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A new software tool for 3D motion analyses of the musculo-skeletal system

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Abstract

Background. Many clinical and biomechanical research studies, particularly in orthopaedics, nowadays involve forms of movement analysis. Gait analysis, video-fluoroscopy of joint replacement, pre-operative planning, surgical navigation, and standard radiostereometry would require tools for easy access to three-dimensional graphical representations of rigid segment motion. Relevant data from this variety of sources need to be organised in structured forms. Registration, integration, and synchronisation of segment position data are additional necessities. With this aim, the present work exploits the features of a software tool recently developed within a EU-funded project ('Multimod') in a series of different research studies.

Methods. Standard and advanced gait analysis on a normal subject, in vivo fluoroscopy-based three-dimensional motion of a replaced knee joint, patellar and ligament tracking on a knee specimen by a surgical navigation system, stem-to-femur migration pattern on a patient operated on total hip replacement, were analysed with standard techniques and all represented by this innovative software tool. Segment pose data were eventually obtained from these different techniques, and were successfully imported and organised in a hierarchical tree within the tool.

Findings. Skeletal bony segments, prosthesis component models and ligament links were registered successfully to corresponding marker position data for effective three-dimensional animations. These were shown in various combinations, in different views, from different perspectives, according to possible specific research interests.

Interpretation. Bioengineering and medical professionals would be much facilitated in the interpretation of the motion analysis measurements necessary in their research fields, and would benefit therefore from this software tool.

Keywords: Gait analysis; Stereophotogrammetry; Videofluoroscopy; Radiostereometry; Surgical navigation; Graphical representation; Registration; Synchronisation

1. Introduction

Quantitative movement analysis is performed in clinical and biomechanical research to comprehend the mechanics of the musculo-skeletal system in simple motion exercises as well as during the execution of complex motor tasks (Cappozzo et al., 2005). Absolute and relative movement of bony segments, of soft tissues and also of prosthesis components are measured using several different techniques. Although important measurement errors are implied (Andriacchi and Alexander, 2000; Chiari et al., 2005; DellaCroce et al., 2005; Leardini et al., 2005b), enormous knowledge has been attained from these techniques, both in healthy and pathological conditions.

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Gait analysis by optical stereophotogrammetry has contributed hugely (Andriacchi and Hurwitz, 1997; Gage, 1993) in many clinical decision processes related to disease diagnosis, treatment indication, and rehabilitation recommendations. In the field of total joint replacement, this analysis has been complemented with more accurate, though less wide-ranging, measurements of the replaced joint kinematics (Banks and Hodge, 2004; Stiehl et al., 2001). Standard single plane fluoroscopy is used together with the CAD models of the prosthesis to reconstruct three-dimensional (3D) position and orientation in space, hereinafter referred to as pose, of the components by using various techniques (Banks and Hodge, 1996; Dennis et al., 1996; Zuffi et al., 1999). Component relative motion is then calculated, which provides important information for the functional assessment of the replaced joint during daily living activities (Banks et al., 2003; Callaghan et al., 2001). More recently, computer assisted surgery has enhanced to a great extent the access of the surgeons to awkward anatomical structures and unknown geometrical references during surgery (Gebhard et al., 2004; Muller-Alsbach and Staubli, 2004; Nizard, 2002). The ability to track bony segments and instrumentation tools allows more accurate surgical actions by a virtual representation of the relevant anatomical structures. Finally, in a much smaller range of motion, radiostereometry has been performed in thousands of patients since the early seventies (Selvik, 1989), particularly in the context of joint replacement (Karrholm et al., 1997; Ryd, 1992). The course of many orthopaedic implants has been predicted in large advance from measurements of implant-to-bone micro motion obtained by relevant double X-ray exposures at several early follow-ups.

After initial utilisation of these techniques separately, the recent trend is for multiple analyses which combine disparate observations from the same patient and look for possible correlations with the scope of thorough assessments of treatments. Full body kinematics and kinetics from gait analysis in total knee replacement patients was integrated valuably with fluoroscopy (Fantozzi et al., 2003). Micro-motion at the component-to-bone interface by radiostereometry was combined with gait analysis to estimate the forces transmitted at the joints (Hilding et al., 1996). Simultaneous fluoroscopy and gait analyses were performed to quantify skin motion artefact at the thigh and shank (Stagni et al., 2005). Combinations of medical imaging, electrogoniometry and electromagnetic tracking have been reported extensively particularly for biomechanical analyses of the knee (Komistek et al., 2005; McPherson et al., 2005). Finally, the progressively more frequent use of bone models reconstructed from medical imaging (Shelburne and Pandy, 2002; Simon and Lavallee, 1998; Van Sint et al., 1997; Otake et al., 2005), also in the context of medical education (Höhne and Pflesser, 1996; Van Sint et al., 2003), increases the need for easily accessible software tools which would enable effective graphical representations of body segment motion.

Results from these techniques are reproduced in several forms but 3D segment motion is fundamental for comprehension and interpretation of the clinical and biomechanical observations. Bone and soft tissue motion, to serve as support to the clinical decisions, must be provided as quantitative measurements but also in a suitable format to be comprehended by any professional. A direct visual representation of the phenomenon is therefore becoming increasingly requested, overcoming the pioneering representations by 2D stick-diagrams in gait analysis, and by overall 'maximum total point motion' in radiostereometry (Valstar et al., 2005). Special graphical features such as transparencies, rendering, and operations on the view camera, are also appreciated. The rare utilisation in the routine practice of these techniques can also be accounted for the limitations of the current tools in managing the complexity of the relevant data. These are heterogeneous, coming from different instruments and processing techniques, and collected with various spatial and temporal references. Customisation of musculo-skeletal models also would need easy management of medical imaging and of spatial registration techniques. The general aim of the present study was to enlarge the access to powerful software tools which would support adequately clinical and biomechanical professionals to merge and report this variety of data in an efficient way.

Very recently, newly developed tools potentially offer solutions to these problems by making available data management and visualisation systems. Among these, the DataManager © (DM, freely available at www.tecno.ior.it/datamanager.htm), developed in the frame of the EU-funded project 'Multimod' (IST-2000-28377), is a promising generic application which allows the combination of a variety of biomedical data from multiple sources into a single environment (Leardini et al., 2005a). It was designed specifically to perform data fusion and multimodal visualisation of disparate data used in biomedical research, in particular to import, organise, view, and operate on a large spectrum of models and measurements. The scope of the present study is to evaluate these features in a variety of possible clinical and biomechanical applications. Particularly, we want to verify whether DM can be considered as a valuable solution to the lack of integration, synchronisation, registration, and accessibility to motion data of the musculo-skeletal system.

2. Methods

The DM is an application generated using the Multimod Application Framework (Viceconti et al., 2004), whose most of the relevant features are reported elsewhere (Leardini et al., 2005a). DM can import 3D volumes in DICOM format, polygonal surfaces in STL or VRML formats, images from JPEG, TIFF, GIF and BMP files, motion data from C3D, PGD (Cappozzo et al., 1995) and ASCII files, the latter thus allowing import of any time-varying vector (marker trajectory, ground reaction force, joint moment) or scalar (EMG signal) entity from gait analysis.