical source of error in the present context is associated with the skin movement artefacts. Due to its origin, this artefact movement has the same frequency content as the bone absolute movement. This predictable circumstance will also appear evident from the results presented in this paper. Thus there is no way of separating the artefact from the actual bone movement by simply using a filter, as opposed to most instrumental errors[2]. However, its effect on the end results may be minimized in the following ways. First of all marker locations (*marker points*) must be chosen so that the above-mentioned relative displacement is minimal, and secondly through a proper choice of the mathematical operator which estimates position and orientation of the bone from skin marker positions. Operators that cope with this problem in an optimization context have been proposed[3–8] and their use in movement analysis is being developed.

For an effective use of both above-mentioned countermeasures against the experimental artefacts, knowledge concerning the characteristics of the artefact movement in various areas of the relevant body segments is required.

This paper presents the results of investigations carried out with the aim of gaining information about the magnitude and the pattern of the skin movement artefacts in the thigh and shank during various motor tasks. This was done exploiting experimental situations whereby an observer, that is a set of axes, reliably rigid with the bone (*bone embedded frame*), could be made available. This was attained using patients wearing external fracture fixators and stereophotogrammetry as well as a fluoroscopic technique with able-bodied subjects. The effect that the artefacts may have on the assessment of bone orientation and therefore on joint kinematics was also investigated by analysis. Instrumental errors associated with the particular photogrammetric system used are also mentioned herein for the purpose of comparison with the skin movement artefacts.

Previous *in-vivo* experimental work dealing with this problem has used bone-embedded reference systems identified on X-ray images[9–13]. Lafortune and Lake[10], and Karlsson and Lundberg[14] report results obtained using markers mounted on a cortical pins. Lately, Stanhope et al.[15] have presented experimental results whereby the bone-embedded frame of reference was obtained using halo pins inserted into the periosteum of the tibia of three volunteer subjects who walked on the level. In these studies skin markers were located on anatomical landmarks among the following: greater trochanter, lateral and medial epicondyles of the femur, and lateral and medial malleoli.

The laboratories

Experiments were carried out in laboratories of an orthopaedic hospital (Motion Analysis Laboratory and Radiological Division of the Istituti Ortopedici Rizzoli).

A passive marker stereophotogrammetric system (ELITE by BTS, Milan, Italy) was used with the sampling frequency set at 100 frames per second. The calibrated field of measurement was approximately 2 × 1.6 × 0.8 m. There was a 20-m walkpath for gait tests. The laboratory (global) system of reference (Figure 1) followed the right hand rule and had the Y axis vertical upwards and the Z axis towards the stereopair. The X axis was directed as the line assigned to the subjects as line of progression in the gait tests.

The experimental set up was assessed using the MAL (Movement Analysis Laboratory) spot check, as described in Cappozzo and Della Croce[16]. This is based on the use of a test object made of a rod that carries two markers (A, B) which define a line. A target point (O) is taken in a known position with respect to the markers on this line and coinciding with a tip of the rod (OA = 1.10 m, and OB = 0.90 m). The tip of the rod is placed in a fixed point in the measurement volume and the rod is made to rotate about it by moving the other end in a 0.40-m radius circle. During this movement the target point O instantaneous position in the laboratory is calculated through simple vector analysis using the reconstructed marker trajectories. Point O laboratory coordinates are also measured directly, and this is done with a higher accuracy than using photogrammetry. This test data allow an estimate of both precision (p_X, p_Y, p_Z) and accuracy (a_X, a_Y, a_Z), estimated as root mean square values, with which the 3-D laboratory coordinates of a target point may be reconstructed. For the above-mentioned motion analysis laboratory and geometry of the test object, relevant values were:

a_X = 2.5 mm; a_Y = 2.0 mm; a_Z = 1.5 mm
p_X = 0.2 mm; p_Y = 0.1 mm; p_Z = 0.3 mm

The results of the MAL test were obtained without submitting experimental data to filtering. On the contrary, during the actual experiments, the reconstructed marker coordinates were filtered using the algorithm provided in D'Amico and Ferrigno[17].

A fluoroscopic RX device (General Electric CGR — Prestilix 1600 X) was also used. It allowed the recording of series of RX images at a given frequency.

constructed with maximal errors on the flexion–extension angle in the order of 8 degrees, on the abduction–adduction angle of 4 degrees, and internal–external rotation angle of 12 degrees.

Conclusions

1. The results reported above confirm that skin-marker artefacts have amplitudes that are usually overwhelming with respect to those of photogrammetric errors.
2. During movement, markers located directly on the skin above anatomical landmarks such as greater trochanter, lateral epicondyle of the femur, head of the fibula, and lateral malleolus undergo displacements relative to the underlying bone which are roughly proportional to the closest joint angular displacement. During walking these are in the range of 10–30 mm. This indicates that these locations are unsuitable for marker placement.
3. Skin markers located on the lateral portion of the thigh and of the shank and far from joint areas may be expected to exhibit smaller artefact movements, and therefore allow for more reliable results.
4. The estimation of knee joint kinematics, for example during walking, using clusters made of skin markers, may be affected by inaccuracies which, for flexion–extension, adduction–abduction, and internal–external rotation, amount to roughly 10, 50 and 100% of the respective movement range angle. This calls for a special effort in improving both experimental protocols and relevant mathematical procedures.
5. Skin markers located on the thigh or on the shank undergo displacements relative to the bone which, besides having significant magnitudes, may be strongly correlated as shown, for instance, by Figures 4, 8 and 9. This circumstance may hinder the possibility of effectively applying optimization approaches for the estimation of relevant rigid body kinematics unless great care is taken in attaching the markers to the body segment and full awareness of the problems highlighted herein is exploited.

The data presented in this paper may be used to review critically some of the experimental protocols used in the past both in research and in clinical contexts. It shows that markers should not necessarily be located on the body segment in such a way that they indicate relevant anatomical landmarks. Minimization of skin movement artefacts must be the prevailing criterion. Knowledge on the laboratory position of anatomical landmarks should be attained indirectly using the above-mentioned 'anatomical calibration' approach (CAST).

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